7th International Conference on Cooperative Control and Optimization

January 31–February 2, 2007

Center for Applied Optimization, University of Florida
Air Force Research Laboratory, Munitions Directorate
Raytheon Inc., Joint Sensor Networks

Hilton University of Florida - Conference Center
Gainesville, FL

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PROGRAM

Wednesday, January 31, 2007 (Century Ballroom B & C)

0700–1700	Registration, Conference Registration Desk
0800–0815	**Welcome Session** Pramod P. Khargonekar, Dean of the College of Engineering, University of Florida Panos M. Pardalos, Department of ISE, University of Florida Robert Murphey, Air Force Research Laboratory, Munitions Directorate
Plenary Session	Chair Panos Pardalos
0815–0900	**Plenary Speaker** Jerzy Filar **Games, Incompetence, Training, and Related Parametric Analysis**
0900–0915	**Coffee Break**
Session W.1	Chair Robert Murphey
0915–0945	Pavlo Krokhmal and David E. Jeffcoat **Analysis of Value-Of-Information in Cooperative Systems of Autonomous Agents with Human Operators-In-The-Loop**
0945–1015	Paul Scerri, Robin Glinton, Sean Owens, Katia Sycara, Dan Rutherford, and Jerry Fudge **Geolocation of RF Emitters with Teams of UAVs**
1015–1030	**Coffee Break**
Session W.2	Chair Clayton Commander
1030–1100	Gokhan Inalhan, Ahmet Cetinkaya, Sertac Karaman, Oktay Arslan, and Mirac Aksugur **Design of a Distributed C2 Architecture for Interoperable Manned/Unmanned Fleets**
1100–1130	Derek Kingston and Randal Beard **UAV Splay State Configuration for Moving Targets**
1130–1200	Yongjie Zhu, Qi Chen, and Umit Ozguner **Waypoint Selection in Constrained Domains**
1200–1315	**Lunch, Albert's Restaurant**

Wednesday, January 31, 2007 (Century Ballroom B & C)

Panel Session Moderator Jonathon How

1315–1445 Jonathon How, Robert Murphey, Krishna Pattipati, Jeff Shamma, and Randal Beard
Future Directions in Cooperative Control

1445–1500 **Coffee Break**

Session W.3 Chair Michael J. Hirsch

1500–1530 Henry L. Pfister and Janusz Zalewski
Using Rough Sets in Enhancement of Cooperative Control Strategies

1530–1600 Brett Bethke, Mario Valenti, and Jonathan How
UAV Task Assignment with Integrated Health Monitoring and Performance Assessment

1600–1630 Meir Pachter, Swaroop Darbha, and Phillip Chandler
Sequential Inspections Using Loitering

1630–1700 Octavia Camps and Mario Sznaier
Robust Cooperative Visual Tracking: A Combined NonLinear Dimensionality Reduction/Robust Identification Approach

Thursday, February 1, 2007 (Century Ballroom B & C)

0700–1200 Registration, Conference Registration Desk

Plenary Session Chair Robert Murphey

0800–0845 **Plenary Speaker** Louis Caccetta
Computational Methods for a Class of Discrete Valued Optimal Control Problems Arising in Defense Applications

0845–0900 **Coffee Break**

Session T.1 Chair Don Grundel

0900–0930 Tomonari Furukawa, Frederic Bourgault and Hugh F. Durrant-Whyte
Coordinated Bayesian Search and Tracking Using Element-Based Method

0930–1000 Andrew J. Sinclair, Richard Prazenica, and David E. Jeffcoat
Simultaneous Localization and Planning for Cooperative Air Munitions

1000–1030 Gregory L. Plett, Dimitri Zarzhitski, and Daniel J. Pack
Out-of-Order Sigma-Point Kalman Filtering for Target Localization using Cooperating Unmanned Aerial Vehicles

1030–1045 **Coffee Break**

Session T.2 Chair Clayton Commander

1045–1115 Yechiel J. Crispin and Marie E. Ricour
Cooperative Rendezvous Between Active Autonomous Vehicles

1115–1145 Khanh D. Pham
Multi-Cumulant Control for Zero-Sum Differential Games: Design-Performance-Measure Statistics and State-Feedback Paradigm

