

# 8th International Conference on Cooperative Control and Optimization

January 30 – February 1, 2008

CENTER FOR APPLIED OPTIMIZATION, UNIVERSITY OF FLORIDA  
AIR FORCE RESEARCH LABORATORY, MUNITIONS DIRECTORATE  
RAYTHEON INC., JOINT SENSOR NETWORKING



## Raytheon

Paramount Plaza Hotel  
Gainesville, FL

Organizers Panos Pardalos ([pardalos@ufl.edu](mailto:pardalos@ufl.edu))  
Robert Murphey ([murphey@eglin.af.mil](mailto:murphey@eglin.af.mil))  
Michael J. Hirsch ([michael\\_j\\_hirsch@raytheon.com](mailto:michael_j_hirsch@raytheon.com))  
Clayton Commander ([clayton.commander@eglin.af.mil](mailto:clayton.commander@eglin.af.mil))

PROGRAM

## Wednesday, January 30, 2008 (Paramount Plaza Hotel)

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- 0700–1700 Registration, Conference Registration Desk
- 0800–0815 **Welcome Session**  
Joseph Hartman, Chair, Department of Industrial and Systems Engineering, University of Florida  
Panos M. Pardalos, Department of Industrial and Systems Engineering, University of Florida  
Robert Murphey, Air Force Research Laboratory, Munitions Directorate
- Plenary Session** Chair Panos Pardalos
- 0815–0900 **Plenary Speaker** Hugh Durrant-Whyte  
**Maximal Information Systems**
- Session W.1** Chair Clayton Commander
- 0900–0930 Oktay Arslan, Berat G. Ulualan, and Gokhan Inalhan  
**Design and Implementation of Communication and Information Distribution Modules for Cooperative Unmanned-Manned Vehicle Networks**
- 0930–1000 Yutau Lee  
**Medium Access Control for Optimal Opportunistic Spectrum Sharing in Cognitive Networks**
- 1000–1015 **Coffee Break**
- Session W.2** Chair Michael J. Hirsch
- 1015–1045 Jiangmin Chunyu and Zhihua Qu  
**A New Multi-Objective Control Design for Autonomous Vehicles**
- 1045–1115 Felix Mora-Camino, Baba Ouattara, and Karim Achaibou  
**Minimum Time Convergence for Aircraft at Merging: A Cooperative Control Approach**
- 1115–1145 Yechiel Crispin  
**Cooperative Control of Multiple Swarms of Mobile Robots**
- 1145–1215 Chin Lua, Jingpeng Tang, Karl Altenberg, and Kendall Nygard  
**Adaptive Swarm Emergent Intelligent Methodologies, Development and Validation**
- 1215–1315 **Lunch, Paramount Plaza Hotel**

## Wednesday, January 30, 2008 (Paramount Plaza Hotel)

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**Session W.3** Chair Robert Murphey

1315–1345 Dimitri Zarzhitsky, Daniel Pack, Marc Schlegel, and Andreas Decker  
**Event-Driven Software Framework for Cooperative Localization of Mobile Targets with Multiple Unmanned Aerial Vehicles**

1345–1415 Andrew Klesh, Anouck Girard, and Pierre T. Kabamba  
**Cooperative Thermalling: Extending the Endurance of Unmanned Aerial Vehicles**

1415–1445 Emily Doucette, Andrew Sinclair, and David Jeffcoat  
**Simultaneous Localization and Planning for Cooperative Air Munitions via Dynamic Programming**

1445–1515 David Anisi and Petter Ogren  
**Minimum Time Multi-UGV Surveillance**

1515–1530 **Coffee Break**

**Session W.4** Chair Alla Kammerdiner

1530–1600 Mark Karwan and Chase Murray  
**A General Modeling Framework for Course Of Action in UAV Routing**

1600–1630 Fernando Fontes, Dalila Fontes, and Amelia Caldeira  
**Model Predictive Control of Vehicle Formations**

1630–1700 Youngrock Yoon, Scott Gruber, Lucas Krakow, and Daniel Pack  
**Autonomous Target Detection and Localization using Cooperative UAVs**

1830 **Conference Reception & Dinner, Paramount Plaza Hotel**

## Thursday, January 31, 2008 (Paramount Plaza Hotel)

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- 0700–1700 Registration, Conference Registration Desk
- Plenary Session** Chair Michael J. Hirsch
- 0800–0845 **Plenary Speaker** Christos G. Cassandras  
**Distributed Optimization for Cooperative Missions in Uncertain Environments**
- Session T.1** Chair Robert Murphey
- 0845–0915 Luca Bertuccelli, Brett Bethke, and Jonathan How  
**Robust Decision-Making in Infinite Horizon MDPs using Scenarios**
- 0915–0945 Khanh Pham  
**New Results in Stochastic Cooperative Games: Strategic Coordination for Multi-Resolution Performance Robustness**
- 0945–1015 Paul Krokhmal and David Jeffcoat  
**On Weakly Cooperative Systems**
- 1015–1030 **Coffee Break**
- Session T.2** Chair Ashwin Arulselman
- 1030–1100 Michael Zabaranin  
**Stochastic Optimization of Sensor Network for Underwater Threat Detection**
- 1100–1130 Clayton Commander, Panos Pardalos, Valeriy Ryabchenko, Sergey Sarykalin, and Stan Uryasev  
**Stochastic Wireless Network Jamming Problems**
- 1130–1200 John Baker, Raymond Holsapple, Anouck Girard, Phillip Chandler, and Meir Pachter  
**Human Operator Aided Decision Processes for Unmanned Aerial Vehicles in a Stochastic Environment**
- 1200–1300 **Lunch, Paramount Plaza Hotel**

## Thursday, January 31, 2008 (Paramount Plaza Hotel)

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**Session T.3**     Chair Clayton Commander

1300–1330     Ivomar Soares, Catherine Mancel, Felipe Franca, and Felix Mora-Camino  
**Cooperative Control for Dependent Flows: The Case of Ground Traffic at Airports**

1330–1400     Jingpeng Tang, Doug Schesvold, Karl Altenberg, Jonathon Pikalek, and Kendall Nygard  
**Hierarchical Control for Forward Air Controller UAV Agents**

1400–1430     Ashwin Arulselvan, Clayton Commander, Michael J. Hirsch, and Panos Pardalos  
**Communication Models for a Cooperative Network of Autonomous Agents**

1430–1500     Kemal Ure, Emre Koyuncu, and Gokhan Inalhan  
**A Mode-Based Hybrid Controller Design for Agile Maneuvering UAVs**

1500–1515     **Coffee Break**

**Session T.4**     Chair Panos Pardalos

1515–1545     Henry Pfister and Janusz Zalewski  
**Combining Rough Sets and Bayesian Networks to Address Uncertainty in Cooperative Control**

1545–1615     Vladimir Boginski and Clayton Commander  
**Formulations of Network Flow Problems Under Uncertainty**

1615–1645     Sergiy Butenko and Balabhaskar Balasundaram  
**Detecting Large Cohesive Subgroups in Networks**

1645–1715     Genshe Chen, Huimin Chen, Tod Schuck, and Erik Blasch  
**Robust Track Association and Fusion with Extended Feature Matching**

