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Introduction

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1.1 Introduction

Given all the attention and investment recently bestowed on unmanned systems, it might seem surprising that this book does not already exist. Even the most cursory internet search on this topic will show professional journal articles, industry symposia proceedings, and technical engineering texts conveying broad interest, substantial investment, and aggressive development in unmanned systems. Yet an internet bookstore or library search for "operations research" combined with "unmanned systems" will come up blank. This book will indeed be the first of its kind.

Historians of military innovation would not be surprised. In fact, they point to a recurring tendency of the study of *usage* to lag *invention*. Such a hyper-focus on engineering and production might be perfectly understandable (for program secrecy, to work the "bugs" out of early production models, or simply because of the sheer novelty of radically new devices) but the effect is often the same: a delayed understanding of how operators could use new hardware in new ways. As the preeminent World War II scientist P. M. S. Blackett observed of the innovations of his time, "relatively too much scientific effort has been expended hitherto on the *production* of new devices and too little in the *proper use* of what we have got." [1] It is ironic that a study of usage is one of the best ways to understand how to develop and improve a new technology; but engineering, not usage, gets the most attention early in an innovation cycle.

One does not need to be a student of military innovation to know that the study of usage is not the engineer's purview. Blackett's counterparts across the Atlantic, Morse and Kimball, noted that the "the branches … of engineering … are involved in the construction and production of equipment, whereas operations research is involved in its use. The engineer is the consultant to the builder, the producer of equipment, whereas the operations research worker

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is the consultant to the *user* of the equipment." [2] Engineering tells you how to build things and operations research tells you how things should be used. In development of new military hardware, however, engineering nearly always has a head start over operations research.

Three of the many ways that engineering overshadows usage early in unmanned systems development have delayed a book such as this from reaching professional bookshelves. The first is that most engineers have not yet recognized that unmanned systems can be so much more than merely systems without a human onboard. This *anthropomorphism*–creating in our own image–was the first fertile ground for engineers, and early success with this approach made it seem unnecessary to conceive of unmanned operations as any different than those studied by operations researchers for decades.

The second reason is that since engineers build *things*, not *operations*, the engineer's approach to improving operations is to refine the vehicles. Such engineering-centered solutions have already been observed in existing unmanned programs, driving up vehicle complexity and cost–without regard to how modifying operational schemes might be a better way to increase operational performance.

The third reason is that since humans are the most expensive "total cost of ownership" (TOC) components of modern military systems, the military and defense industries have been content to lean on "manpower cost avoidance" as the overriding value proposition for unmanned systems. For now, unmanned systems are convincingly sold on cost alone–there is no reason for program managers to answer questions about operational value that no one is yet asking. The engineer's present task is to keep development and production costs lower than equivalent manned systems for a given level of performance–not to explore the performance–cost trade space.

The historian of military innovation would be quick to clarify that usage lags invention mostly in the *initial* phases of maturation. Engineers and program managers pre-occupied with production can indeed be quite successful. In the case of unmanned vehicle development, second- and third-generation variants have already replaced prototypes and initial production models in the fleet, field, and flightline. Major acquisition programs (such as the Global Hawk and Predator systems) are already out of adolescence. Now that well-engineered platforms are employed on a much larger scale, a growing cadre of operations research analysts are at last being asked to answer operational questions–questions of usage.

While the three reasons cited above are among those that have heretofore preempted this book, they also constitute an initial set of topics for the operations researcher. What we might now call "operations research for unmanned systems" is emerging with three main themes:

- *The Benefits of "Unmanning":* While the challenges of removing humans from platforms are still manifold and rightfully deserve our attention, operations researchers are now looking past the low hanging fruit of "unmanning" these systems–such as less risk to humans, longer sortie duration, higher *g*-force tolerance–to develop entirely new operations for unmanned systems and to discern new ways of measuring effectiveness.
- *Improving Operations:* The introduction of large numbers of unmanned vehicles into a legacy order of battle may transform warfare in profound ways. Some authors in the defense community have coined the term "Age of Robotics" to refer to this transformation, but from an analytical perspective, this term (like "Network Centric Warfare" and others of their ilk) is still more rubric than operational concept. While a full appreciation of such a new age may remain elusive, operations researchers are approaching the study

of unmanned collectives in a more modest way. Through careful study and operational experimentation with smaller groups of vehicles, these analysts are starting to build evidence for claims of increasing returns and show why and how they may be possible (or, just as importantly, not).

- *The True Costs of Unmanned Systems:* The only "unmanned" part of today's unmanned systems are the vehicles – the humans have been moved somewhere else in the system. The life-cycle cost savings accrue to the platforms, but is the overall system cheaper? In some systems, centralized human control and cognition may be a much more costly approach, requiring substantially more technological investment, greater manning, and networks with much higher capacity than legacy manned systems. Analyzing this trade space is an area of new growth for operations research.

