Improving Allied Performance in the Battle of the Atlantic: A GA Approach

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1 Introduction

1.1 Historical Background

The second world war was the most devastating conflict in human history. Fought by the Allies consisting of the UK, France, the US, and the USSR and their respective dependants and minor allies and the Axis consisting of Nazi Germany, Italy, Japan, and their respective dependants and minor allies. Despite the eventual victory of the allies in the conflict, their was a stretch between June of 1940 and June of 1941 where the UK and her empire were the only great power left on our side. World war two started in September of 1939, with Britain and France on the side of the allies and Germany being the only active Axis member. On June 25, 1940, France was forced to surrender to the Axis. Italy and several smaller European nations had joined the Axis earlier the same year, and it looked like Japan was gearing up to join as well.[2] Unfortunately, help was more than a year away. Although sympathetic to the Allied cause, the Soviet Union would not be able to join the war until June of 1941 and the United States would not be able to join the war until December of 1941.[2] Until then, Britain had to stay in the war and keep the Axis occupied in non-European theatres like North Africa to prevent a buildup of Axis military strength while the other great powers prepared to join.

In order to keep Britain in the war, the British isles needed raw materiel and manpower shipped in from across her empire as well as military materiel provided from the US on credit. The Germans were aware of this vulnerability, and exploited it in the Battle of the Atlantic. The German plan was to disrupt British Shipping by mass deployment of commerce raiding submarines called 'U-Boats' with the goal of sinking as much shipping gross registered tonnage as possible, starving out the British and forcing a surrender.[2] Thankfully, the efforts of the German navy were ultimately unsuccessful. The allies won the battle of the Atlantic, but at great cost. Tens of thousands of lives were lost and 2895953 gross registered tonnage of allied shipping was lost between June 1940 and June 1941 alone.[7]

1.2 Problem Statement

Historically, the locations of U-Boats and the potential outcome of convoy routes was neither known nor computable. Before the development of Centimetric Radar and the cracking of the German Enigma machine, convoy routes were planned to minimize shipping loss with minimizing distance travelled used as a heuristic for route planning.[3] Nowadays, we can do better. U-Boat location data is publicly available as is convoy routing and losses data. We can answer the question: can we plan better than historical convoy routes using a genetic algorithm? If the answer is yes, we can determine just how much shipping could have been saved had better routes been chosen.

2 Methodology: The Genetic Algorithm Approach

2.1 Overview

For this problem, I decided to go with a Genetic Algorithm approach. Individuals consisted of paths across the Atlantic from the three main sources of Britain-bound convoys in the June 1940 - June 1941 period: Halifax, Gibraltar, and Sierra Leone. The world space was constructed by reviewing databases of U-Boat encounters and historical U-Boat locations day by day and mapping this data to locations in the German Naval Grid System. Fitness of an individual was defined as the expected tonnage loss of the candidate route for the individual's convoy class. Parent selection was done by MPS with Recombination done by swapping route subsections for convoy routes with coinciding nodes. Parents were selected to make an offspring set equal in size to the target population count. Survivors to the next generation were then selected by $\mu + \lambda$ with the lowest tonnage loss individuals in both the current generation and the offspring set combined. The Genetic Algorithm was run for 100 generations.

2.2 Constructing the World Space

The world space for route planning was based on the German Naval Grid system. This system segments the Atlantic ocean into sections with the centre point of each section intended to be 480 nautical miles from the centre of each adjacent section.[5] Convoy paths can be represented using this grid system as a sequence of grid square identifiers between the convoy source node and one of two convoy destination nodes in the UK. The convoy source nodes were BB for Homeward from Halifax, CG for Homeward from Gibraltar and ET for Sierra Leone to UK. The destination nodes were AM and AN, the two nodes making up the mainland UK. See Figure 1

Each square had a month-by-month breakdown of estimated probability of U-Boat encounters in that square. This was based on an in-depth survey of over 1500 U-Boat daily position reports against whether or not convoys passing through that grid square encountered a U-Boat that month from over 400