1830             **Conference Reception & Dinner, Paramount Plaza Hotel**

## Friday, February 1, 2008 (Paramount Plaza Hotel)

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- Plenary Session**      Chair Robert Murphey
- 0815–0900      **Plenary Speaker** Richard Murray  
**Cooperative Control, Optimization, and Information Flow**
- Session F.1**      Chair Clayton Commander
- 0845–0915      Julie Bellerose, Daniel Scheeres, and Anouck Girard  
**Dynamics and Control of Surface Exploration Robots on Near Earth Objects**
- 0915–0945      Ulrik Nilsson, Petter Ogren and Johan Thunberg  
**Towards Optimal Positioning of Surveillance UGVs**
- 0945–1015      Ozgur Araz and Rakesh Nagi  
**Incorporating Weather System in Cooperative UAV Search: Probabilistic Approach**
- 1015–1030      **Coffee Break**
- Session F.2**      Chair Michael J. Hirsch
- 1030–1100      Pedro Lima and Daniel Pack  
**Maximizing Search Coverage using Future Path Projection for Cooperative Multiple UAVs with Limited Communication Ranges**
- 1100–1130      Rakesh Nagi and Moises Sudit  
**Priority-based Assignment and Routing of a Fleet of Unmanned Combat Aerial Vehicles**
- 1130–1200      Johan Thunberg, Petter Ogren, and David Anisi  
**A Comparative Study of Task Assignment and Path Planning Methods for Multi-UGV Missions**
- 1200–1230      Sivakumar Rathinam, Waqar Malik, Saikumar Yadlapalli, and Swaroop Darbha  
**Algorithms for the Dubins Traveling Salesman Problem**
- 1230–1330      **Lunch, Paramount Plaza Hotel**

## Friday, February 1, 2008 (Paramount Plaza Hotel)

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- Session F.3**      Chair Ashwin Arulselman
- 1330–1400      Nicolas Lechevin, Camille-Alain Rabbath, and Marc Lauzon  
**Distributed, Near-Optimal Network Enabled Weapon-Target Assignment for Combat Formations**
- 1400–1430      Alla Kammerdiner, Antonio Mucherino, and Panos Pardalos  
**Application of Monkey Search Metaheuristic to Solving MAP Instances**
- 1430–1500      John Bode II and David Jacques  
**Optimal Control of the Weapon Operating Characteristic with Control Inequality Constraints**
- 1500–1530      Jamie Kelly, Makoto Kumon, Benjamin Lavis and Tomonari Furukawa  
**Real-time Recursive Bayesian Estimation Using a Graphics Processing Unit and its Application to Micro Aerial Vehicles**
- 1530              **Conference Adjournment.**

## Maximal Information Systems

HUGH DURRANT-WHYTE

*ARC Centre of Excellence for Autonomous Systems, The University of Sydney, Australia*

Information provides a quantitative metric for describing the value of individual systems components in autonomous systems tasks such as tracking, mapping and navigation, search and exploration; tasks in which the objective is information gain in some form. An information model is an abstraction of system capabilities in an anonymous form which allows *a priori* reasoning on the system itself. By construction, information measures have properties of composability and additivity and thus provides a natural means of modeling and describing large scale systems of systems.

This talk will begin by describing how information measures arise naturally in autonomous tracking, mapping and navigation, search and exploration tasks. It is then demonstrated that the performance of individual sensors and platforms can be modeled using these information measures and that system-level performance metrics can be computed. These ideas are illustrated in a series of tasks involving mixed air and ground autonomous systems. These include flight-tests of cooperative UAVs engaged in tracking and navigation tasks, mixed UAV, ground vehicles and human operatives, engaged in mapping and picture compilation operations, and operations involving multi-platform search in constrained environments. In each, it is shown how information provides both a performance metric and design objective underpinning large-scale systems of systems operation.

# Design and Implementation of Communication and Information Distribution Modules for Cooperative Unmanned-Manned Vehicle Networks

OKTAY ARSLAN, BERAT GOKHAN ULUALAN, AND GOKHAN INALHAN

*Department of Aeronautics and Astronautics, Istanbul Technical University, Turkey*

Communication and data distribution in cooperative unmanned/manned vehicle networks is a challenging problem due to mission-driven complex information flow requirements. In addition, while achieving fleet-level coordination, the unmanned/manned airborne fleet network must also remain in communication with other non-fleet entities such as commander units as well as ground stations, information nodes which forward requests and enhance situational awareness. Because of such needs, data exchange across not only similar units, but also across dissimilar units (ground stations-vehicles) becomes a critical factor.

In this work, we present the design and implementation of a **Link-16** like heterogeneous communication and information distribution module for teams of unmanned and manned vehicles, and ground assets. The module has several communication interfaces including Ethernet, CAN and serial link. The module implements a customized routing algorithm that takes the data taken from these different communication interfaces and routes them to the destination addresses according to the real-time updated routing tables. With this communication module, teams of heterogeneous vehicles as well as virtual vehicles in simulation environment, ground stations, and other units may exchange their tactical and sensor information across the whole network. Also, this module supports communication at the intra-team and inter-team levels, with individual units on the vehicles acting as communication bridges across different levels. We discuss the software and the algorithmic design of the communication module and how it is adapted to our previously developed network simulator architecture and experimental UAVs. We conclude by presenting several test case studies that involve real-time task/target assignment, and the lessons learned throughout the design and implementation evolution.

# Medium Access Control for Optimal Opportunistic Spectrum Sharing in Cognitive Networks

YUTAE LEE

*Department of Electrical and Computer Engineering, University of California, Davis*

Spectrum scarcity is becoming a major issue for service providers interested in either deploying new services or enhancing the capacity for existing applications. On the other hand, recent extensive measurements indicate that, at any given time and location, a large portion of the licensed spectrum of deployed wireless communication network is found to remain unused for significant periods of time. To enable more efficient usage of spectral resources and also to provide spectrum for emerging wireless communication technologies, it is suggested that secondary (unlicensed) users are allowed to access to momentarily unoccupied spectral resources. The basic design principle is that the secondary users identify available spectrum resources and communicate in a manner that limits the level of interference perceived by primary users. Due to hardware and energy constraints, a secondary user may not be able to perform full-spectrum sensing or may not be willing to monitor the spectrum when it has no data to transmit. Based on the theory of Partially Observable Markov Decision Process (POMDP), we develop an analytic framework for opportunistic spectrum access and then propose a cognitive Medium Access Control (MAC) protocol that optimizes the delay and throughput performance of secondary users limiting the interference perceived by primary users. Finally, we show by illustrative examples and numerical results that our protocol achieves opportunistic performance improvement.