1.2 Background and Scope

As recent as the late 1990s, unmanned vehicles were still seen as a threat to the legacy defense investments of the world's leading defense establishments. Even the mildest endorsements of their value to the warfighter for anything but the most mundane military tasks were met with derision, suspicion, and resistance. At the same time, more modest militaries and their indigenous industries – unconstrained by the need to perpetuate big-ticket, long-term acquisition strategies – began to develop first-generation unmanned platforms and capabilities that could no longer be denied by their bigger counterparts.

Concurrently and independently, innovations in secure, distributed networking and high-speed computing – the two most basic building blocks of advanced unmanned systems – began to achieve the commercial successes that made unmanned military vehicles seem more viable as a complement to legacy platforms in the fleet, field, and flight-line. But while the war on terror has seen focused employment of surveillance drones and explosive ordinance disposal robots, defense budget reductions are spurring a more widespread use of unmanned military systems more for the cost savings they provide than for the capabilities they deliver.

The five-year future of unmanned systems is uncertain, except in one respect: every new operational concept or service vision produced by the world's leading militaries *expect* that unmanned vehicles will be a major component of future force structures. The details of this expectation – which platforms will garner the most investment, what technological breakthrough will have the most impact or where unmanned systems will have their first, game-changing successes – are the subject of intense speculation. This book will be successful if it helps bring some operational focus to the current debate.

While it is common to assert that increasing returns must surely accrue as more unmanned hardware is connected to a larger "network-enabled" systems of systems, engineers still concentrate on the robotic vehicles, unable to conceive of how unmanned collectives might indeed perform better than merely the sum total of all the vehicles' individual performance. Without better analyses of group operations, the engineer's solution to improving the performance of a collective is simply to engineer better performance into each vehicle of the group. Network engineers have been the loudest advocates for "networked effects," but like the hardware engineers they have largely ignored operations research, devoting their efforts to engineering architectural standards and interconnection protocols. To make matters worse, in many cases the *process* (engineering activity) has become the *product*.

This book will benefit readers by providing them with a new perspective on how to use and value unmanned systems. Since there is no other place where these types of analyses are yet assembled, this book will serve as a seminal reference, establishing the context in which operations research should be applied to unmanned systems, catalyzing additional research into the value of unmanned platforms, and providing critical initial feedback to the unmanned systems engineering community.

Good operations research analysis is at once digestible by operators and informative to specialists, so we have attempted to strike a balance between the two. Fortunately, nearly all defense community operators have a solid technical education and training (albeit somewhat dated), and can follow the main arguments from college-level physics, statistics, and engineering. Chapters in this book should briefly refresh their education and bring it into operational context. Defense engineers, by contrast, are expert at their applicable "hard science," but must be informed of operational context. This book should confirm for a technical audience that the writers understand the most important technical issues, and then show how the technical issues play out in an operational context. Both will buy this book expecting to learn something more than they already know about unmanned systems; this book will have to approach this learning experience from both of these perspectives.

1.3 About the Chapters

Fourteen chapters follow this introduction. Considering that unmanned vehicle systems development is by nature multidisciplinary, there are certainly many ways that these chapters might be appropriately arranged. The editors opted to arrange the chapters on a continuum from individual problems to analyses of vehicle groups, then to organizational issues, and finally to broad theoretical questions of command and control. Some of the topics may be new intellectual ground for many readers. For this reason, the editors have tried to ensure each chapter has enough basic context for a general audience with some mathematical background to digest each chapter, no matter what the subject. They also hope that this will satisfy readers who come to this book for, say, unmanned vehicle routing techniques, to stay for a discussion of Test and Evaluation or TOC.

Huang Teng Tan and Dr. Raymond R. Hill of the US Air Force Institute of Technology provided the first chapter, *The In-Transit Vigilant Covering Tour Problem for Routing Unmanned Ground Vehicles*. One might rightly wonder why Air Force researchers care about unmanned ground vehicles, but the answer is simple: the US Air Force has a significant Force Protection mission at its many bases worldwide, and the total ownership costs of human sentries are high. Unmanned sentries can augment and replace humans at lower costs. This chapter provides a formal discussion of how to efficiently address the covering tour problem, or in other words, what is the best way for a robotic sentry to "make its rounds." There are obvious border patrol and civilian security applications of this research.

The next chapter, *Near-Optimal Assignment of UAVs to Targets Using a Market-Based Approach* by Dr. Elad Kivelevitch, Dr. Kelly Cohen, and Dr. Manish Kumar, is an application of "market-based" optimization to sensor–target pairings. This family of optimization techniques is inspired by economic markets, such as in this example where unmanned vehicles act as rational economic agents and bid for targets using a valuation and trading scheme. The authors show the benefits and limits of this approach to obtaining a fast, reliable optimization under conditions of high uncertainty.