1145–1215 Harish Mukhami, Jonathan Pikalek, Karl Altenburg, and Kendall E. Nygard
Swarm Intelligence for Formation Flight with Autonomous UAVs

1215–1315 **Lunch, Albert's Restaurant**

Thursday, February 1, 2007 (Century Ballroom B & C)

Session T.3 Chair Theresa Wilson

1315–1345 Jacob Yadegar, Junxian Wang, Abhishek Tiwari, Harish Chandra, and Joseph Yadegar
Unmanned Vehicle Navigation based on Peano-Cesaro Fractal Sweep

1345–1415 Wenchuan Cai, Liguo Weng, Ran Zhang, Mingjin Zhang, and Y. David Song
Virtual Leader Based Formation Control of Multiple Unmanned Ground Vehicles: Control Design, Off-line Simulation and Real-time Experiment

1415–1445 Joel M. Esposito, Matthew G. Feemster, and Erik T. Smith
Contact Point Selection for the Swarm Manipulation Problem

1445–1500 **Coffee Break**

Session T.4 Chair Michael J. Hirsch

1500–1530 Yoonsoo Kim, Da-Wei Gu, and Ian Postlethwaite
Real-Time Optimal Time-Critical Target Assignment for UAVs

1530–1600 Jason C. Derenick and John R. Spletzer
Second-order Cone Programming Techniques for Coordinating Large-Scale Robot Teams in Polygonal Environments

1600–1630 Mesut Yavuz and David E. Jeffcoat
An Analysis and Solution of the Sensor Scheduling Problem

1630–1700 Dan Shen, Genshe Chen, Jose B. Cruz Jr, and Khanh Pham
An Adaptive Sequential Game Theoretic Approach to Coordinated Mission Planning For Aerial Platforms

1830 **Conference Reception & Dinner, Albert's Restaurant**

Friday, February 2, 2007 (Century Ballroom B & C)

Invited Session	Chair Panos Pardalos
0800–0845	Vitaliy A. Yatsenko, Panos M. Pardalos, and Michael J. Hirsch **Cooperative Control of Multiple Agents and Search Strategies**
0845–0900	**Coffee Break**
Session F.1	Chair Don Grundel
0900–0930	Xiaofei Huang **Distributed Cooperative Optimization**
0930–1000	Alla Kammerdiner, Pavlo Krokhmal and Panos M. Pardalos **On Some Characteristics of the Distribution of Hamming Distance Values between Solutions of the Multidimensional Assignment Problem**
1000–1030	Michael G. Johnston Jr. and David E. Jeffcoat **Error Analysis for Image-Based Geo-Location**
1030–1045	**Coffee Break**
Session F.2	Chair Michael J. Hirsch
1045–1115	Cory Dixon and Eric Frew **Decentralized Extremum-Seeking Control of a Cooperative Team of Nonholonomic Vehicles to Form a Communication Chain**
1115–1145	Jason R. Marden, Gürdal Arslan, and Jeff S. Shamma **A Game Theoretic Formulation of the Dynamic Sensor Allocation Problem**
1145–1215	Clayton W. Commander, Panos M. Pardalos, Valeriy Ryabchenko, Oleg Shylo, and Stan Uryasev **Recent Advances in Eavesdropping and Jamming Communication Networks**
1215–1315	**Lunch, Albert's Restaurant**

Friday, February 2, 2007 (Century Ballroom B & C)

Session F.3 Chair Clayton Commander

1315–1345 Sai Krishna Yadlapalli, Waqar Malik, Sivakumar Rathinam, and Swaroop Darbha
Path Planning with Precedence Constraints for a Collection of Dubin's Vehicles

1345–1415 Hongliang Yuan, Vivian I. Gottesman, Falash Mark, Zhihua Qu, Eytan Pollak, and Jiangmin Chunyu
Cooperative Formation Flying in Autonomous Unmanned Air Systems with Application to Training

1415–1445 Paul Deignan
Efficient Calculation of Multi-Sensor/Multi-Agent Entropic Maps

1445–1515 Kamran Fatahi, Abolfazl Ghaemi, and Panos Pardalos
On Designing Algorithms For Solving Multidimensional Assignment Problem: An AI/OR Approach

