Unmanned Aerial Vehicle Logistics Modeling and Performance: A Demonstration of Integrative Data Science

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ABSTRACT: Some of the most profound advances in science occur when the intellectual resources from one discipline are brought to bear on the unresolved problems of another discipline. There is emerging recognition of the potential for data science to act as the catalyst for this interaction. The research presented here is intended as both a demonstration of potential of integrative data science more broadly, and as a contribution to the research areas of logistics and unmanned and autonomous vehicle operations. This research presents an integration of the spatial analytic and visualization techniques of Geographic Information Science, with the modeling and solution procedures for highly combinatorially complex problems from Location Science and Operations Research. The context for the problems solved is the operation of unmanned aerial vehicle platforms, and the goals are to both broaden the understanding of these vehicles in logistics operations, and to be able to discern the mix of platform types that perform most efficiently.

KEYWORDS: unmanned aerial vehicles, autonomous logistics, location science, integrative data science

Integrating GIScience and Location Science

Some of the most profound advances in science occur when intellectual resources from one discipline are brought to bear on the unresolved problems of another. Geographers have long recognized that some of the most dramatic mixing of ideas, objects, or cultures happens at boundaries. This is as true of the boundaries between disciplines as it is of the boundaries between nations. The advance of data science as a discipline is, in some measure, a recognition that it is the commonalities among scientific approaches, and the places where disciplines can come together that offer the most fruitful ground for basic scientific advance.

This research describes one effort to exploit the opportunity for integrative data science. Two areas of research are examined for their integrative potential, Location Science (a sub-discipline of geography with extensive ties to Operations Research (OR)) and GIScience (GISci). Both research areas address problems that can be highly data intensive: GISci has long addressed problems with massive datasets (e.g. global remote sensing data, detailed census enumerations), and the problems addressed in Location Science are often highly combinatorially complex, requiring the management of extraordinarily large datasets in the solution process. The integration of these research areas is examined in the context of unmanned aerial vehicles (UAV) – where the data demands and modeling structures are still in their infancy. More specifically, this research demonstrates how spatial analytic techniques can be employed to develop spatially aware scenarios, how those scenarios can be used as the basis for solving UAV logistics problems, and how the data resulting from this integration can be used to understand the performance of UAVs in a logistics operation.

Background

The background for this research lies primarily in two areas: the ties between the Operations Research and Geography, and the data and modeling needs for UAVs, particularly in the context of logistics.

Location Science: Integrating GIScience and OR

Although perhaps an oversimplification, the genesis of the field of Location Science lay in the realization 1) among OR practitioners that a significant subset of their problems are fundamentally spatial in nature, and 2) among geographers that many of their spatial problems require optimization techniques in order to generate the best solutions. This mutual recognition of the benefits of collaboration, and a dependency on each other's expertise is the foundation of Location Science (Hale & Moberg, 2003). However, it has been shown that, while some GIS platforms offer the means to model and solve location science problems, the methods used to provide these solutions are generally based on heuristics that often produce sub-optimal results (Curtin, Voicu, Rice, & Stefanidis, 2014). In contrast these same problems can be solved optimally if the spatial data is integrated with OR optimal solution procedures (Curtin, Hayslett-McCall, & Qiu, 2010).

It may be that the key to further advances in the integration of GISci and Location Science lies in identifying the data structures and models on which both depend and where the best methods from each research area can be applied. It is possible that this search for integration will lead to the ability to address research questions that neither discipline could sufficiently solve in isolation.

Optimization Models for Unmanned Aerial Vehicles

Transportation researchers recognize that technological advances in transport modes can revolutionize travel, and in turn have profound influence on cultural and economic conditions. Over centuries, advances in shipping, rail transport, air travel, and personal automobiles have been the stimuli for these transportation revolutions. It is possible – although as yet undetermined – that the advent of UAVs may contribute to the next revolution in transportation. If there is even a small chance that this is the case, the potential for positive change or for catastrophic negative consequences demands that the scientific community put significant effort into understanding these changes.

The development of UAV technology is happening at a rapid pace. There is increasing research interest in the operation of UAVs including their navigation abilities, measures to increase safety, and their impact on transportation planning. Of particular interest here is the modeling of optimal logistics behavior; that is, how can unmanned vehicles be directed to most efficiently deliver materiel given constraints on time, cost, and access. This research seeks to contribute by demonstrating how the integration of methods can lead to greater understanding of the performance of UAVs in logistics operations.

