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Tactical behavior optimization for a UGV teams

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Abstract

As combat increasingly shifts to robotic entities, these machines will progressively take over the roles traditionally performed by soldiers. A crucial aspect of future military robots is their ability to coordinate operations (swarming), which involves adapting each action to the real-time or projected joint operations landscape using available resources. This paper presents and explores a potential approach to adaptive and coordinated path planning for Unmanned Ground Vehicles (UGVs) in complex tactical environments. The task is mathematically modeled as a multi-criteria operational research problem, and a computer application has been developed to experiment with and test the proposed concept. The complexity of the solution and the overall significance of this field are areas of active research globally, and interest is growing, especially in light of a deteriorating security environment.

Keywords: UGV maneuver, SWARM, terrain analysis, cross-country movement, off-road navigation.

1. Introduction

Thanks to the rapid development of modern technologies, we are seeing an unprecedented boom in their application in the military. This research, which aims to evaluate the influence of micro-relief shapes on the mobility of military vehicles, is a crucial step in understanding and improving future military operations. These operations face revolutionary changes that are unmatched by anything we have seen in the military.

Army technology is influencing the ways of combat. It is evident from historical experience that the degree of difference in the advancement of the technology used fundamentally affects their outcome, in addition to technological superiority in the quality and quantity of combat (and other) assets, one of the critical elements on the battlefield is the area of command and control (C2—Command and Control). This is intended to maximize the effectiveness of using armed forces through "optimal management" in current operational conditions, with the development and use of AI and other advanced tools playing a pivotal role.

Modern trends in operational-tactical decision-making involve approaches based on so-called “planning to the width”, which is based on the concept of iterative forecasting and optimization of friendly courses of action. This supports the immediate decisions of commanders and staff, primarily at the tactical levels of command, and is implemented through permanent virtual modeling and simulation of combat activities during a military operation.

With the COAs optimization being carried out in such a way that a large number of possible variants, configurations, procedures, and tactical scenarios are simulated/calculated during the planning and management process of the operation, each partial simulation is evaluated by the coefficient of operational effectiveness and entered into a graph/tree of possibilities. Given the difficulty of implementing accurate forecasts for socio-economic systems, it is more appropriate to approach individual simulations as a potential that has a variant effect on the activities of friendly forces. Thus, rather than the exact variant of the enemy's advance under the given conditions, the variant representing a critical state or situation for the enemy's units is sought.

In the context of the transition of combat to robotic entities, the procedures provided by the soldiers will be continuously retaken by robotic entities. Thus, one of the decisive components of the capability of future military robots is their operational coordination (swarming) capability, which adapts each course of action within actual or estimated common operations picture, in real-time, and with available assets. This paper solves and discusses a possible approach to operational adaptive and coordinated UGV path planning in a complex tactical environment. The task is mathematically modeled as an operational research (multi-criteria) problem, and a computer application was developed for the proposed concept's experimentation and testing. The complexity of a solution and the general importance of this field are subjects of research activities worldwide, and within a deteriorated security environment, shared interest is on the increase.

2. State of the art analyses

To explore the state-of-the-art theory of graph-based models for strategy and movement of military forces in land operations, it is possible to issue from various research projects and articles in fields like operations research, military strategy, graph theory, and computer science. Research projects that explore the state-of-the-art are often interdisciplinary, involving collaboration between military institutions, universities, and research organizations. These projects typically integrate concepts from operations research, computer science, artificial intelligence, and military science. Hereafter are expressed some notable papers, research projects, and sources that cover this topic:

- "A novel differential evolution algorithm for threat-oriented weapon system planning", IEEE 2015, Can Liu; Bingfeng Ge; Kewei Yang; Jiang Jiang; Mengjun Li. A model of threat-oriented weapon system planning is first proposed, wherein countries must decide how much and when to develop weapons under a number of certain constrains to mitigate or even neutralize threats as much as possible. experimental results illustrate that the proposed differential evolution with neighborhood revision algorithm has an outstanding performance.

- "Optimizing an Autonomous Robot's Path to Increase Movement Speed", Gorgoteanu, Damian; Molder, Cristian; Vlad-Gabriel Popescu; Grigore, Lucian Ștefăniță, 2024. The goal of this study is to address the challenges associated with identifying and planning a mobile land robot's path to optimize its speed in a stationary environment. The robot's locomotion system and the characteristics of the terrain are the elements that must be taken into account when the planner is considering the limitations that affect the robot's progress.