1515 **Conference Adjournment**

Games, Incompetence, Training, and Related Parametric Analysis

Jerzy A. Filar

Department of Mathematics and Statistics, University of South Australia

In classical strategic game theory the pay-offs are fully determined directly by players' choices of strategies. However, a player may not be capable of executing a chosen strategy due to lack of skill/capability otherwise known as "incompetence". A common approach to dealing with incompetence is to devote resources to "training/learning" that may be in the form of investment in new technologies or capabilities. In practice, such efforts will rarely eliminate incompetence completely but can reduce it to more acceptable levels, especially if other players do not invest in similar incompetence reduction strategies. Of course, in general, all participants may engage in these training activities and the problem of how to model and assess the benefits (if any) of these training efforts leads to many fascinating questions in game theory and optimization as well as to some, mathematically very challenging, parametric analysis problems. Indeed, it is natural to conjecture that - depending on the structure of solutions to these analyses - incompetence may easily induce "tacit", or even formal, cooperation in the behavior of otherwise non-cooperative players. Arguably, anti-ballistic missile treaties are manifestations of this induced cooperation.

In this presentation we outline some approaches to the modeling, analysis, and solution of instances of this difficult class of problems. In particular, a method for examining incompetence in certain games is introduced, examined, and illustrated. Along with the derivation of general characteristics, a number of interesting special behaviors are identified. The latter are shown to be the result of special forms of the game and/or the incompetence matrices. A simplified application to capability investment decisions in the military is discussed.

In addition, we consider a class of parametric optimization problems that arise naturally in this context. We demonstrate that in certain situations, even small changes in a parameter can lead to dramatic changes in optimal solutions. We outline a recent, unified, theory for determining when this phenomenon arises. Surprisingly, perhaps, this theory relies on some powerful results and techniques - such as those of Gröbner bases and complex algebraic varieties - developed by pure mathematicians but rarely used in the kind of practical applications that stimulated these investigations.

Analysis of value-of-information in cooperative systems of autonomous agents with human operators-in-the-loop

Pavlo Krokhmal[1] and David E. Jeffcoat[2]

[1]*Department of Mechanical and Industrial Engineering, University of Iowa*
[2]*Air Force Research Laboratory, Munitions Directorate*

We consider cooperative search system comprised of autonomous search agents that are supervised by human operators-in-the-loop. The cooperation among autonomous agents is facilitated via cueing, or exchange of information on target locations, search directions, etc. In this talk we investigate the impact of human supervision on the system's performance.

Geolocation of RF Emitters with Teams of UAVs

Paul Scerri[1], Robin Glinton[1], Sean Owens[1], Katia Sycara[1], Dan Rutherford[2], and Jerry Fudge[2]

[1] *Robotics Institute, Carnegie Mellon University*
[2] *L-3 Communications Integrated Systems*

In this talk we will describe work on an application where a team of UAVs uses Relative Signal Strength Indicator (RSSI) sensors to locate Radio Frequency (RF) emitting ground vehicles in some environment. Such a capability has both civilian, e.g., locating lost hikers and military, e.g., locating adversaries in a large area, applications. RSSI sensor readings are very noisy and multiple emitters will cause overlapping signals to be received by the sensor. Finding emitters requires multiple signals from different UAVs, hence requiring cooperation between the UAVs. To estimate the location of the emitters each UAV has a Binary, Grid-based, Bayesian Filter. To build a coherent distributed picture given tight communication limitations, the UAVs share only those sensor readings that induce the largest changes in their local distribution. Each UAV translates its estimate of emitter locations to a map of *entropy* and then plans a path that will maximize the reduction in entropy (or conversely provide the highest information gain.) Planned paths are shared with a subset of other UAVs to both minimize overlapping search and prevent collisions. Experiments in a medium fidelity simulation environment show the approach to be lightweight and effective. Evaluation of the approach with physical UAVs are discussed and compared with simulation results.