Methods: ALOFT – the Autonomous Logistics Optimization Family of Tools

This research effort has produced an integrated set of models and tools to address unmanned and autonomous logistics. The data needs and scenario development, modeling and solution procedures, and methods for visualizing model outputs have been combined into a testbed environment to analyze logistics operations with a focus on the unmanned and autonomous elements of those systems.

Scenario Development Process

To address the autonomous platform mix problem, a comprehensive data collection process is critical. This effort must include platform data collection, knowledge of the facilities from which the platforms will operate and any delivery locations, and data regarding the materiel to be delivered.

The set of logistics scenarios should be realistic approximations of the environments under which the platforms for delivery will need to operate. When possible the pedigree of the scenario should be checked against the expert knowledge of those working in the system; e.g. logistics experts who plan for increased integration of UAVs in their operations. Figure

1 illustrates a scenario where military assets are employed for a rescue and recovery mission with both seabased and land based facilities.

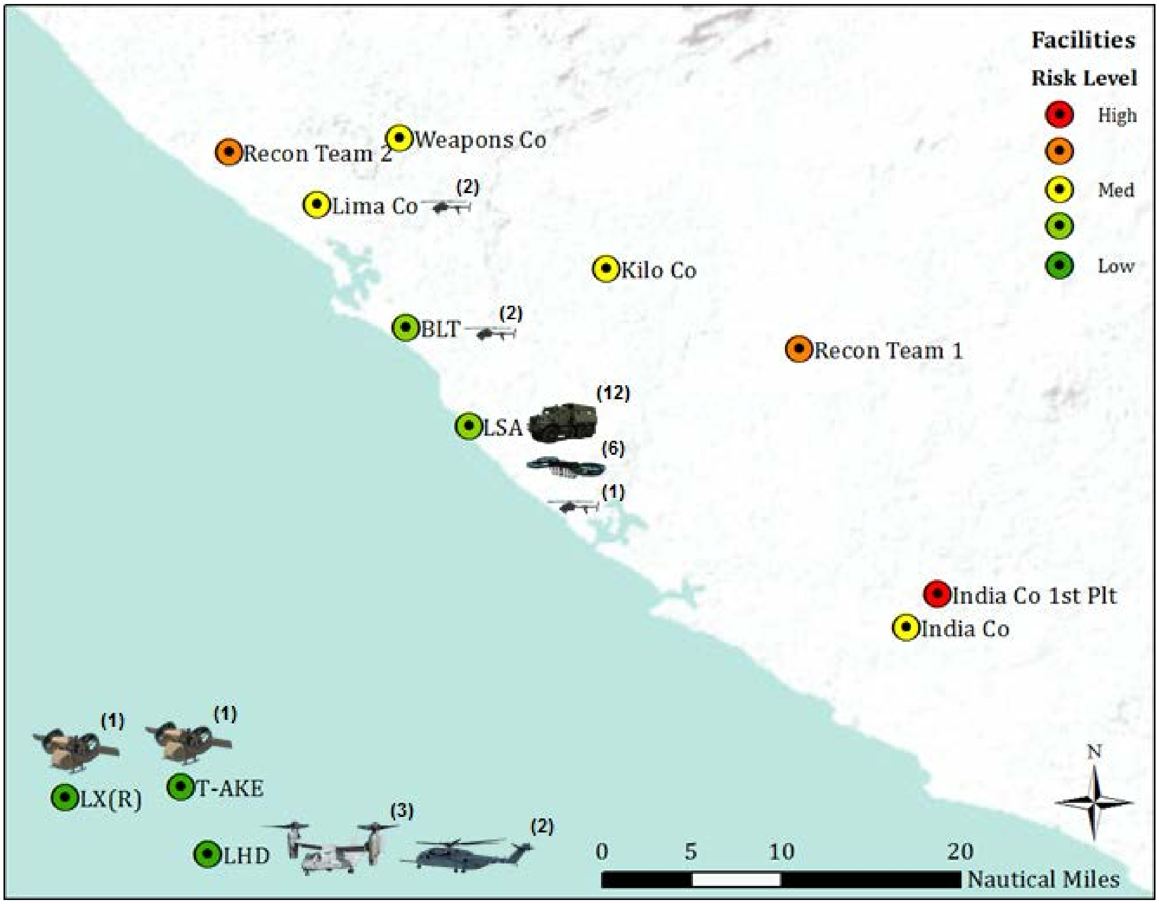


Figure 1: An example logistics scenario with unmanned aerial vehicle platforms assigned to some facilities. This scenario represents a relief and rescue mission in coastal West Africa.