- "Strategic maneuver and disruption with reinforcement learning approaches for multi-agent coordination", Derrik E. Asher, Anjon Basak, John Fossaceca, The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology 2022. In this paper are present overviews of prominent works in the Reinforcement learning (RL) domain with their strengths and weaknesses for overcoming the challenges associated with performing autonomous strategic maneuver and disruption in military contexts.

- "The analysis interface of dynamic network analysis for networked military organizations", IEEE 2022, Jincai Huang; Qing Cheng; Guangquan Cheng, School of Information System and Management, National University of Defense Technology, Changha, Hunan, China. The work of the paper shows promise as an effective interface of dynamic network analysis for Networked Military Organization (NMO), which is regarded a complete analysis framework for networked military organizations.

- "A multi-modal discrete-event simulation model for military deployment", Uğur Z. Yıldırım, Barbaros Ç. Tansel, İhsan Sabuncuoğlu, Simulation Modelling Practice and Theory 2009. This paper introduces a logistics and transportation simulation that is used to provide insights in-to potential outcomes of proposed military deployment plans. Simulation provided valuable insights as to when and what percentage of units would be at their designated destinations if the original plan had to be modified for more urgent deployment of military units.

Using graph theory for modeling and strategizing the movement of army forces in terrain involves sophisticated mathematical and computational approaches. These methods allow military planners to optimize routes, understand connectivity, and simulate various strategic scenarios. Here are some concepts and approaches:

- Shortest Path Algorithms: i) Dijkstra's Algorithm: Widely used for finding the shortest path in a weighted graph, this algorithm is employed to determine the most efficient route for moving forces across a terrain, ii) A Algorithm*: An extension of Dijkstra's, A* incorporates heuristics to guide the search for the shortest path more efficiently, particularly useful in dynamic environments where conditions may change rapidly, iii) Bellman-Ford Algorithm: Useful for graphs where edge weights may change over time or where there are negative weights, reflecting challenging or deteriorating conditions on the battlefield.

- Dynamic and Time-Varying Graphs: i) Temporal Graphs: Used to model scenarios where the graph's structure changes over time, such as when specific routes become impassable or new routes are discovered. Temporal graphs help in planning movements in environments where conditions are rapidly evolving, ii) Event-Driven Graphs: These graphs change in response to specific events (e.g., an enemy ambush or a natural disaster), allowing for adaptive strategies that quickly adjust to new realities on the ground.

- Game Theory and Graphs: i) Nash Equilibria in Networked Games: Used in scenarios where multiple opposing forces interact, game theory is combined with graph theory to model strategic decision-making, predicting how each side might optimize their movements based on the anticipated actions of the other, ii) Zero-Sum Games: Used to model direct conflicts where one side's gain is precisely the other side's loss, focusing on optimizing strategies for territory control and force movement.

- Optimization of Movement and Resource Allocation: i) Linear and Integer Programming on Graphs: Optimization techniques efficiently allocate resources and plan movements. Integer programming is particularly relevant for decisions involving discrete units (e.g., battalions or vehicles), ii) Heuristics and Metaheuristics: These approaches, such as genetic algorithms or simulated annealing, help in finding near-optimal solutions to complex movement problems where exact solutions are computationally infeasible.

- Interconnected Multi-Layered Networks: i) Multi-Layer Networks: In complex operations involving different types of units and assets (land, air, sea, cyber), multi-layered graphs represent interactions be-tween different domains, allowing for coordinated strategies across different operational layers, ii) Interdependency Modelling: Analyses how disruptions in one layer (e.g., cyber-attacks on communications) may affect operations in another layer (e.g., ground troop movements), enhancing resilience and strategic planning.

- Collaborative and Decentralized Control: i) Decentralized Algorithms: Enable units to make local decisions based on limited information, useful in environments where central communication is disrupted. This is often modeled using distributed algorithms in graph structures; ii) Swarm Intelligence: Inspired by biological systems, swarm algorithms model the collective behavior of decentralized units (like drones or small infantry units) to achieve strategic objectives without central coordination.