# A New Multi-Objective Control Design for Autonomous Vehicles

JIANGMIN CHUNYU AND ZHIHUA QU

*Department of Electrical Engineering and Computer Science, University of Central Florida*

In this research, a nonlinear control design is proposed for a team of wheeled mobile robots to operate cooperatively in a dynamically evolving environment, to track their virtual leader(s), to avoid static/moving obstacles, and each other. Toward this end, a multi-objective control problem is formulated, and the control is synthesized by generating a potential field force for each objective and combining them through analytical analysis and design. Different from standard potential field methods, the composite potential field utilized in this paper is, in general, time-varying in order to account for moving obstacles and vehicle motion, and the resulting control is a velocity-scaled force control as forces are scaled and combined according to the velocities of virtual vehicle, obstacles, and neighboring vehicles. The proposed control is reactive, requires only local feedback, admits topology changes of sensing and communication network, and also addresses the problem of excessive oscillations typically occurring when many vehicles are in close proximity to obstacles and each other. It is shown that oscillation can be suppressed by utilizing both nonlinear damping and velocity-scaled forces.

To the best of our knowledge, the proposed design is the first systematic approach to accommodate and achieve multiple objectives of cooperative motion, tracking of virtual command vehicle(s), obstacle avoidance, and oscillation suppression. Basic conditions and key properties are derived using rigorous Lyapunov analysis and theoretical proof. The results are illustrated by several simulation examples including cooperative motion of a team of vehicles moving through urban settings with static and moving obstacles as well as narrow passages.

# Minimum Time Convergence for Aircraft at Merging: a Cooperative Control Approach

FELIX MORA-CAMINO<sup>1</sup> , BABA OUATTARA<sup>2</sup> AND KARIM ACHAIBOU<sup>1</sup>

<sup>1</sup>*The French Civil Aviation Institute, Toulouse, France*

<sup>2</sup>*EAMAC/ASECNA, Niamey, Niger*

To face the development of air transportation, automation of air traffic control has become necessary to improve airspace capacity as well as safety levels. New satellite based navigation systems as well as new communication channels with enhanced performances allow the performance of cooperative control between neighboring aircraft.

In this research the problem of automatic merging of a set of aircraft flying along parallel routes is considered. The aim of the cooperative manoeuvre is to perform in minimum time the merging manoeuvre so that the swarm of aircraft is transformed in a single string. The dynamics of the cooperative aircraft are taken as hybrid. A minimum time optimal control problem, considering aircraft operational performances as well as minimum separation constraints, is formulated. Once a common scheduling solution, based on relative positions and aircraft performances, has been proposed by the air traffic control system, each follower aircraft makes use of a minimum time merging solver to generate its reference trajectory in accordance with the planned trajectory of its leader. At the level of each aircraft, the guidance along the planned trajectory can be performed using the differential flatness property of standard transportation aircraft while feedback loops allow to update the reference trajectories to compensate for guidance deviations (e.g., effect of winds and aircraft non nominal performance).

# Cooperative Control of Multiple Swarms of Mobile Robots

YECHIEL CRISPIN

*Department of Aerospace Engineering, Embry-Riddle Aeronautical University*

A method for the cooperative control of a group of swarms of mobile robots is presented. The advantage of multiple swarms is the parallel search for a common goal, in addition to the implicit parallelism built in each independent swarm.

Within the group, each swarm of mobile robots performs its mission autonomously. The cooperative motion of the robots belonging to each swarm in the group is governed by a system of stochastic difference equations which describe the motions of each individual robot in the swarm as a directed random search towards a collective specific goal. Within the network of each specific swarm, the location of the best solution is transmitted to each robot in that swarm and serves as its cooperative control signal.

This method is applied to the problem where a group of swarms searches for multiple minima or multiple objects in a given domain such as in the problem of detecting mines in a mine field. We then show that the same control method can solve the problem of swarms formations, where several swarms of mobile robots are initially dispersed over a given domain in the plane. The group of swarms is set into controlled motion such as to bring the group into a final prescribed organized formation of multiple swarms, where each swarm gathers at a prescribed location of a structured arrangement.

# Adaptive Swarm Emergent Intelligent Methodologies, Development and Validation

CHIN LUA<sup>1</sup>, JINGPENG TANG<sup>2</sup>, KARL ALTENBERG<sup>3</sup>, AND KENDALL NYGARD<sup>1</sup>

<sup>1</sup>*Department of Computer Science & Operations Research, North Dakota State University*

<sup>2</sup>*Department of Mathematical Science, University of Minnesota-Crookston*

<sup>3</sup>*Department of Accounting & Information Systems, North Dakota State University*

We describe software implementing swarm behaviors that achieve goals adaptively and intelligently without sacrificing the local, autonomous, reactive behaviors. The simulated actions are validated in every time step via a software layer that obeys physical laws and movement mechanics of unmanned vehicles such as Unmanned Air Vehicles (UAVs) and Unmanned Space Vehicles (USVs). The strategies are bottom-up and follow a general design architecture.

# Event-Driven Software Framework for Cooperative Localization of Mobile Targets with Multiple Unmanned Aerial Vehicles

DIMITRI ZARZHITSKY, DANIEL PACK, MARC SCHLEGEL, AND ANDREAS DECKER

*Department of Electrical and Computer Engineering, U.S. Air Force Academy*

The main goal of our research is to develop an autonomous, cooperative, and heterogeneous Multiple Unmanned Aerial Vehicles (MUAVs) system that uses heterogeneous on-board sensors to search, detect, and locate moving ground targets. The necessary technologies have matured to make an implementation on hardware UAVs possible. A nontrivial challenge for the implementation is tying together the control, sensor, and communication technologies. Therefore, in this research, we present a high-performance software architecture that integrates interdependent air-to-air control, sensor, and communication network functionalities into a cohesive intelligence, surveillance, and reconnaissance (ISR) system. A novel aspect of our approach is the event-driven implementation. Instead of an explicitly specified flow of information and control through the entire system, each individual component reacts autonomously and independently to several non-deterministic mission events. Employing parallel software engineering techniques, we created a multi-threaded, cross-platform, distributed software operating environment that optimizes utilization of available processing resources to improve UAV performance on the ISR task.

# Cooperative Thermalling: Extending the Endurance of Unmanned Aerial Vehicles

ANDREW T. KLESH, ANOUCK GIRARD, AND PIERRE T. KABAMBA

*Department of Aerospace Engineering, University of Michigan*

Motivated by cooperative exploration missions, this research considers the use of thermals to extend the endurance of multiple unmanned aerial vehicles (UAVs). The mission of the UAVs is to travel through a given area and identify updrafts. These updrafts may be used to raise the altitude of the UAVs thus extending their glide time. The UAVs communicate the location of each rise or fall in their altitude to each other in order to form a map of the area. This map can then be used to identify areas of interest that may be potential thermals. The subsequent problem of correctly identifying these thermals based on imperfect map creation is addressed through the use of force potentials. This problem is also examined from the viewpoint of information collection based on Shannons channel capacity equation. Both methods yield paths that achieve the intended result, to elevate the aircraft to higher altitudes, while benefiting from cooperation. Several illustrations are given of example flight paths.