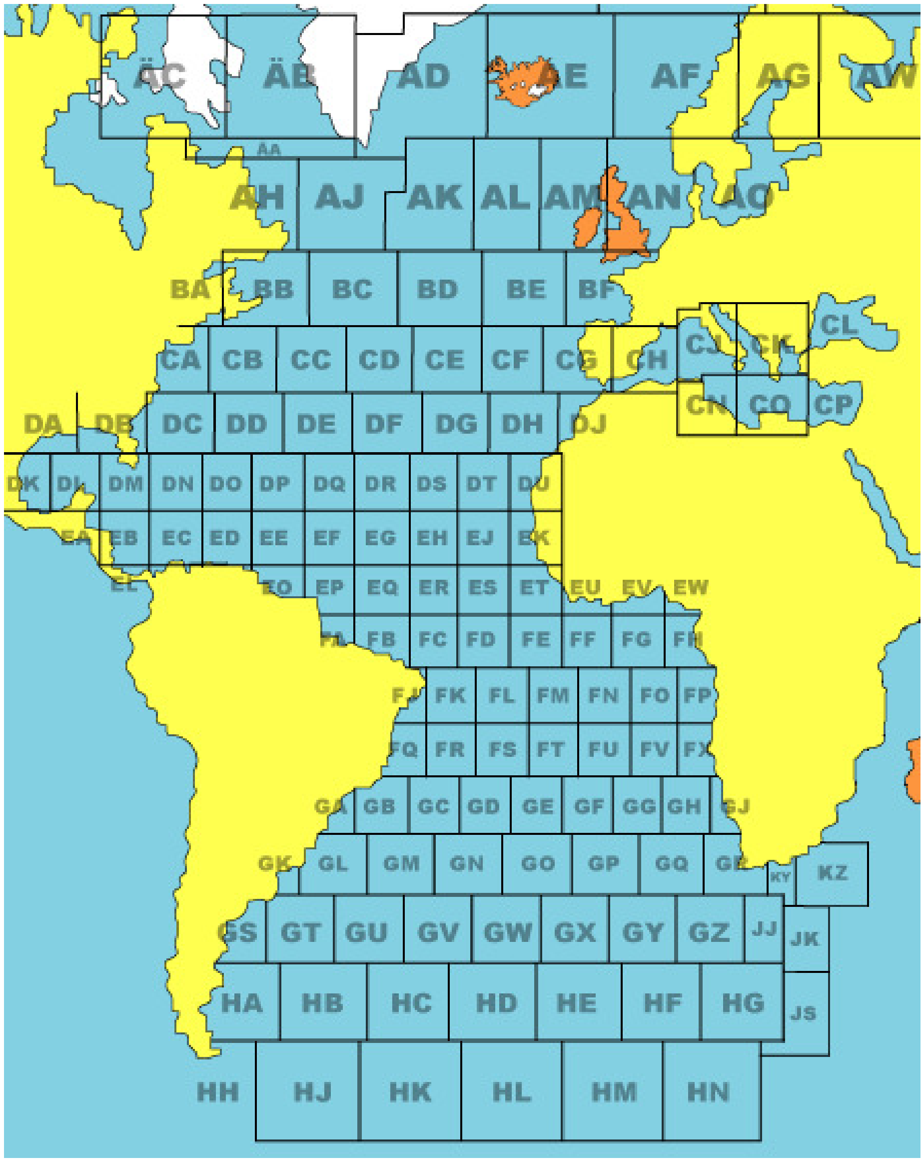

Figure 1: The German Naval Grid system over the Atlantic Ocean.[4] Note that BB is the source node for Halifax, CG is the source node for Gibraltar, and ET is the source node for Sierra Leone.

convoy after action reports. I personally conducted this survey. Data was provided courtesy of uboat.net and warsailors.com.[4][6] This survey also yielded the expected loss per encounter value used for fitness calculation.

