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Eric Gutierrez, Jonathan Juett, Christopher Kiekintveld

Introduction

The United States Customs and Border Protection agency and the United States Border Patrol are tasked with securing the U.S. borders against illegal entry of people and goods. Due to limited resources, it is not possible to have a constant security presence at every point along the border, and intelligent criminals are constantly seeking ways to circumvent security measures. Given this context, an important question facing analysts and decision makers for the Border Patrol is how to effectively allocate the available resources at both the strategic and tactical levels to maximize border security. We use a game-theoretic framework coupled with simulation and genetic algorithms to generate, analyze, and visualize patrolling and resource allocation strategies. The goal of the analysis is to find effective strategies to improve interdiction rates. Game theory is used to account for the adversarial aspect of the problem, in which criminals will adapt to new security policies. Simulation and genetic algorithms provide scalability to analyze more complex patrolling problems with realistic problem features including varying terrain and movement costs.

Border security is an important element in the national security focus of the United States in the last decade. The United States Customs and Border Protection agency (CBP) and the United States Border Patrol (USBP) under the Department of Homeland Security (DHS) both have the primary responsibility to defend and secure both land and sea borders. Technology and highly trained personnel have been incorporated into a national strategy that is aimed at securing the U.S. borders from illegal intrusion.¹ This includes the detection and apprehension of illegal trafficking of humans, drugs, weapons, contraband, and the prevention of terrorist activity.

Since the 1990s, the USBP has adopted an operational strategy that focuses on preventing illegal entry into the U.S. through deterrence.² This has included deploying a combination of infrastructure, manpower, and technology to detect and apprehend individuals involved in illegal activity, as well as executing legal strategies to deter illegal activity based on the risk of being caught and prosecuted. While many illegal entry attempts take place at official ports of entry (POEs), others take place in the long and sometimes remote stretches of border in between POEs.³ In these areas, the Border Patrol uses patrols and sensor technology to detect illegal entry attempts.⁴ Due to limitations in resources and the difficulty in making precise estimates about the total flow of illegal activity that is undetected, it is not always possible to assess how successful the patrolling strategies are, since apprehension data alone does not provide a

¹ "Border Patrol National Strategy 2012-2016." *U.S. Customs and Border Protection*, 2012, available at: http://www.krgv.com/files/2012-2016_BP_Strategy.pdf.

² Nunez-Neto, Blas. "Border Security: The Role of the U.S. Border Patrol." *Cornell University ILR School* (2008).

³ "Border Patrol National Strategy 2012-2016."

⁴ Joel Predd, Henry Willis, Claude Setodji and Chuck Stelzner. "Using Pattern Analysis and Systematic Randomness to Allocate U.S. Border Security Resources." *RAND: Homeland Security and Defense Center* (2012).

complete picture. The objective of our work is to provide improved analysis capabilities to better understand and optimize the effectiveness of patrolling and resource allocation strategies.

Our approach is based on a game-theoretic framework. Game theory is a way to mathematically model and analyze decision problems with multiple decision makers, including adversarial situations. The approach involves specifying the possible decisions that each player in a game can make, and the outcomes that result from different combinations of actions chosen by each player. Richer game formalisms can account for sequential decisions, uncertainty, asymmetric information, and other complexities. A large number of solution concepts have been developed for predicting behaviors in games, which in turn can be used to recommend strategies to the players.⁵

An important feature of game theory for security domains is the use of randomized strategies. In security domains like border patrolling, adversaries (e.g., transnational criminal organizations) are constantly using surveillance to gather intelligence about security operations to adapt their actions to avoid detection and interdiction. If security operations, such as patrols, are too predictable, it makes it easy for adversaries to learn patterns in the security operations that can be exploited. Using randomization can be an effective way to improve the efficiency of security policies, and game-theoretic models can be used to identify the right ways to randomize for a specific problem based on predicting the adversaries' responses to security policies.