# Simultaneous Localization and Planning for Cooperative Air Munitions via Dynamic Programming

EMILY A. DOUCETTE<sup>1</sup>, ANDREW J. SINCLAIR<sup>1</sup>, AND DAVID JEFFCOAT<sup>2</sup>

<sup>1</sup>*Department of Aerospace Engineering, Auburn University*

<sup>2</sup>*Air Force Research Laboratory, Eglin Air Force Base*

This work centers on the real-time trajectory planning for the cooperative control of two aerial munitions that are attacking a ground target in a planar setting. Sensor information from each munition is assumed available, and the individual target-location estimates are fused in a weighted least squares fashion. The variance of this combined estimate is used to define a cost function. The problem is posed to design munition trajectories that minimize this cost function. This research describes the solution of the problem by a dynamic-programming method. Development and validation of the method by application to several problems with known solutions is presented. The dynamic-programming method establishes a set of grid points for each munition to traverse based on the initial position of the munition relative to the target. The method determines the optimal path along those points to minimize the value of the cost function and consequently decrease the value of uncertainty in the estimate of the target location. Numerical solutions are presented along with computational run times to indicate that this method proves effective in trajectory and target location estimation.

# Minimum Time Multi-UGV Surveillance

DAVID ANISI<sup>1</sup> AND PETTER OGRÉN<sup>2</sup>

<sup>1</sup>*Department of Optimization and Systems Theory, Royal Institute of Technology, Sweden*

<sup>2</sup>*Department of Autonomous Systems, Swedish Defence Research Agency*

This research addresses the problem of concurrent task and path planning for a number of surveillance Unmanned Ground Vehicles (UGVs) such that a user defined area of interest is covered by the UGVs' sensors in minimum time. We first formulate the problem, and show that it is in fact a generalization of the Multiple Traveling Salesmen Problem (MTSP), which is known to be  $\mathcal{NP}$ -hard. We then propose a solution that decomposes the problem into three subproblems.

The first is to find a maximal convex covering of the search area. Most results on static coverage use disjoint partitions of the search area, e.g., triangulation, to convert the continuous sensor positioning problem into a discrete one. However, by a simple example, we show that a highly overlapping set of maximal convex sets is better suited for minimum time coverage. The second subproblem is a combinatorial assignment and ordering of the sets in the cover. Since Tabu Search algorithms are known to perform well on various routing problems, we use it as a part of our proposed solution. Finally, the third subproblem utilizes a particular shortest path sub-routine in order to find the vehicle paths, and calculate the overall objective function used in the tabu search. The proposed algorithm is illustrated by a number of simulation examples.

## A General Modeling Framework for Course of Action in UAV Routing

MARK KARWAN AND CHASE MURRAY

*Department of Industrial and Systems Engineering, University at Buffalo - SUNY*

Consider a set of geographically-dispersed tasks that are to be performed by a fleet of heterogeneous UAVs. Each UAV's capabilities dictate its effectiveness at performing a given task. An initial mission plan, assigning each task to a UAV at a particular time, is assumed to be known.

Suppose that during the course of executing this initial plan, an event occurs that requires the reassignment of UAVs to tasks (e.g., a task location is changed, a new task is identified, or a particular UAV is no longer available). Multiple objectives should be considered when performing course of action re-allocation of UAVs to tasks, including the maximization of overall mission effectiveness, the minimization of changes to the initial plan, and the minimization of total distance traveled.

We present a general modeling framework for dynamic UAV re-allocation problems. A variety of extensions to this general framework are provided, such as re-fueling operations, UAV capacity limitations, flexible time windows, and assignments of multiple UAVs to a single task. Particular scenarios may be modeled by selecting a combination of these extensions.

## Model Predictive Control of Vehicle Formations

FERNANDO FONTES<sup>1</sup>, DALILA FONTES<sup>2</sup>, AMELIA CALDEIRA<sup>3</sup>

<sup>1</sup>*Department of Mathematics for Science and Technology, University of Minho and ISR-Porto, Portugal*

<sup>2</sup>*Faculty of Economics, University of Porto and LIAAD INESC Porto L.A., Portugal*

<sup>3</sup>*Department of Mathematics, ISEP, Portugal*

We propose a two-layer scheme to control a set of vehicles moving in formation. The first layer, the trajectory controller, is a nonlinear controller since most vehicles are nonholonomic systems and require a nonlinear, even discontinuous, feedback to stabilize them. The second layer, the formation controller, aims to compensate for small changes around a nominal trajectory maintaining the relative positions between vehicles. We argue that the formation control can be, in most cases, adequately carried out by a linear model predictive controller accommodating input and state constraints. This has the advantage that the control laws for each vehicle are simple piecewise affine feedback laws that can be pre-computed off-line and implemented in a distributed way in each vehicle.

# **Autonomous Target Detection and Localization using Cooperative Unmanned Aerial Vehicles**

YOUNGROCK YOON, SCOTT GRUBER, LUCAS KRAKOW, AND DANIEL PACK

*Department of Electrical and Computer Engineering, U.S. Air Force Academy*

This research describes our on-going efforts toward the development of a team of autonomous and cooperative multiple unmanned aerial vehicles (UAVs) capable of detecting and localizing mobile ground targets. In particular, we present hardware implementation issues associated with the novel sensor fusion technique for heterogeneous sensors onboard multiple UAVs. The cooperative system we are developing is autonomous the processor onboard each UAV makes sensing, control, and communication decisions and is capable of accurately locating targets cooperatively.

# Distributed Optimization for Cooperative Missions in Uncertain Environments

CHRISTOS CASSANDRAS

*Department of Electrical and Computer Engineering, Boston University*

A cooperative mission involves the coordination of multiple controllable agents that share a common objective, often in an uncertain environment, with possible limitations imposed on cross-agent communication. In a multi-traveling-salesman type of problem, a “mission” is the process of controlling the movement of the agents to identify and ultimately visit (alone or in synchronized groups) “target points” with associated “rewards” so as to maximize the total collected reward.

In this work, we will show how to formulate and solve a receding horizon optimization problem adopting a “hedge-and-react” as opposed to an “estimate-and-plan” approach, thus bypassing the combinatorial and stochastic complexity of explicitly assigning vehicles to target points. We will present a key stability property and illustrate this approach through applications to a laboratory setting involving small autonomous robots with wireless communication capabilities. In a “coverage control” mission, agents with sensing capabilities are tasked with the problem of cooperatively discovering target points. We will discuss a distributed optimization approach aimed at (locally) maximizing the joint detection probabilities of random target points and illustrate its operation through an interactive software demonstration for environments that include multiple polygonal obstacles.

# Robust Decision-Making in Infinite Horizon MDPs using Scenarios

LUCA BERTUCCELLI, BRETT BETHKE, JONATHAN HOW

*Department of Aeronautics and Astronautics, Massachusetts Institute of Technology*

UAV sequential decision-making problems can often be cast in a Markov Decision Process (MDP) framework, and in this paper, we investigate infinite horizon, finite-state, finite-action MDPs where some of the elements of the transition model may be uncertain or poorly known. MDPs are known to be sensitive to the model parameters, and our goal is to experimentally quantify this sensitivity and find policies that are robust to parameter variations. We assume that some of the model parameters lie in a known uncertainty set, and extend a recently introduced Sigma Point algorithm to generate a small number of appropriately chosen instances (or scenarios) for the model parameters. The optimal policy for each of these scenarios is then found through value iteration. We show performance tradeoffs of using these policies, and in particular, numerically demonstrate the sensitivity of the optimal policy using this small number of scenarios, in the context of a UAV health management problem. Our results yield a robust policy which exhibits some conservatism in a nominal setting but shows dramatic performance improvement over other policies in a worst case setting.