Design of a Distributed C2 Architecture for Interoperable Manned-Unmanned Fleets

Ahmet Cetinkaya[1], Sertac Karaman[1], Oktay Arslan[1], Mirac Aksugur[1], and Gokhan Inalhan[2]

[1] *Controls and Avionics Lab, Istanbul Technical University*
[2] *Department of Aeronautics and Astronautics, Istanbul Technical University*

The increasing use of unmanned vehicles in civilian and military domains has driven critical requirements for synchronized and safe interoperability of manned-unmanned systems. In this work, we explore the effects of these requirements on the design of Command and Control(C2) Architectures from a micro (pilot information interface with unmanned vehicles) and a macro (coordinated operations of joint manned-unmanned vehicle fleets) perspective.

Towards this end, an experimental network simulator is developed for joint real-time simulation across manned-unmanned fleets, and the mission control center. The hardware structure within the network simulator is tailored to mimic the distributed nature of each of the vehicle's processors and communication modules. Equipped with 3D flight simulation displays and touch-screen C2 interface at the desktop pilot level, the platform also allows us to test a variety of centralized and distributed pilot-unmanned fleet coordination algorithms.

The results for the real-time fleet task assignment problem indicate that, the distributed UAV cooperative control scheme interoperating with the pilot at the supervisory role, provides higher responsiveness to dynamic scenarios in which allocation of capabilities and resources across the scenario becomes critical. Motivated by this, we consider the design of a distributed C2 Architecture in which predefined role and inter-dependance of each element is expanded such that command and control can be shifted across pilots and mission controllers in real-time and on need basis.

UAV Splay State Configuration for Moving Targets

Derek Kingston and Randal Beard

Department of Electrical Engineering, Brigham Young University

Cooperative surveillance problems require members of a team to spread out in some fashion to maximize coverage. In the case of single target surveillance, a team of UAVs angularly spaced (i.e. in the splay state configuration) provides the best coverage of the target in a wide variety of circumstances. In this paper we propose a decentralized algorithm to achieve the splay state configuration for a team of UAVs tracking a moving target. We derive the allowable bounds on target velocity to generate a feasible solution as well as show that, near equilibrium, the overall system is exponentially stable. Monte Carlo simulations indicate that the surveillance algorithm is asymptotically stable for arbitrary initial conditions. We conclude with hardware tests to show the practical feasibility of the splay state controller.

Waypoint Selection in Constrained Domains

Yongjie Zhu, Qi Chen, and Umit Ozguner

Department of Electrical and Computer Engineering, Ohio State University

For autonomous vehicle navigation, especially when the operation area is a constrained domain, waypoints should be selected to satisfy both the vehicle dynamics and the area constraints. The problem is related to many others, from a so-called sofa problem, to path planning algorithms like A-star, to potential field approaches. It has a number of new applications, on the ground with autonomous cars, in the air, with UAV's flying around buildings.

This paper presents a waypoint selection strategy taking into account the dimensions of the free space and practical aspects of motion generation. The study focuses on several cases corresponding to different situations, we shall provide examples of parking maneuvers in a constrained parking zone.

The strategy can be designed in the framework of hybrid systems. In the higher level, first we divide the whole parking spot into a few cells around the goal parking position and specify the area near the parking slot as the target cell. This cell is a highly constrained area since as long as the vehicle entered this cell the "pose" must meet some requirements so that parking maneuver can be easily finished within this small cell. Secondly, the planar cell structure is extended to three dimensions space and the orientation is expressed by the vertical dimension. And now, given a vehicle pose, we can index it by x, y, z information of each cubic cell. Third, for each cell, that has the different pose, a corresponding waypoint selection method is developed in the lower level considering vehicle dynamic motion constrains.

In low level, both the vehicle desired (parking) position and its initial position is defined by two points on the longitudinal direction. A mainline approach and a number of special cases are investigated.

The maneuvering task is finished by approaching the target cell and tracking the final parking position. We provide simulations with a Dubin's car model. Hardware implementation is underway.

Using Rough Sets in Enhancement of Cooperative Control Strategies

Henry L. Pfister[1] and Janusz Zalewski[2]

[1]*Air Force Research Laboratory, Munitions Directorate*
[2]*Department of Computer Science, Florida Gulf Coast University*

Previous research on modeling cooperative control strategies with Bayesian belief networks (BBNs), reported at the 6th Conference on Cooperative Control, suggested that the uncertainty of each autonomous agents knowledge of the actual state of all of the cooperating agents, which becomes a key issue in reaching the objective of a team of agents, can be mitigated by applying the concept of BBNs. By representing the uncertainty in a set of state variables as a joint probability distribution, a BBN can model the cause and effect relationships among these variables by incorporating new evidence about them, as soon as it becomes available.