Border patrol is a highly complex domain, with extremely large strategy spaces and factors such as varying vehicle capabilities and terrain features to consider in the models. The analysis of such problems using game theory is very challenging from both a modeling and computational perspective. We develop a simulation tool called GAMMASys that aids in this analysis. The tool uses multi-agent simulations to study the game, including the use of genetic algorithms to approximate optimal strategies and Monte Carlo techniques to approximate the interdiction rate for different combinations of strategies. Using these simulation techniques allows us to model relatively large areas, varying terrain, multiple vehicle types, multiple patrolling agents, and other realistic features. We can also use GAMMASys to support visualization of the simulations and resulting strategies.

GAMMASys

GAMMASys (Genetic Algorithm for a Map-based Multi-Agent System) is a multi-agent simulation tool based on game theory and genetic algorithms for analyzing patrolling strategies. It has three main features that provide a unique combination of capabilities. First, it supports analysis and visualization of patrolling strategies for a relatively complex domain model that captures a large physical area with varying terrain types and multiple mobile agents with different capabilities and movement speeds. The strategies of both the patrolling and evading agents are captured using randomized policies on a hexagonal grid. Second, our model explicitly accounts for the adversarial interactions between the players by using a game-theoretic framework. This leads to the use of randomized, unpredictable strategies to keep the opponent guessing. Third, our solution methods are based on genetic algorithms and simulation. While

⁵ Camerer, Colin. *Behavioral Game Theory: Experiments in Strategic Interaction* (New York: Russell Sage Foundation, 2003).

these techniques cannot guarantee optimal solutions, they are highly scalable and allow us to analyze much more complex scenarios than can be solved with optimal game-theoretic solution algorithms. Our results provide evidence that the solutions achieved by these approximation methods are of high quality.

Our game model has multiple agents, including both patrolling (defending) agents and evading (attacking) agents. The patrolling agents (i.e., border patroller) attempt to capture the evading agents (i.e., smugglers) before the evading agents can reach their goal. The game takes place on a hexagonal grid that models the movement of the agents in a two-dimensional physical area. Figure 1 shows an example of the current user interface for GAMMASys, including a sample scenario. In this case a 16x16 grid is shown as an overlay to a real satellite map image of a border area taken from Google Maps. The grid squares have different colors (encoded by the user) that represent different kinds of terrain (e.g., grassland, water, desert, etc.). Both agent types can have different transportation types (e.g., foot, car, ATV, boat, etc.), and the movement speed of the agent depends both on the vehicle type and the terrain. The defender cannot communicate with other defenders and cannot detect the attacker except by occupying the same grid space. The game ends when either the defender captures the attacker, or the attacker reaches its target node. We also include two different preferences for the attacker. Attackers prefer both to reach the target without being caught, and to reach the target by the shortest possible route. This behavior is controlled by a *caution* parameter, with more cautious attackers placing a higher weight on evading capture.

Figure 1: GAMMASys Tool depicting a 16x16 grid with terrain representing an outlay of a portion of Colorado National Monument (Satellite Image from Google Maps).

The results of the game for specific agent strategies can be visualized using the tool shown in Figure 1. The visualization shows the decisions made by the defender and attacker agents during the course of the game, including the final outcome. The visualization aspect of GAMMASys brings a more realistic environment to the game simulation, and allows an analyst to better understand the outcome of the game and the suggested strategies.

Another key functionality of the tool is to generate suggested patrolling strategies for the defender. We currently model defender strategies using random movement probabilities based on

only the current location, which are called Markov strategies.⁶ The defender has a probability of travelling along each of the six facial directions of a hexagonal node, or staying inside the hexagon. This class of strategies is restricted, which means that it may not contain the optimal strategy. However, it is highly efficient from a computational perspective. In future work we plan to introduce additional strategy representations. Even for this restricted class of strategies, searching the space for an optimal one is an extremely difficult computational problem. We turn to genetic algorithms as a way to approximate the solution. We create a large population of patrolling strategies, and during each iteration of the algorithm we evaluate the fitness of each strategy. This is done by first calculating the best path for an attacker to take against this specific patrolling strategy, taking into account the attackers' caution. The capture probabilities for each path are estimated using Monte Carlo simulation. Finally, the best strategies from each generation are kept for the next generation, and a number of new candidate strategies are created using crossover and mutation. This process is motivated (loosely) by biological evolution, and is an effective heuristic approach for finding good strategies quickly in a very large space.