# **New Results in Stochastic Cooperative Games: Strategic Coordination for Multi-Resolution Performance Robustness**

KHANH PHAM

*Air Force Research Laboratory, Kirtland Air Force Base*

A class of multi-person, single-objective decision problems is introduced. Strategic decision makers are supposed to have a complete linear stochastic model of the interactive situation in which they are engaged with the presence of stationary Wiener random disturbances. They are assumed to simultaneously make rational decisions from finite sets of available strategies according to some strategy adjustment process. A strategy adjustment process considered herein is the enforceable Pareto cooperative agreement which determines how decision makers select their strategies at any time instant as a function of perfect information sampling and their own actions. In particular, decision makers do not know the strategies taken by others and do not know the integral-quadratic form of utility functions. The first important aspect of the resulting linear-quadratic vector optimization problem is to develop a computationally efficient and tractable procedure that describes higher-order characteristics of the global utility uncertainty induced by Chi-squared random variable, with respect to all realizations of the underlying stochastic process. The second important aspect of the problem is to equip cooperative decision makers a utility statistics-based negotiation mechanism by which each decision maker influences the distribution and robustness of the global utility through the optimization of their own utility functions. Surprisingly, both compactness from logic of state-space model description and quantitatively from probabilistic knowledge of stochastic disturbances can be utilized to derive an effective numerical procedure that generates all the higher-order statistics (i.e., mean, variance, skewness, kurtosis, and etc.) associated with the Chi-squared global utility with respect to sample realization uncertainty. It is also shown that a multi-objective design synthesis of shaping the realized global utility distribution under Pareto strategic coordination is feasible for distributed multi-agent control that in turn guarantees on something stronger than averaged performance.

## On Weakly Cooperative Systems

PAVLO KROKHMAL<sup>1</sup> AND DAVID JEFFCOAT<sup>2</sup>

<sup>1</sup>*Department of Mechanical and Industrial Engineering, University of Iowa*

<sup>2</sup>*Air Force Research Lab, Eglin Air Force Base*

We consider modeling and analysis of distributed systems where the individual members may not share a common objective, and discuss methods for quantification of the effects of cooperation in such systems that operate in uncertain environments. The behavior and evolution of weakly cooperative systems are modeled using the methods of Markov processes.

# Stochastic Optimization of Sensor Network for Underwater Threat Detection

MICHAEL ZABARANKIN

*Department of Mathematical Sciences, Stevens Institute of Technology*

A two-stage stochastic optimization problem for optimal sensor placement for protecting an anchored vessel from underwater threats has been considered. The second stage adapts the detection algorithm to environmental conditions (e.g., ambient noise, etc.) and, as a result, combines signals from sensors optimally. Various network configurations with the same number of sensors have been considered, and among those, an optimal network configuration has been identified.

## Stochastic Wireless Network Jamming Problems

CLAYTON COMMANDER<sup>1</sup>, PANOS PARDALOS<sup>2</sup>, VALERIY RYABCHENKO<sup>2</sup>, SERGEY  
SARYKALIN<sup>2</sup>, AND STAN URYASEV<sup>2</sup>

<sup>1</sup>*Air Force Research Laboratory, Eglin Air Force Base*

<sup>2</sup>*Department of Industrial and Systems Engineering, University of Florida*

We extend previous results which focused on deterministic formulations of the wireless network jamming problem. This problem seeks to determine the optimal number and placement locations for a set of wireless jamming devices to sufficiently suppress a communication network according to some specified criterion. The present research introduces stochastic variants of those formulations which account for the fact that the exact topology of the network to be jammed may not be known entirely. Particularly, we consider instances in which several topologies are considered likely, and develop robust scenarios for placing jamming devices which are able to suppress the network regardless of which candidate topology is realized. We derive several formulations and include percentile constraints to account for a variety of scenarios. Case studies are presented and the results are analyzed. We conclude with directions of future research.

# Human Operator Aided Decision Processes for Unmanned Aerial Vehicles in a Stochastic Environment

JOHN BAKER<sup>1</sup>, RAYMOND HOLSAPPLE<sup>2</sup>, ANOUCK GIRARD<sup>1</sup>, PHIL CHANDLER<sup>2</sup>, AND MEIR PACTER<sup>3</sup>

<sup>1</sup>*Department of Aerospace Engineering, University of Michigan*

<sup>2</sup>*USAF Control Science Center, Wright-Patterson Air Force Base*

<sup>3</sup>*Department of Electrical and Computer Engineering, Air Force Institute of Technology*

In this research, we consider an Intelligence, Surveillance, and Reconnaissance scenario where a human operator, working with multiple UAVs, is tasked to provide feedback regarding the nature of a collection of pre-selected objects of interest. A controller onboard the ground station controlling the UAVs uses this feedback to determine an appropriate mission plan.

A small unmanned aerial vehicle (SAV) loiters at a high altitude where it may survey a large territory. The operator decides which objects in the SAVs field of view are of interest and which are clutter. Then a team of micro unmanned aerial vehicles (MAVs) is assigned individual tours to investigate the potential targets at a lower altitude. As a MAV flies over an assigned object, the operator must determine if the object has a distinguishing feature that identifies the object as a target. The key parameters for a decision are the operators response, the operators random response time, the number of objects the controller must still decide upon and the amount of the MAVs remaining fuel reserve. The stochastic controller takes this information into account and performs an analysis to compute expected information gain of a revisit. This expected information gain is used to compute a cost threshold. An expected cost for a revisit is determined using a linear model. Then if this expected cost is smaller than the computed threshold, the MAV will revisit the object from a different approach heading than its original heading.

Revisits are often useful because they can provide additional information regarding a potential target from a different approach heading. For example, a feature may only be visible from the rear of the object of interest, hence if a MAV approaches the object from the front, the operator will not see the distinguishing feature.

In previous studies, automatic target recognition was used for making some of the decisions in both the SAV and the MAVs. This paper investigates the use of human feedback alone for target recognition. Using a multiple UAV simulation tool, different reward schemes for calculating expected information gain are examined and compared with each other and against a maximum operator delay revisit threshold.

## Cooperative Control for Dependent Flows: The Case of Ground Traffic at Airports

IVOMAR SOARES<sup>1</sup>, CATHERINE MANCEL<sup>1</sup>, FELIPE FRANCA<sup>2</sup>, AND FELIX MORA-CAMINO<sup>1</sup>

<sup>1</sup>*The French Civil Aviation Institute, Toulouse, France*

<sup>2</sup>*Federal University of Rio de Janeiro, Brazil*

With the sustained increase in air transportation, resulting in increased operational costs, potential danger with conflictive traffic conditions and delays for passengers and airlines, ground traffic has become a critical issue for many airports. In this research, the ground traffic at an airport is considered to be composed of two dependent flows: aircraft and servicing vehicles. Aircraft and service vehicles move respectively along a network of taxi-ways and a network of service roads with some interactions (crossings). The involved vehicles are considered to follow hybrid dynamics where the discrete events corresponding to a transition between two operational states for a vehicle are triggered by other events. It is assumed in this study that there is only one type of service vehicles and also that all vehicles belong to a common pool which attends every arriving or departing aircraft. The objective here is to propose a global control structure which allows to reduce overall aircraft traffic delays. This control structure is composed of three levels: a traffic supervision level, a short term planning level and a traffic control level. The supervision level performs a diagnostic of airport ground traffic and generates update requests towards the short term planning level. The short term planning problem can be formulated as a non standard two level programming problem where at the upper level, aircraft path and scheduling are determined while at the lower level service vehicles are assigned to the aircraft. Finally at the traffic control level, decentralized decision making, based on priority rules and local evaluations, is performed.