3. Approach to the solution

This paper introduces the possible approach to optimizing the cooperative ground maneuver in operational conditions. Generally, we search for the minimum of the overall tactical cost within all combinations of maneuvers of particular entities leading to the tactical objective (reaching the particular area or destination for each entity, for instance). Fundamentally, calculating the overall/total tactical costs could be a complex problem, and many ways could be selected. In our case, we take into account the following principles and logic:

- The graph topology is selected as a regular square/matrix node basement and eight connections from each node to the surrounding nodes with
- The entity could move only to a surrounding node in one step.
- The weight between the nodes considers the cost of movement, including geographic and tactical criteria (approachability, security, logistics, consumption, vehicle resistance, etc.)
- An additional "teaming" value could describe all possible deployment configurations, which could bring further benefits or penalties.

The following formula demonstrates the optimization intent:

$$TTOP_{\ UGV} = min \rightarrow \sum_{i=1}^{n}(Tp_i + BF(1,..,n)) \quad (1)$$

where:

$TTOP_{UGV}$ - UGV Team Tactical Optimal Performance

n – UGV count

i – index

Tp_i – Tactical Path of UGV_i

BF(1..n) – Benefit function of all UGVs (n) deployment configuration within motion defined by particular Tactical Paths.

The generic solution to this problem lies in investigating all possible configurations of UGV maneuvers and calculating the total sum of "operational cost" composed from the Tactical price of each UGV path and the sum of benefit function values. Even so, selecting the configuration with a total minimum operational cost is trivial; the number of combinations could be vast and complicate the practical application of this solution, mainly when we consider the operational graph of a million nodes and eight million weights (usually large 2D matrix with 1000 x 1000 and up).

Based on the mentioned fact, where the TSP approach is fundamentally convenient but computationally very expensive, we come to another potential approach, which is inspired by the "Dijkstra shortest path algorithm" principles with "online" weight calculation and could be characterized by following conceptual steps:

1. We follow Dijkstra's algorithm to evaluate the path cost in all nodes for all vehicles within the graph. These minimal paths fulfills primary axes in an N-dimensional structure, constituting an N-dimensional graph (NdimG).

2. Filling this structure follows Dijkstra's principles, and the calculated sum of particular UGV cost + BF for all combinations of options within one step is 8n. If n = 3, the possibilities create 64 values integrated within the NdimG. integrating a particular topology within the graph changes the number of adjacent nodes from 8 to 64.

3. The length of the base axes is about the initial graph node count, creating a relatively large structure (hundreds of MB for n=2 and far beyond the TB when n=3). Thus, additional heuristics are vital.

4. Dijkstra's algorithm is applied within this NdimG graph, and the shortest path codes the configuration of "optimal" positions per vehicle at each step.

This approach creates an initial conceptual solution for further evolvement and experimentation. It introduces many challenges for further integration, mainly data compression and heuristics, which could drastically de-crease the state space search. Within the requirement of the time-acceptable solution, there was an upgraded Dijkstra algorithm with an indexed sorting instead of a Fibonacci heap, which sped up the solution of the shortest path in the four mil. node graph up to 35ms. Basically, the indexed sorting implemented in the algorithm comes from the simple principle:

```
// Function to sort and return the indices

std::vector<int> indexSort(const std::vector<int>& arr) {
        // Create a vector of indices
        std::vector<int> indices(arr.size());
// Initialize indices to 0, 1, 2, ..., n-1
        for (int i = 0; i < arr.size(); ++i) {
                indices[i] = i;
        }
// Sort indices based on comparing values in arr
        std::sort(indices.begin(), indices.end(), [&arr](int a, int b) {
                return arr[a] < arr[b];
        });
        return indices;
}
```

However, the indexed array adaptation to the current range requirement allows us to deal with extensive arrays/sets coming from the Dijska iterations applied to the graphs with 10^8 (10 000 x 10 000) nodes, which will be described in a subsequent article.

Another potential for speed-up in parallelization was discovered, as highlighted in Figure 1; on average, more than 200 operations within the iteration could be run concurrently, creating a speed-up potential of more than 100+ times.