2.3 Individual Representation

Individuals consisted of a sequence of grid spaces with space at index 0 being the start location of the convoy route the individual is a candidate solution for and the final index being a node in the UK (AM or AN). Each individual also kept track of their expected loss per U-Boat encounter, which was a historical calculation on the performance of the convoy the individual is a candidate for. Individuals are generated by a blind search between their convoy's start space and one of the two end spaces AM and AN.
Individual fitness was calculated according to the function

$$f(i) = \Sigma_s \Sigma_g P(U|m_s, g) * EL(i)$$

Where s is the list of voyages by month made by the convoy the individual is a candidate solution for, m_s is the month of each voyage, g is the list of grid squares in the candidate solution's route, $P(U|m_s, g)$ is the probability of encountering a U-Boat in a given grid square in a particular month, and $EL(i)$ is the expected loss for this individual's convoy class per U-Boat encounter from historical data. This fitness function yields an estimated GRT loss by this individual's candidate route. Since fitness is worse when $f(i)$ is higher and better as $f(i)$ approaches 0, this is a minimization problem.

2.4 Parent Selection and Introducing Variation

Each generation, p parents are chosen at random from the population where p is the population size of a convoy class. Parents are chosen according to multi-pointer selection. A temporary population of p offspring is generated from this parent set. All individuals in both the current generation and the temporary population may have mutation applied to them, not just offspring, a technique for pathfinding GAs found during literature review.[1]
Recombination is performed according to a recombination probability. (See section 2.6) Recombination can occur if two parents share a grid space in their candidate routes that are neither one of the parent's start spaces nor the UK spaces. Recombination swaps the two sub-paths of the parents after the shared space to generate offspring. See figures 2, 3 for an example of how Recombination works.
Mutation is done according to a mutation probability. (See section 2.6) Mutation occurs by selecting a grid space in a candidate's route as a mutation start point. A mutation end point is then selected further along the route. All intermediate spaces are removed. A blind search is made between the start and end point with the restrictions that this new subpath cannot be longer than the original route and that the new total route length cannot be higher than 6500 nautical miles.