Analysis and Results of Experiments

We now show some initial results of experiments conducted using GAMMASys. The first provides a motivating scenario. Figure 2 shows an attacker with two possible destinations for intrusion. Because random directions are chosen for the defender path, it would be of low probability for a straight path to be generated, so GAMMASys must use a genetic algorithm to generate a large amount of strategies to find the best one to respond to the attacker's shortest path. In Figure 3, the attacker is taking the shortest path from its source node to the target node, regardless of its observation of the defender's locale in the beginning time steps of the simulation (the Defender's Zone). The defender will be able to capture the attacker in most simulations based on the attacker's inability to adapt to the defender's location even though it observed that the defender tended to frequent an area of nodes at the beginning of the game simulation.

Figure 2: ATV Attacker/Defender

(1 Source, 2 Targets)

Figure 3: ATV Takes Shortest Path

⁶ Geyer, Charles J. "Practical Markov Chain Monte Carlo." *Statistical Science* 7:4 (1992): 473-483.

One characteristic of these examples is that both of these players are of the same unit type and it can be assumed that they both move at the same speed. We also want to investigate what would happen to the capture rates if these players travelled at different speeds based on vehicle type. We conducted an experiment varying the delay speed of attackers and defenders to analyze how delay affects the capture rate. Delay refers to the amount of time that an agent will spend in a single hexagon during the simulation, and differences in the delay are expressed as ratios of the relative speed of the two players.

Figure 4: Average of Best Captures

Based on delay.

Figure 5: Max of Best Captures

Based on delay.

Figures 4 and 5 depict the results of the average-best and maximum-best captures based on speed delay between the attackers and defenders. The results shown are averaged over 50 trials. Figure 4 shows the average of the best performing strategy over all trials, while Figure 5 shows only the best case over all fifty trials (simulating random restarts as part of the solution algorithm). The genetic algorithm is allowed to run for up to 500 generations, but GAMMASys contains a feature to cut off test cases if the capture rate does not improve within a certain number of generations to save computation time. Because of this, the graphs limit the range to 300 based on the solutions of the tests in both Figures 4 and 5.

Figure 6: Defender's Initial Moves

Attacker observing defender's initial moves and reacting with caution

Figure 7: Max of Best Captures

Max of best captures of multiple defenders vs. attacker with caution.

In Figure 3, the attacker observed the Defender's Zone from the defender's initial moves, and set its path straight to the target. This was due to the attacker having no caution. When the caution is altered, the attacker will move slower throughout the hexagonal nodes, and will attempt to move outside the Defender's Zone and then find the shortest path to the target node. Figure 7 shows the overall best capture rates when using multiple patrollers ranging from one to five defenders, while the attacker has a caution value of one million. In this case, the capture rates of all test cases reach nearly one hundred percent and converge at similar rates. The results are also similar to test cases with zero caution. As seen in Figures 4 and 5, the slower the attacker moves the more captures the defender can achieve, if the generated strategies are effective. Figures 8 and 9 also show that an attacker with no caution may be more difficult to catch than an attacker with a high caution value. When conducting a grid size test between 3x3, 5x5, 10x10, and 15x15, the capture rate of attackers with both a caution value of zero and one million seem to be around the same. This could be for a number of reasons, but most likely because the terrain is uniform and the tests conducted are not challenging for the defender. In Figure 9, capture rates increasingly drop when more source and target nodes are added, but increase when a fifth set of source and target nodes are introduced. In future work we plan to introduce additional tests, including scenarios more challenging to the defender which should show these patterns more clearly.

Figure 8: Average Best Captures

Averaged best Captures for grid Sizes.

Figure 9: Average Best Captures

Figure 9: Averaged best captures for multiple source/target nodes.

Related Work

Several studies have introduced methods to enhance patrolling strategies. For example, experiments have been conducted to produce effective patrolling strategies using multiple autonomous robots. This experiment used a *swarm* approach, where the defenders could communicate.⁷ A similar experiment using police patrolling was also conducted. This program used weights to symbolize importance of patrol areas.^{8 9} A RAND study focused on using

⁷ Alessandro Marino, Lynne Parker, Gianluca Antonelli and Fabrizio Caccavale, "Behavioral Control for Multi-Robot Perimeter Patrol: A Finite State Automata Approach." (2009), available at: ieeexplore.ieee.org; Nicola Gatti Nicola, Sofia Ceppi and Francesco Amigoni, "Extending Algorithms for Mobile Robot Patrolling in the Presence of Adversaries to More Realistic Settings," *Proceeding WI-IAT '09 Proceedings of the 2009 IEEE/WIC/ACM International Joint Conference on Web Intelligence and Intelligent Agent Technology* 02 (2009): 557-564.