There is a problem, however, when the information available is so scarce that it cannot be assessed in terms of probability distributions. Then, a technique based on rough sets, which are sets dealing with vagueness on their boundaries, becomes useful because it allows deriving at least partial conclusions about data and building knowledge based on it. This research explores applying rough set theory to enhance Bayesian belief networks to model a cooperative control strategy for a team of autonomous agents. Cooperative control strategy models are constructed and tested using belief network and rough set algorithms to assess the advantages and limitations of this approach.

UAV Task Assignment with Integrated Health Monitoring and Performance Assessment

Brett Bethke[1], Mario Valenti[2], and Jonathan How[1]

[1]*Department of Aeronautics and Astronautics, Massachusetts Institute of Technology*
[2]*Department of Electrical Engineering, Massachusetts Institute of Technology*

The capabilities of unmanned aerial vehicles (UAVs) are becoming increasingly sophisticated, allowing them to carry out more complex missions. These missions require task assignment algorithms that deliver good performance while meeting the real-time demands of the mission. Typically, task assignment algorithms assume a static vehicle performance model which is used to make predictions about the overall cost of a particular assignment. The static model approach may lead to poor results when the performance of one or more vehicles differs from the model's predictions due to inaccurate initial modeling, environmental disturbances, or the occurrence of vehicle failures. We present a method to update the performance model in real-time based on observed vehicle health and performance data. This approach allows a tasking system to adapt to changes in vehicle health, allowing for improved performance over the static model approach. Experimental results incorporating the use of a vision-based tracking system into an indoor multi-UAV flight testbed will be presented.

Sequential Inspections Using Loitering

Meir Pachter[1], Swaroop Darbha[2,3], and Phillip R. Chandler[2]

[1]*Department of Engineering, Air Force Institute of Technology*
[2]*Air Force Research Laboratory, WPAFB*
[3]*Department of Mechanical Engineering, Texas A&M University*

A set of objects of interest is to be sequentially inspected by a a camera equipped mobile autonomous vehicle (MAV). Upon arriving at an object of interest, an image of the object is sent to a human operator, who, upon inspecting the image, sends his feedback to the MAV. The feedback from the operator may consist of the pose angle of the object and whether he has seen any distinguishing features of the object. Upon receiving the feedback, the MAV uses this information to decide whether it should perform a secondary inspection of the object of interest. A secondary inspection has a reward (or value or information gain) that is dependent on the operator's feedback. There is an associated cost of reinspection and it depends on the delay of the operator's feedback. It seems reasonable to let the MAV loiter for a while near the most recently inspected object of interest so that it expends a small amount of endurance from the reserve after receiving the feedback from the operator. The objective is to increase the information and hence, the total expected reward about the set of objects of interest. Since the endurance of the MAVs is limited, the loiter time near each object of interest must be carefully determined. We devote this paper to the determination of this issue through the use of Stochastic Dynamic Programming.

Robust Cooperative Visual Tracking: A Combined NonLinear Dimensionality Reduction/Robust Identification Approach[1]

Octavia Camps[2] and Mario Sznaier[2]

[1] *This work was partially supported by AFOSR grant FA9550-05-1-0437 and NSF grant ITR-0312558*