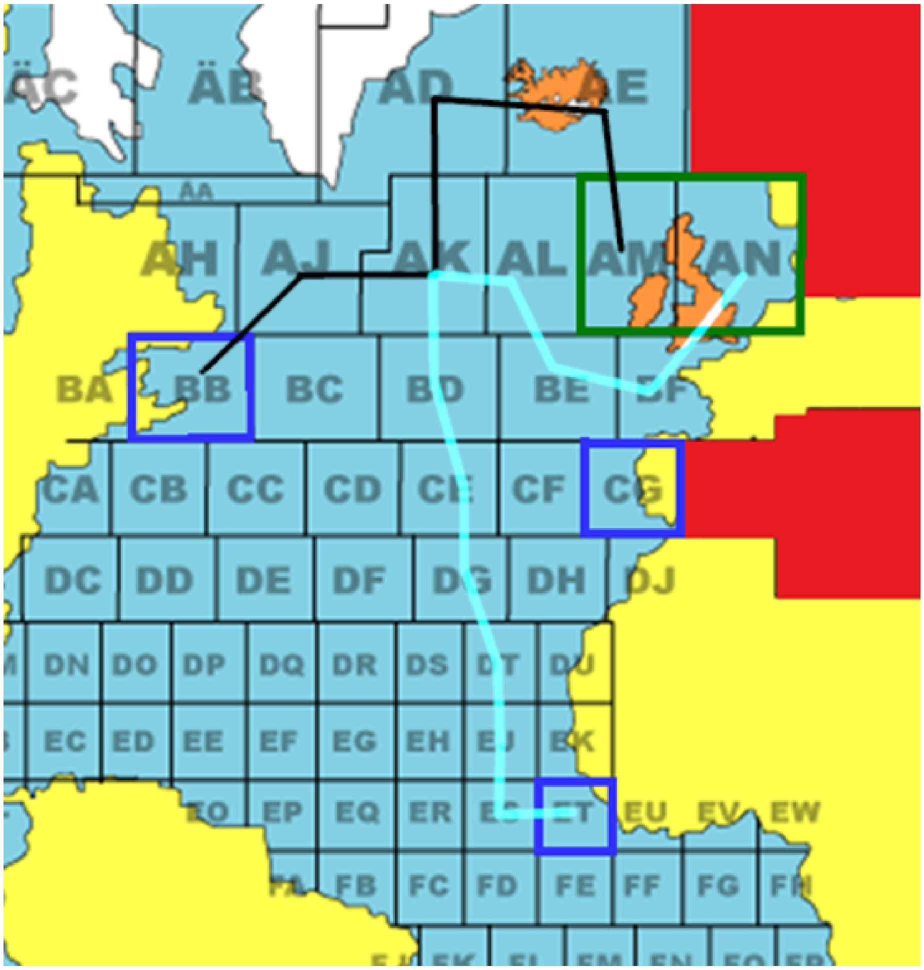

Figure 2: Two parent paths for which recombination is possible. Note how both paths pass through grid space AK. See figure 3 for offspring of this recombination.

2.5 Survivor Selection

Survivors are selected according to $(\mu + \lambda)$ selection. The current generation and the offspring set are ranked and the target population for each convoy class is selected from the top candidates of this unified ranked set. The population remains persistent for each convoy class across all generations.

2.6 Hyperparameters

The following Hyperparameter values were used for the genetic algorithm. These were tweaked to run in the lowest time possible without incurring a GRT loss

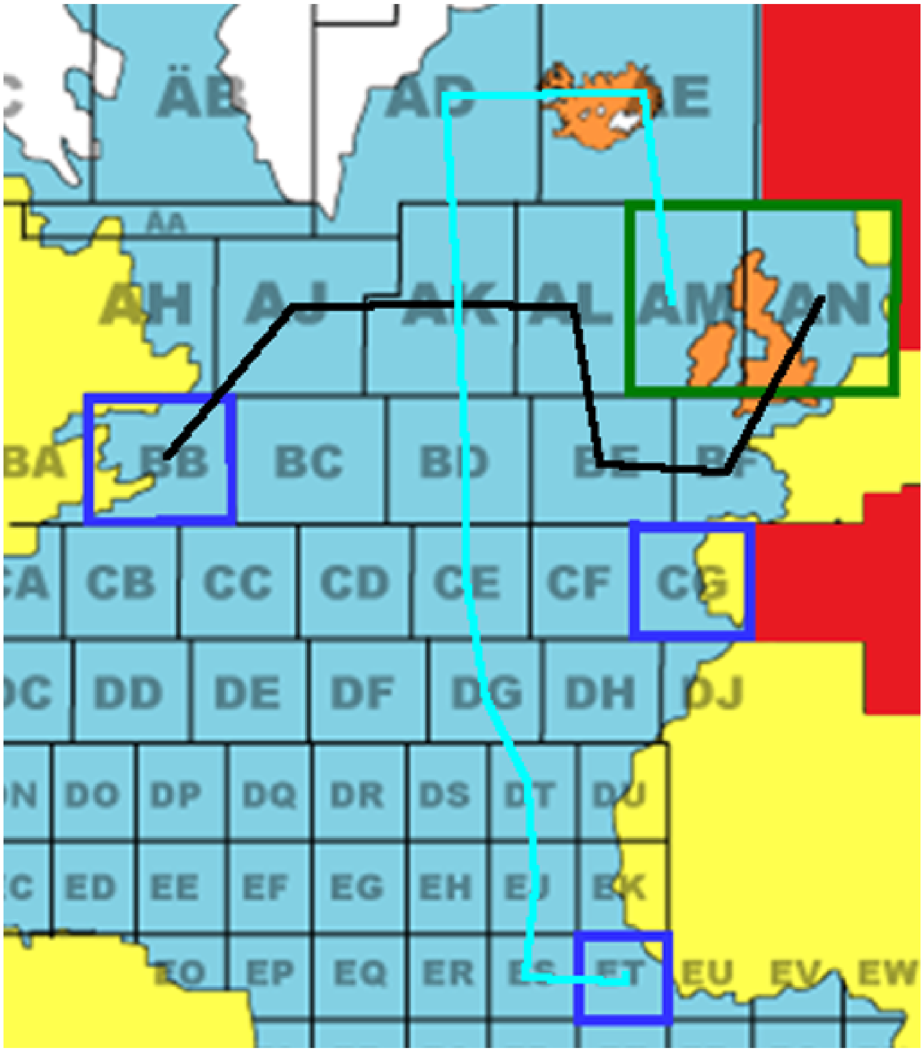

Figure 3: Continued from Figure 2. After recombination, the paths after the coincident grid space are swapped in the offspring.