## Hierarchical Control for Forward Air Controller UAV Agents

JINGPENG TANG<sup>1</sup>, DOUG SCHESVOLD<sup>2</sup>, KARL ALTENBERG<sup>3</sup>, JONATHON PIKALEK<sup>2</sup>, AND  
KENDALL NYGARD<sup>2</sup>

<sup>1</sup>*Department of Mathematical Science, University of Minnesota-Crookston*

<sup>2</sup>*Department of Computer Science & Operations Research, North Dakota State University*

<sup>3</sup>*Department of Accounting & Information Systems, North Dakota State University*

We describe a real-time hierarchical architecture for controlling heterogeneous UAVs carrying out forward air controller hunter-killer missions with communication relays. The high-level control utilizes Bayesian Decision Analysis. The detailed low-level control is achieved through message passing and state machines. We demonstrate a computer simulation and animation of the system.

# Communication Models for a Cooperative Network of Autonomous Agents

ASHWIN ARULSELVAN<sup>1</sup>, CLAYTON COMMANDER<sup>2</sup>, MICHAEL J. HIRSCH<sup>3</sup>, AND PANOS PARDALOS<sup>1</sup>

<sup>1</sup>*Department of Industrial and Systems Engineering, University of Florida*

<sup>2</sup>*Air Force Research Laboratory, Eglin Air Force Base*

<sup>3</sup>*Raytheon Inc., Joint Sensor Networking*

We consider the problem of maximizing the total connectivity for a set of wireless agents in a mobile ad hoc network. That is, given a set of wireless units each having a start point and a destination point, our goal is to determine a set of routes for the units which maximizes the overall connection time between them. Known as the *cooperative communication problem in mobile ad hoc networks (ccpm)*, this problem has several military applications including coordination of rescue groups, path planning for unmanned air vehicles, and geographical exploration and target recognition. The *ccpm* is  $\mathcal{NP}$ -hard; therefore heuristic development has been the major focus of research. In this work, we survey the *ccpm* examining first some early combinatorial formulations and solution techniques. Then we introduce new continuous formulations and compare the results of several case studies (using exact and heuristic approaches). We note that by removing the underlying graph structure, we are able to create a more realistic model of the problem as supported by the numerical evidence.

# A Mode-Based Hybrid Controller Design for Agile Maneuvering UAVs

KEMAL URE, EMRE KOYUNCU, AND GOKHAN INALHAN

*Department of Aeronautics and Astronautics, Istanbul Technical University, Turkey*

The ability of a UAV to autonomously design and execute agile maneuvers in complex and dynamic environments, is a low-level enabling technology for cooperative control of UAV fleets that is driven by performance goals. In this work we develop a structured finite state automaton that spans the full-flight-envelope maneuvers of a UAV, and we design a nonlinear sliding manifold control system that tracks the outputs of this automaton. In general, it is a very challenging task to describe general motion of unmanned air vehicles and design a single control law that handles the reference tracking. From the inspection of well-known smooth aerobatic maneuvers and more complex combat maneuvers, we see that this task can be quantized by decomposing general maneuvers to maneuver modes in which both the system dynamics and control task is simplified. The trajectory generation is then simplified to the task of time and duration sequencing of the maneuver modes and the selection of specific maneuver parameters (referred as modal inputs).

# Combining Rough Sets and Bayesian Networks to Address Uncertainty in Cooperative Control

HENRY PFISTER<sup>1</sup> AND JANUSZ ZALEWSKI<sup>2</sup>

<sup>1</sup>*Air Force Research Laboratory, Eglin Air Force Base*

<sup>2</sup>*Department of Computer Science, Florida Gulf Coast University*

Results on modeling cooperative control strategies with Bayesian belief networks (BBN's) and rough sets, reported at previous conferences on Cooperative Control, applied the concept on BBN's to mitigate uncertainties in the knowledge and state of cooperating agents by using the rough set reasoning to incorporate the new evidence that is not necessarily in a form of probability distributions. The advantage of this approach is in the fact that BBN reasoning can be enhanced by rough sets, even if the available information (evidence) is incomplete and vague, which can still lead to improvements in the decision making process.

However, the method assumes that the additional evidence is collected beforehand and supplied to the BBN off-line, which makes sense for reasoning about external processes at the management levels but is not well suited for real-time decision making. To make this type of reasoning more applicable to cooperative control under real-time conditions, two public domain tools have been used to collect relevant information in cooperation to enhance the reasoning process. The BBN tool does the essential inference and is fed with supplementary information from the rough set tool, which collects evidence in real time directly from the field or other sources. The advantages and limitations of this approach are discussed in the presentation.

## Formulations of Network Flow Problems Under Uncertainty

VLADIMIR BOGINSKI<sup>1</sup> AND CLAYTON COMMANDER<sup>2</sup>

<sup>1</sup>*Department of Industrial and Systems Engineering, University of Florida*

<sup>2</sup>*Air Force Research Laboratory, Eglin Air Force Base*

Network flow problems have a wide variety of important applications in many areas. Although deterministic formulations of these problems are well-studied, in many practical situations one has to deal with uncertainties associated with possible failures of network components (e.g., some arcs have a probability of failure). Formulations and optimal solutions of these problems need to be adjusted to take into account these uncertainty factors. The main difficulty arising in addressing these issues is the dramatic increase in the computational complexity of the resulting optimization problems. We propose LP-based solution methods for network flow problems under a set of failure scenarios, which allow to find robust solutions in polynomial time.

## Detecting Large Cohesive Subgroups in Networks

SERGIY BUTENKO<sup>1</sup> AND BALABHASKAR BALASUNDARAM<sup>2</sup>

<sup>1</sup>*Department of Industrial and Systems Engineering, Texas A&M University*

<sup>2</sup>*Department of Industrial Engineering & Management, Oklahoma State University*

The concept of a cohesive subgroup was first introduced in social network analysis, but is also used (under different names, such as cluster or module) in several other important application areas, including wireless networks, telecommunications, and graph-based data mining. One of the earliest and most popular graph models used for studying cohesive subgroups was the clique model, however, the clique approach describes an “ideal” cohesive subgroup and is overly restrictive. In this talk, we will discuss alternative approaches that relax various aspects of the ideal definition of a cohesive subgroup. We will discuss advantages and disadvantages of each model, algorithms for detecting the corresponding cohesive subgroups and results of computational experiments with social, biological and random networks.