⁸ Adriano Melo, Mairon Belchior, and Vasco Furtado, "Analyzing Police Patrol Routes with the Simulation of the Physical Reorganization of Agents," (2005).

pattern/trend analysis and systematic randomness to better distribute resources to border zones to increase interdiction rates. This study addressed the problem that intruders will change their tactics based on border patrol actions. Their solution was to implement systematic randomness into the decision-making process of allocating resources to border zones, which would make border patrol actions less predictable.¹⁰ A program has also been designed that uses a genetic algorithm that is similar to the one used by GAMMASys to observe adversarial interaction in war games. This genetic algorithm was used to increase attacker strategies, while GAMMASys uses a genetic algorithm to generate stronger patrolling strategies for the defender.¹¹

Recommendations and Conclusion

Like many intelligence entities, USBP is collecting information and developing usable intelligence. GAMMASys provides a new tool for analyzing different intelligence data and resource allocation questions, and supports the analyst in exploring various “what if” scenarios. During the analysis phase, GAMMASys can be used to create patrolling strategies and to assess their effectiveness in simulation. Some organizations do not use the intelligence cycle depicted in Figure 10, but recording intruder detection and the use of GAMMASys can be conducted in phases similar to the “Collection” and “Analysis” phases.¹²

Figure 10: The Intelligence Cycle with Recommendations.

While GAMMASys is initially targeted at border patrolling scenarios, we note that patrolling is a common operation across many security domains and the tool could be useful for analysis in

⁹ Chawathe S. Sudarshan, "Organizing Hot-Spot Police Patrol Routes," In *Intelligence and Security Informatics, 2007 IEEE* (2007): 79-86.

¹⁰ Predd, Willis, Setodji and Stelzner, "Using Pattern Analysis and Systematic Randomness to Allocate U.S. Border Security Resources."

¹¹ Timothy E. Revello and Robert McCartney, "Generating War Game Strategies Using a Genetic Algorithm." In *Evolutionary Computation, 2002. CEC'02. Proceedings of the 2002 Congress on* vol. 2 (2002): 1086-1091.

¹² Lowenthal, Mark M.. *Intelligence: from Secrets to Policy*. 5th ed. (Los Angeles: SAGE/CQ Press, 2012); Todd Bascatow, Dennis Bellafiore, Donna Bridges and Susan Harter. "Intelligence Process." *Intelligence Process | The Learner's Guide to Geospatial Analysis*, available at: <https://www.e-education.psu.edu/sgam/node/15>.

these domains as well. One example of how this program could be altered is for the use of Unmanned Aerial Vehicle (UAV) patrolling. The terrain on the grid could be changed to represent weather patterns, cloud positions, or obstacles, such as buildings or mountain ranges. It would also be interesting to explore combinations of ground-based and air-based units to identify strong joint patrolling strategies, as well as to incorporate the possibility for ground-based sensors that could enhance patrolling activities.

Our development of GAMMASys is ongoing, and we plan to explore more sophisticated defender and attacker strategies in the future, as well as better terrain/vehicle models, observation models, and other features. We also plan to continue working to improve the solution algorithms to enable faster solutions and to explore more complex scenarios. However, the most immediate goal is to use the existing simulations to explore questions of interest to analysts. These can include a variety of resource use and allocation questions, such as the impact of terrain and movement costs on the number of defender resources required, the value of randomization in improving patrolling, and the impact of attacker caution and learning rates on the overall optimal strategies. We believe that the capability to provide insight into both the details of patrolling strategies and the higher-level strategic questions of resource allocation will make tools like GAMMASys an increasingly important tool for intelligence analysts and decision makers. Our initial results provide a proof of concepts for this in the border security domain.