Optimization Modeling and Solution

While the focus of this research article is the integration of GISci and Location Science methods, a significant element is the set of optimization models that permit solutions to problem instances generated in the scenario development process. A detailed formulation will appear in a companion article but is summarized here. This formulation includes three objectives (minimum cost, minimum risk, minimum unmet demand) and a composite objective. Constraints include platform range limits, platform capacity limits, and restrictions on platform access to facilities.

Integration and Generation of a Testbed Environment

Tools for scenario development, methods for executing optimal solution procedures, and means of visualizing and querying the results of those models are combined into the ALOFT testbed environment. For this research ArcGIS is used for spatial scenario development, supporting database management, and visualization tools. Gurobi is used for linear programming solution procedures. Python libraries provide the bridge between these sets of tools.

Results

The results generated by integrating GIScience and Location Science in the ALOFT testbed environment fall into three categories. First, the testbed environment itself represents an advance, given the novel integration of spatial analytic methods, optimization modeling and solution procedures, and visualization methods. Figure 2 shows an example of the output from this integration. The scenario results, including the flights of the individual unmanned aerial systems can be viewed and queried providing information about the facilities visited, the amount and type of materiel delivered, and the cost and distance parameters of the flight.

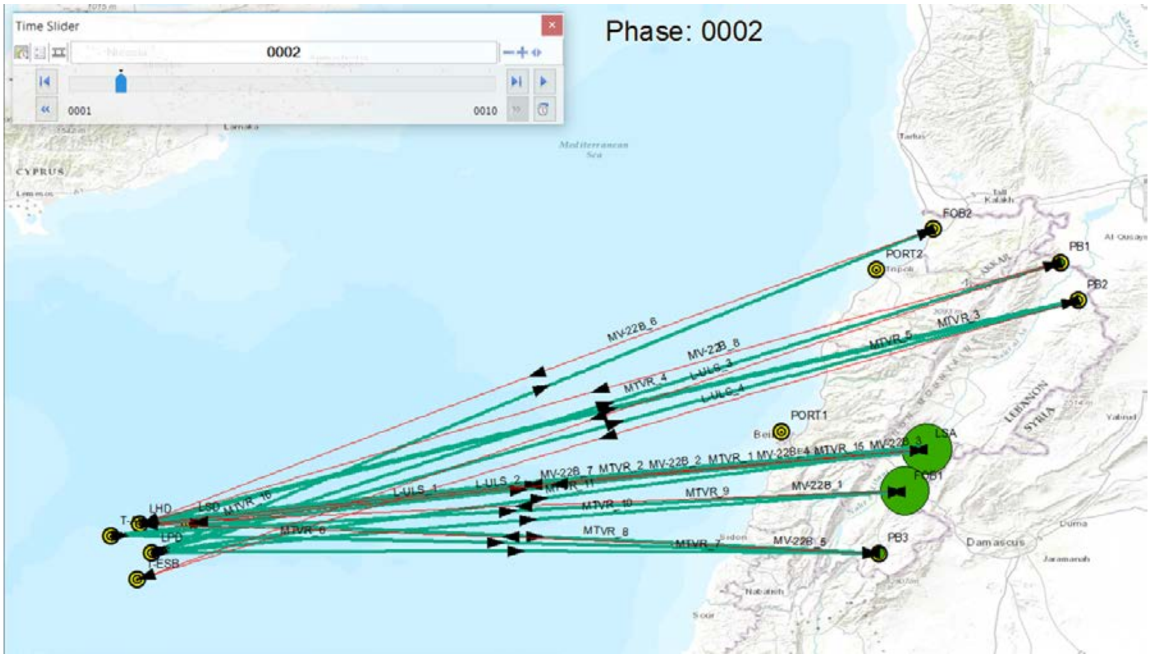
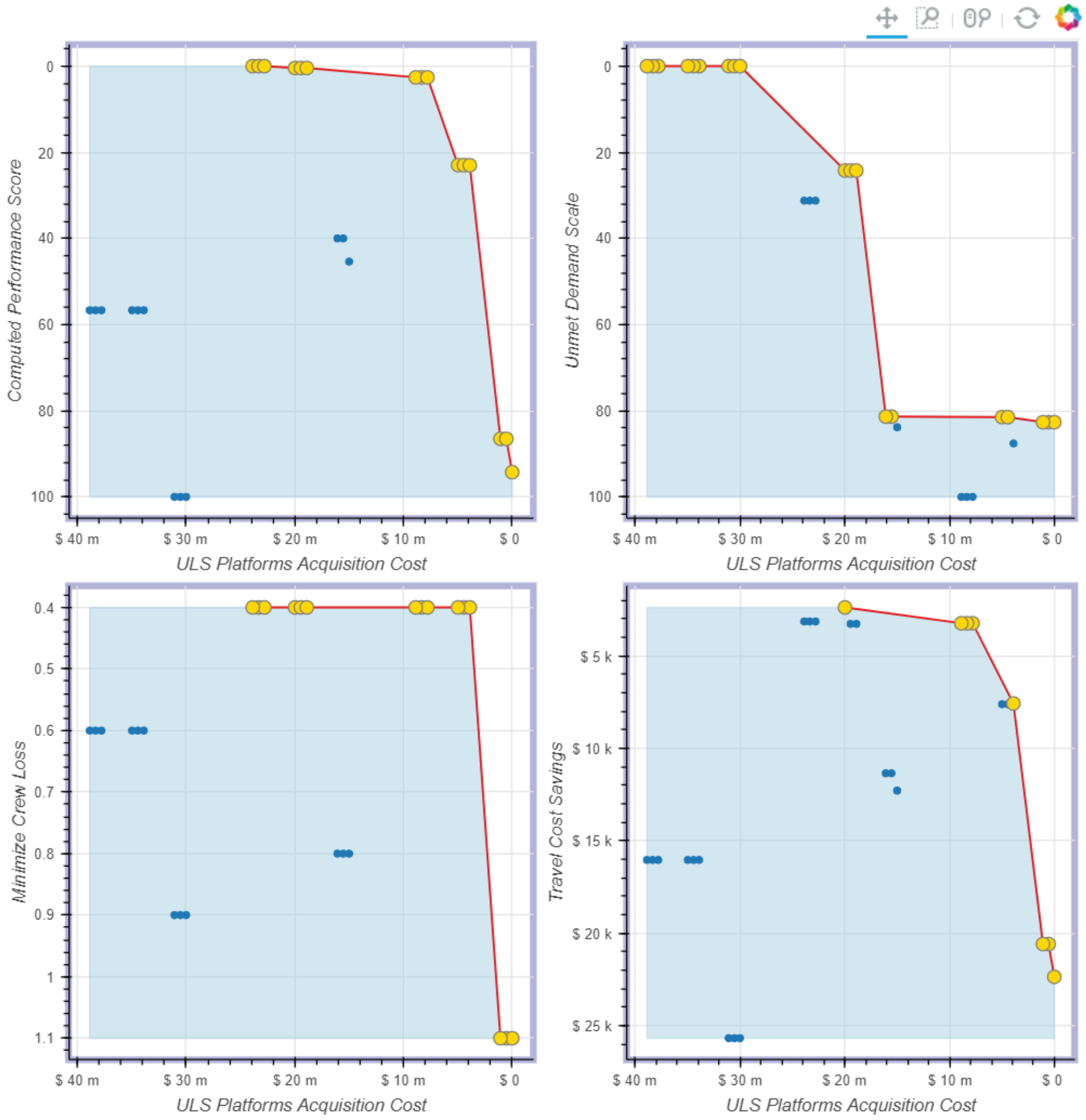