## Robust Track Association and Fusion with Extended Feature Matching

GENSHE CHEN<sup>1</sup>, HUIMIN CHEN<sup>2</sup>, TOD SCHUCK<sup>3</sup>, AND ERIK BLASCH<sup>4</sup>

<sup>1</sup>*DCM Research Resources, LLC.*

<sup>2</sup>*Department of Electrical Engineering, University of New Orleans*

<sup>3</sup>*Lockheed Martin*

<sup>4</sup>*Air Force Research Laboratory, Wright-Patterson Air Force Base*

In this research, we propose new data processing architecture and fusion algorithms for improved target classification and tracking accuracy using distributed and, possibly, legacy-sensor platforms. Although there exist data fusion systems that can handle sensor fusion problems for various purposes, they are not publicly available, tied to real sensor data, or general enough to incorporate the state-of-the-art fusion algorithms. We present a robust data fusion algorithm that can incorporate variable dimension target types/classes at the fusion center when receiving distributed sensor reports and/or local tracks.

# Cooperative Control, Optimization and Information Flow

RICHARD MURRAY

*Department of Control and Dynamical Systems, California Institute of Technology*

Over the past decade, rapid progress in optimization-based estimation and control combined with advances in real-time networking and computation have led to new approaches in integrated guidance, navigation and autonomy for both single and multiple vehicle systems.

In this talk we survey some of recent research in cooperative control of multi-vehicle systems, using a common mathematical framework to allow different methods to be described in a unified way. We then focus on a few key technical areas in which there has been significant progress with the possibilities of changing the way we design modern aerospace systems: real-time spatio-temporal planning, networked control systems, and the role of topology in stability and performance of cooperative systems.

# Dynamics and Control of Surface Exploration Robots on Near Earth Objects

JULIE BELLEROSE, DANIEL SCHEERES, AND ANOUCK GIRARD

*Department of Aerospace Engineering, University of Michigan*

Over the past decade, a few solo-robotic landing missions have been sent to near Earth objects at modest cost, providing a basic understanding of their environment. These missions can diversify and be improved upon by having multiple landers which contribute also to increasing an overall mission reliability. Since the gravity on an asteroid is low, a wheeled vehicle would likely bounce back from hitting the surface, and be difficult to control. Instead we considered hopping robots. We developed a first order model of the dynamics of hoppers to estimate the total time and distance covered from an initial bounce to a stop due to friction and restitution coefficients. From this dynamical model, hoppers could easily investigate the surface by controlling their initial velocity; one would just need to estimate to desired distance to be covered. To extend the single hopper control law to collaborative landers, we apply dynamic extension and sliding-mode control to discrete formation control.

## **Towards Optimal Positioning of Surveillance UGVs**

ULRIK NILSSON, PETTER OGREN AND JOHAN THUNBERG

*Department of Autonomous Systems, Swedish Defence Research Institute*

Unmanned Ground Vehicles (UGVs) equipped with surveillance cameras present a flexible complement to the numerous stationary sensors being used in security applications today. However, to take full advantage of the flexibility and speed offered by a group of UGV platforms, a fast way to compute desired camera locations to cover an area or a set of buildings, in response to e.g. an alarm, is needed. Building upon earlier results in terrain guarding and sensor placement we propose a way to find candidate guard positions that satisfy a large set of view angle and range constraints simultaneously. Since the original problem is  $\mathcal{NP}$ -complete, we do not seek to find the true optimal set of guard positions. Instead, a near optimal subset of the candidate points is chosen using a scheme with a known approximation ratio of  $O(\log(n))$ . A number of examples are presented to illustrate the approach.

# Incorporating Weather System in Cooperative UAV Search: Probabilistic Approach

OZGUR ARAZ<sup>1</sup> AND RAKESH NAGI<sup>2</sup>

<sup>1</sup>*Department of Industrial Engineering, Arizona State University*

<sup>2</sup>*Department of Industrial and Systems Engineering, University at Buffalo - SUNY*

In this research, we consider a fleet of UAVs performing a search mission in a bounded area where targets are located. The search strategy is a cooperative one, rather than a centralized one due to low bandwidth and the dynamics in the system. Our solution method is a Dynamic Programming (DP) algorithm for computing the trajectories of multiple UAVs from a mission starting point with the objective of cooperatively searching the set of fixed targets. The algorithm presented in this research calculates a gain function for maximizing the number of targets found in the area. Each vehicle maintains a dynamic map of probabilities indicating where the targets are likely to exist and where other vehicles have already been routed.

The main contribution of this research is the inclusion of weather systems in the field of search. Weather systems are important in UAV routing because they directly affect the sensor performance as well as UAV navigability. Weather systems are incorporated in the DP algorithm by altering vehicle cognitive maps so that they generate path plans that avoid the systems.

# Maximizing Search Coverage using Future Path Projection for Cooperative Multiple UAVs with Limited Communication Ranges

PEDRO LIMA AND DANIEL PACK

*Department of Electrical and Computer Engineering, US Air Force Academy*

In this research, we present future path projection as a novel method for multiple Unmanned Aerial Vehicles (UAVs) with limited communication ranges to cooperatively maximize the coverage of a large search area. For multiple cooperative UAVs to perform an effective search mission, the critical status and sensor information collected by each UAV must be shared with all other UAVs in the group. In an ideal environment where there is no communication limitation, all involved UAVs can share the necessary information without any constraints. In a more realistic environment, UAVs must deal with limited communication ranges. The communication range limitation, however, introduces a challenging problem for multiple UAVs to effectively cooperate. In the proposed method, each UAV constructs an individual probability distribution map of the search space which includes predictions of the future paths of UAVs as they move beyond their communication ranges. The probability distribution map describes the likelihood of detecting targets within the search space. The overall, collective UAV search patterns are governed by decisions made by each UAV within the group, based on each individual probability distribution map. We show that the collective search patterns generated by cooperative UAVs using the proposed method significantly improve the search area coverage when compared to similar search patterns produced by other mitigation strategies designed to overcome the communication range limitation. We validate the effectiveness of the proposed path projection method using simulation results.

# Priority-based Assignment and Routing of a Fleet of Unmanned Combat Aerial Vehicles

RAKESH NAGI AND MOISES SUDIT

*Department of Industrial and Systems Engineering, University at Buffalo*

This paper considers the strategic routing of a fleet of Unmanned Combat Aerial Vehicles (UCAVs) to service a set of predetermined targets from a prior surveillance mission. Targets are characterized by their priority or importance level, and minimum and maximum service levels that respectively represent the lower bound of munitions for destruction and upper bound of munitions to limit collateral damage. Additional constraints to be respected are the payload capacities of the (possibly heterogeneous) UCAV fleet and the range based on fuel capacity and payload transported. The vital aspect of this paper is the integrated optimal utilization of available resources - weaponry and flight time - while allocating targets to UCAVs and sequencing them to maximize service to targets based on their criticality.

The complexity of the problem is addressed through a decomposition scheme with two problems: A target assignment problem (modeled as a minimum cost network flow problem) and a vehicle routing problem, which in turn splits into multiple decision traveling salesman problems, one for each UAV. A Tabu Search Heuristic is developed to coordinate the two problems. Using test problems we establish the applicability of this approach to solve practical-sized problems.