A chapter discussing naval applications of unmanned underwater vehicles comes next. In *Considering Mine Countermeasures Exploratory Operations Conducted by Autonomous Underwater Vehicles*, Dr. Bao Nguyen, David Hopkin, and Dr. Handson Yip look at ways to evaluate the performance of Commercial Off-The-Shelf (COTS) unmanned underwater vehicles in searches for underwater mines. They present and discuss measures of effectiveness and compare and contrast different search patterns.

Optical Search by Unmanned Aerial Vehicles: Fauna Detection Case Study, by Raquel Prieto Molina *et al.*, is a very interesting chapter that harkens back to some of the very early operations research work from World War II. Readers familiar with Koopman's *Search and Screening*[3], for example, will note the strong parallel between this chapter and World War II research on lateral range curves and the inverse cube law. Both were trying to describe the basic physics of visual detection (Prieto *et al*., are, of course dealing with artificial visual detection), and how it impacts search patterns and detection probabilities.

There are many cases in modern military operations where a clever scheme or algorithm devised *in silico* unravels when it is placed in operation in a real environment. Recognizing this, Dr. Matthew J. Henchey, Dr. Rajan Batta, Dr. Mark Karwan, and Dr. Agamemnon Crassidis show how algorithms might compensate for environmental effects in *Flight Time Approximation Model for Unmanned Aerial Vehicles: Estimating the Effects of Path Variations and Wind*. While crafted for air vehicles, this research could be adapted for any unmanned vehicles operations where delay or resistance are encountered (such as set and drift at sea, reduced trafficability on land, or interruption by an adversary in any medium).

For many militaries and corporations, unmanned vehicles are now major acquisition programs, requiring high-level analyses of alternatives (AOAs) not just between vehicles, but between human–vehicle hybrid systems. Fred D. J. Bowden, Andrew W. Coutts, Richard M. Dexter, Luke Finlay, Ben Pietsch, and Denis R. Shine present a template for these types of studies in *Impacts of Unmanned Ground Vehicles on Combined Arms Team Performance*. While specific to Australian Army trade-off analyses, this chapter is certainly useful for other AOA analyses in both cabinet departments and corporate executive suites.

With respect to human–vehicle hybrids, how much human work should robots actually do? All senior military officials will insist that a human must always be in the loop, but in many cases this is just to confirm an automated solution before weapons are employed. But how much was this human involved in the automated solution, and how reliable is the robot's "thinking"? Patrick Chisan Hew's chapter, *Processing, Exploitation, and Dissemination: When is Aided/Automated Target Recognition "Good Enough" for Operational Use?,* offers a formal mathematical treatment to this and similar questions of the operational and ethical impact of automated cognition.

Also exploring the man–machine trade-space is *Analyzing a Design Continuum for Automated Military Convoy Operations,* by David M. Mahalak. This chapter used logistics convoy operations to show how automated control can supplant human control in a continuum of increasingly automated convoys. This is yet another chapter that applies to a broader range of vehicles and operations.

Continuing along the continuum to higher levels of organizational problems, another chapter from Dr. Raymond R. Hill (this time with Brian B. Stone, also of the US Air Force Institute of Technology), *Experimental Design for Unmanned Aerial Systems Analysis: Bringing Statistical Rigor to UAS Testing,* addresses new operational test and evaluation issues wrought by the introduction of unmanned systems.

It has long been assumed that automated systems are cheaper than manned systems. As this introduction has stated, however, this has not been as well investigated as investments in unmanned vehicle systems should warrant. Dr. Ricardo Valerdi and Captain Thomas R. Ryan, Jr., US Army, address this issue and provide costing techniques in *Total Cost of Ownership (TOC): An Approach for Estimating UMAS Costs.*

Part of the TOC of any system are the costs associated with logistics and maintenance. Major Keirin Joyce, Australian Army, discusses modeling techniques for logistics operations with a focus on how well current logistics models can support unmanned vehicle operations. In a very important section of this chapter, *Logistics Support for Unmanned Systems,* Major Joyce extrapolates from current models and operations to address logistics support challenges for future unmanned systems.

As more systems are automated and dispersed throughout the battlespace or commercial work environment, there is an increasing need to understand how networks of collectives are effectively operated and controlled. *Organizing for Improved Effectiveness in Networked Operations* by Dr. Sean Deller, Dr. Ghaith Rabadi, Dr. Andreas Tolk, and Dr. Shannon R. Bowling combines concepts of interaction patterns in biochemistry with modern agent-based modeling techniques to explore a general model of command and control in a distributed, networked system.

Two chapters addressing theoretical topics complete the volume. *An Exploration of Performance Distributions in Collectives* by Jeffrey R. Cares compares individual and collective performance in competition, using baseball as a proxy. In *Distributed Combat Power: The Application of Salvo Theory to Unmanned Systems*, the same author shows how Hughes' Salvo Equations might be modified to evaluate outcomes from missile combat between large platforms when advanced unmanned vehicles are employed.

References

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