Figure 2: Detail of the results of a logistics operation with unmanned aerial vehicle platforms. Facility, platform, and delivery parameters can be visualized and queried.

Second, statistical results regarding platform performance, and comparisons across platform mixes are provided from the scenarios and models. As one element of these results, Figure 3 shows Pareto tradeoff curves that can indicate to decision-makers how platform mixes perform with regard to a series of objective function values, and how this performance is associated with the cost to acquire those platforms. Consider that not only are the optimization problems being solved highly combinatorially complex, but when many variant problem instances are solved across many logistics scenarios, the resulting data for analysis is multiplied, requiring more sophisticated data scientific storage and manipulation processes, and the increased involvement of statistical analysis.



But third – and perhaps most importantly – this integration across disciplines allows for ongoing experimentation into the nature of logistics operations involving unmanned systems. The testbed environment is not intended to dictate the logistics decisions that should be made using UAVs, but rather as a means of understanding the nature of those operations under different conditions. The most significant result of this exercise is the generation of additional knowledge about how UAVs can be employed, and where the idiosyncrasies of those systems are not well modeled with current capabilities.

Conclusions

The research presented here attempts to make contributions at several levels. At a practical level the ALOFT system and its testbed environment provides a means of generating geographic scenarios, implementing optimal logistics formulations, and displaying and analyzing the results of those implementations to evaluate unmanned vehicle performance. However, while those results may be useful for developing particular logistics plans and vehicle acquisition plans, it is the greater understanding of UAVs through the process of experimenting with scenarios and optimal logistics models that represents the value in this integrative process.

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