# A comparative study of task assignment and path planning methods for multi-UGV missions

JOHAN THUNBERG<sup>1</sup>, DAVID ANISI<sup>2</sup>, AND PETTER OGRE<sup>1</sup>

<sup>1</sup>*Department of Autonomous Systems, Swedish Defence Research Agency*

<sup>2</sup>*Department of Optimization and Systems Theory, Royal Institute of Technology, Sweden*

Many important problems involving a group of unmanned ground vehicles (UGVs) are closely related to the multi travelling salesman problem (m-TSP). This paper comprises a comparative study of a number of algorithms proposed in the literature to solve m-TSPs occurring in robotics.

The investigated algorithms include two mixed integer linear programming (MILP) formulations, a market based approach (MA), a Voronoi partition step (VP) combined with the local search used in MA, and a deterministic and a stochastic version of the granular tabu search (GTS).

To evaluate the algorithms, a m-TSP is derived from a planar environment with polygonal obstacles and uniformly distributed targets and vehicle positions. The results of the comparison indicate that out of the decentralized approaches, the MA yield good solutions but requires long computation times, while VP is fast but not as good. The two MILP approaches suffer from long computation times, and poor results due to the decomposition of the assignment and path planning steps. Finally, the two GTS algorithms yield good results in short times with inputs from MA as well as the much faster VP. Thus the best performing centralized approach is the GTS in combination with the VP

## Algorithms for the Dubins Traveling Salesman Problem

SIVAKUMAR RATHINAM<sup>1</sup>, WAQAR MALIK<sup>2</sup>, SAIKUMAR YADLAPALLI<sup>2</sup>, AND SWAROOP  
DARBHA<sup>2</sup>

<sup>1</sup>*Nasa Ames Research Center*

<sup>2</sup>*Department of Mechanical Engineering, Texas A&M University*

Given a set of targets on a Euclidean plane, the objective of the Dubins TSP is to find a minimum distance path for a fixed wing Unmanned Aerial Vehicle (UAV) that visits each of the targets exactly once and satisfies the constraint on the maximum turn rate of the UAV. Currently, there are no results in the literature to estimate the optimal cost of this Dubins TSP even for a small number of targets. In this work, we discretize the angles of approach at each target, and formulate the relaxed Dubins TSP as a One in a set Asymmetric Traveling Salesman Problem (OATSP). As the discretizations become finer, the optimal cost of the OATSP must approach the optimal Dubins TSP cost. First, we solve the OATSP as a function of the number of discretizations at each target and show how the optimal cost of the OATSP behaves with the number of discretizations. Secondly, for each discretization, we develop three algorithms that produce a feasible solution to the OATSP. We then compare the performance of all the algorithms with the optimal cost of the OATSP and show how one can extend these algorithms to the multiple vehicle case. We also give the average computation time required for each of the algorithms. This will give an insight into the tradeoff between the ability to get close to the optimal Dubins solution versus the amount of computation time available.

# Distributed, Near-Optimal Network Enabled Weapon-Target Assignment for Combat Formations

NICOLAS LECHEVIN<sup>1</sup>, CAMILLE-ALAIN RABBATH<sup>2</sup>, AND MARC LAUZON<sup>2</sup>

<sup>1</sup>*Numerica Technologies, Inc.*

<sup>2</sup>*Defence R&D, Canada*

A stochastic Network Enabled Weapon-Target Assignment Scheme (NEWTAS) is proposed to control multiple formations of combat vehicles. NEWTAS is formulated as a target sequencing problem, where each formation is assigned to a sequence of tactical targets in such a way that a global utility function is maximized while constraining the total energy expenditure of the combat vehicles. Each sequence is defined as an ordered list of targets to be visited by a given formation. The set of sequences constitutes the so-called multi-routing, which is such that all the targets are visited at least once.

## **Application of Monkey Search Metaheuristic to Solving MAP Instances**

ALLA KAMMERDINER, ANTONIO MUCHERINO, AND PANOS PARDALOS

*Department of Industrial and Systems Engineering, University of Florida*

Multidimensional assignment problem (MAP) can be viewed as a higher dimensional extension of the linear assignment problem. We apply Monkey search metaheuristic for solving randomly generated instances of MAP. MAP is a recently proposed novel metaheuristic approach for global optimization inspired by the behavior of a monkey climbing trees looking for food.

The branches of a search tree are constructed as perturbations between two neighboring feasible solutions of MAP. The monkey mark and update these branches leading to good solutions as it climbs up and down the tree. A wide selection of perturbations, which are inspired by other metaheuristic methods for global optimization (i.e. simulated annealing, harmony search, etc), can be utilized by Monkey search.

# Optimal Control of the Weapon Operating Characteristic with Control Inequality Constraints

JOHN V. BODE II AND DAVID R. JACQUES

*Department of Aeronautics and Astronautics, Air Force Institute of Technology*

Further refinement of the optimal employment of autonomous unmanned aerial vehicles is addressed. Several scenarios of an airborne munition or sensor-craft searching a battlespace for stationary targets with various distributions of false targets are examined. The optimal scheduling of control variables, the probability of target report (PTR), and area coverage rate (Q) in the vector control problem are formulated with control inequality constraints. These optimal problem formulations allow solutions that maximize the probability of target attack while also allowing various constraints to be placed upon the probability of false target attacks. Analysis has shown that the optimal solutions are highly sensitive to the particular heuristic chosen for the relationship between the receiver operating characteristic (ROC) curve parameter,  $c$ , and area coverage rate. Several different heuristics for that particular relationship have been studied and the results shown. These results show the optimal dynamic scheduling of the parameters of sensor threshold and area coverage rate. In addition, the use of control inequality constraints shows the existence of natural corner points that can be observed by calculus of variation techniques.

# Real-time Recursive Bayesian Estimation Using a Graphics Processing Unit and its Application to Micro Aerial Vehicles

JAMIE KELLY, MAKOTO KUMON, BENJAMIN LAVIS AND TOMONARI FURUKAWA

*School of Mechanical and Manufacturing Engineering, The University of New South Wales*

This research presents the implementation of a graphics processing unit (GPU) for real-time recursive Bayesian estimation (RBE) and its application to micro aerial vehicles (MAVs). Irrespective of the type of numerical technique for RBE, particle-based, grid-based or element-based, the target space is represented on a nodal basis, and the prediction and the update processes for each node in RBE are carried out independently. Therefore, the GPU, which processes pixel images in a parallel manner, is well suited for RBE and can accelerate the RBE to achieve real-time computation. The theoretical contributions of the paper include the formulation of the RBE which does not concern whether the target is detectable and its implementation into the GPU.

The preliminary numerical investigations show successful implementation through validation and verification as well as real-time performance even when the number of nodes exceeds one million. The proposed approach was further used for the RBE by a rotary-wing MAV equipped with a GPS and a compass to identify its global state, a camera to detect a target and a wireless module to communicate with the ground station. Although the ground to search for a target was vast and thus made the number of nodes considerably large, the proposed approach could execute RBE while the MAV was flying and observing the ground.