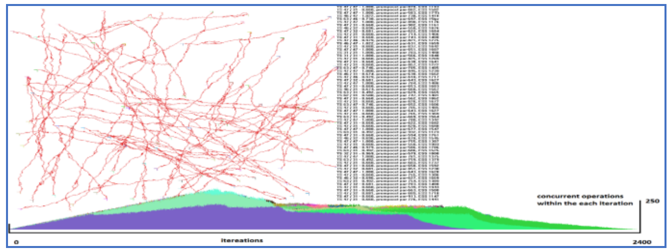

Figure 1: graph of the possible concurrent operations within one iteration of the shortest path search

Based on the mentioned principles, the C++ application was developed, and the following pictures show the initial results with two UGVs on the synthetic model. A land deployment coordination correspondence is highlighted with the new N-dimensional structure (2D, in this case, basic maneuverability graph 100x100, and NdimG 10000 x 10000), where the coordinated path was searched and presented in Figure 2-4

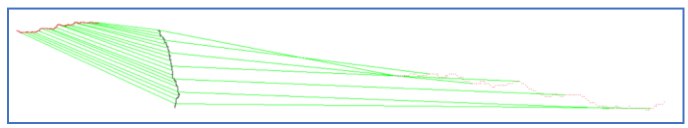

Figure 2: An example of the solution on the synthetic data set: two coordinated tactical paths, red and black, within an area of 100x100 nodes in the graph with eight directional topologies. On the right (downscaled by 100) is the correspondence with the dataset used for the optimization, represented by the matrix 10000 x 10000. Each node points to the 512 adjacent nodes representing the combination of both paths

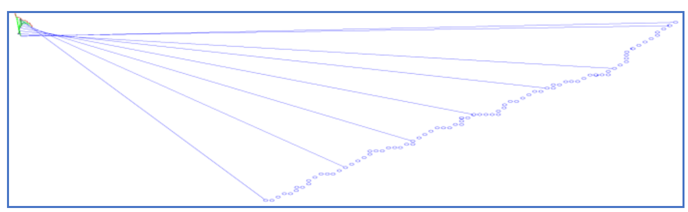

Figure 3: Another example of the solution of two coordinated tactical paths. Red and black represent the landscape results (area 100x100). On the right (blue, downscaled by 30), the correspondence with the original dataset represented by the 2D matrix is highlighted. The dimension of each axe is the all-node count =100 x 100 = 10000, with 64 edges from each node to the adjacent nodes

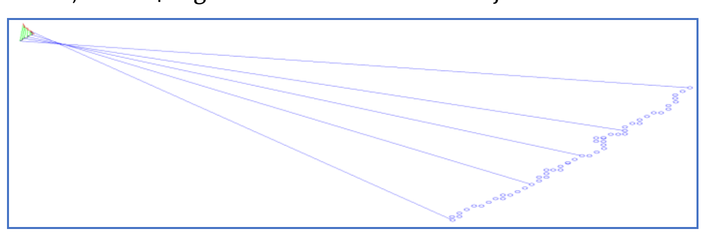

Figure 4: Another example of the solution described in Figures 2 and 1

The algorithm creates the potential for further improvement and resolution optimization, which has a critical impact on the searched state space and could quickly exceed the memory capacity of contemporary information technology.

4. Conclusion

Coordinated Tactical Unmanned Ground Vehicle (UGV) maneuvers are critical in modern military operations, as they enhance the effectiveness and safety of missions in complex environments. These maneuvers allow multiple UGVs to work in synergy, enabling them to cover more ground, execute complex tasks simultaneously, and respond dynamically to changing battlefield conditions. By coordinating their actions, UGVs perform flanking maneuvers, create diversions, and provide real-time intelligence, all while minimizing hu-man risk. This coordination maximizes operational efficiency, as UGVs are deployed in dangerous or inaccessible areas, executing missions precisely and reducing the need for direct human involvement, thus preserving lives and resources.

In conclusion, the presented solution shows the possible approach in the area of the ground-coordinated maneuver related to the tactical characteristics and relation linked to the traversability cost map and teaming benefit function. The paper describes an initial algorithm of the solution and principles which is searched in trans-formed N-dimensional structure (N corresponds with the number of UGV), practically applied up to the 3 UGVs, because of the dramatical state space increase, which is beyond the memory capacity of contemporary computers. In any case, the described principle is the subject of intensive research, and, with applied heuristics, its limitations could be significantly improved.

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