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performance penalty:

mutation probability: 0.05

recombination probability: 0.80

maximum convoy route length: 6500 nautical miles

population size: 100 per convoy class

generation count: 200

2.7 Alternate Solution: Dijkstra's Algorithm for Semi-Historical Route Selection

Unfortunately, exact tonnage loss for the time range June, 1940 - June, 1941 is not available in a satisfactorily exact quantity for the three relevant convoy classes. But, we do know how the convoy routes were decided (see 1.2), which was by taking the shortest oversea route between the convoy start location and the UK. To compare our solution to a semi-historical equivalent, I chose Djikstra's pathfinding algorithm as the alternate solution. This solution yields the shortest sequence of grid spaces between the source node and the UK for each convoy class. We can take these routes and apply our fitness function to get an estimate tonnage loss for each convoy route.

3 Results

The results for each convoy after termination of the Genetic Algorithm are visible in Table 1. The results for each convoy from the routes generated by Dijkstra's algorithm are visible in Table 2. The paths generated by Djikstra's algorithm were [BB, AJ, AD, AE, AM] for Homeward from Halifax, [ET, EJ, DS, DG, CF, BE, AM] for Sierra Leone to UK, and [CG, BE, AM] for Homeward from Gibraltar. The paths generated by our GA solution were [BB, AH, AA, AD, AE, AN] for Homeward from Halifax, [ET, FD, ER, EG, DQ, DE, CC, CB, BB, AJ, AD, AE, AN] for Sierra Leone to UK, and [CG, BE, AM] for Homeward from Gibraltar.

Convoy	Loss of best solution (in GRT)
HX	67664.3
HG	73200.0
SL	124960.0

Table 1: GRT losses for best route of each convoy generated by our GA solution. HX is Homeward from Halifax, HG is Homeward from Gibraltar, and SL is Sierra Leone to UK.

Convoy	Loss of best solution (in GRT)
HX	90927.5
HG	73200.0
SL	189024.0

Table 2: GRT losses for best route of each convoy generated by Dijkstra's algorithm. HX is Homeward from Halifax, HG is Homeward from Gibraltar, and SL is Sierra Leone to UK.

4 Discussion

4.1 Interpreting Results

Our results show a clear performance gap between the historical problem approach and our own. Our solution lost 265,824.3 GRT, which while not ideal, is still nearly 90000 GRT less than the Dijkstra's algorithm approach which lost 353,151.5 GRT. The paths generated by our algorithm also seem to have an emergent reasoning behind each. In the case of Homeward from Halifax, the GA path moves up as far north as it can and follows the edge of the arctic ocean until it is north of the UK at which point it moves directly to the UK. This is a smart plan, as much of this route is out of the operating range of most U-Boats due to distance from German occupied Europe and extremely low water temperature. The Sierra Leone route it comes up with has the convoy move across the Atlantic to American territorial waters before moving North to the Arctic circle and following the same path as Homeward from Halifax. This is also a very cunning approach, as the Germans cannot attack the convoy most of the route either because of range or out of a desire not to violate American territorial waters and bring America into the war early. Homeward from Gibraltar follows a more historical approach, presumably because it starts too close to German controlled sea to make a break across the Atlantic in the same way our Sierra Leone convoy does worth it.

4.2 Potential Future Work

We've shown that convoy supply routes can generally be planned with a genetic algorithm and yield positive results. An obvious future extension of this work would be designing a system for predicting U-Boat encounter probability without relying on historical data, allowing its application to convoy routing tasks in the modern war environment.

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