[2] *Department of Electrical and Computer Engineering, Northeastern University*

In this presentation we consider the problem of robustly tracking multiple targets using several, not necessarily registered, cameras. In principle, tracking targets using multiple cameras should increase robustness against occlusion and clutter since, even if the targets appear largely occluded to some sensors, the system can recover by using the others. Furthermore, examining data from spatially distributed cameras can reveal activity patterns not apparent to single or closely clustered sensors. However, as we will illustrate with several examples, although intuitively appealing, multi-camera tracking *does not necessarily improve robustness* unless efficient coordination mechanism are available to (i) reject incorrect measurements, and (ii) maintain consistent identity labels of the targets across views. In this presentation we will describe a new approach to accomplish these goals that does not require feature matching or camera calibration. The key idea is to exploit the high spatial and temporal correlations between frames and across views by (i) associating to each viewpoint a set of intrinsic coordinates on a low dimensional manifold, and (ii) finding an operator that maps the dynamic evolution of points over manifolds corresponding to different viewpoints. Once this operator has been identified, correspondences are found by simply running a sequence of frames observed from one view through the operator to *predict* the corresponding current frame in the other view. It is worth emphasizing that this approach substantially increases robustness not only against occlusion and clutter, but also against appearance changes. In addition, it provides a scalable mechanism for sensors to share information under bandwidth constraints. These results will be illustrated with several examples. (Some of these examples can be found at `http://robustsystems.ee.psu.edu`). Finally, we will address the issues of reconfigurability and point out to connections with information based complexity, duality and semidefinite programming.

Computational Methods for a Class of Discrete Valued Optimal Control Problems Arising in Defense Applications

Louis Caccetta

Department of Mathematics and Statistics, Curtin University of Technology

We consider a general class of optimal control problems where the control functions are assumed piecewise constant and only take on values from a finite discrete set. The aim in such a problem is to find a sequence of discrete control values and a corresponding set of exact switching times (i.e., times where control should switch between the discrete values) such that a given functional representing cost or risk is minimized. Such problems arise in a range of applications. One application is the "Transit Path Problem", where an object such as a robot or vehicle (air, naval, space or land) needs to traverse a specified region (discrete or continuous) between two points in a prescribed time so as to avoid detection. The objective is to find a path for the object which satisfies the time constraints and which minimizes the total risk of detection. The risk function is not simple and depends on a range of factors such as the environment, the types of sensors, the speed, direction, and position of the vehicle.

The main difficulty with these problems is that the range of some of the controls is discrete and hence not convex. Since the gradients with respect to the switching time parameters are discontinuous, ordinary gradient based solution methods perform poorly. An additional difficulty is to determine exactly how many switching times are involved in an optimal solution. We address the first difficulty by using the Control Parameterization Enhancing Transform (CPET) and the second difficulty by solving a sequence of problems which are transformed via CPET.

With respect to the transit path problem our strategy involves a two stage approach. The first stage involves a discretization of the problem and the solution of a constrained path problem in a network. The second stage involves the use of an optimal control model and a solution procedure that utilizes the solution obtained from the first stage.

In this talk we present a range of models and solution methods as well as discuss in detail a number of applications arising in the defense area.

Coordinated Bayesian Search and Tracking Using Element-based Method

Tomonari Furukawa[1], Frederic Bourgault[2] and Hugh F. Durrant-Whyte[3]

[1]*Department of Mechanical and Manufacturing Engineering, University of New South Wales*
[2]*Department of Mechanical & Aerospace Engineering, Cornell University*
[3]*Australian Centre for Field Robotics, University of Sydney*

This paper presents the application of the element-based method to the multi-objective mission of cooperative autonomous systems such as search and tracking within the recursive Bayesian estimation framework. The element-based method has various advantages over the conventional recursive Bayesian estimation techniques such as grid-based methods, sequential Monte-Carlo methods including particle filters and quasi-sequential Monte Carlo methods. Represented by a set of elements of irregular shape, the target space of any geometry can be well approximated by without noticeable errors. In addition, the use of shape functions for element definition allows the target PDF to be continuously and thus accurately represented over the target space.

Having the autonomous search and tracking formulated within the recursive Bayesian estimation framework, the efficacy of the element-based method has been investigated. Its comparison to the grid-based method in the representations of the target space and the function defined over the space first shows that the element-based method requires less than 10% of the nodes of the grid-based method to achieve the same accuracy. The application of the element-based method to marine search-and-rescue (SAR) scenarios then has demonstrated its computational efficiency over the grid-based method and ability for effective search and rescue while maintaining information collected.

Simultaneous Localization and Planning for Cooperative Air Munitions

Andrew J. Sinclair[1], Richard Prazenica[2], and David E. Jeffcoat[3]

[1] *Department of Aerospace Engineering, Auburn University*
[2] *Department of Mechanical and Aerospace Engineering, University of Florida*
[3] *Air Force Research Laboratory, Munitions Directorate*

This paper considers the cooperative control of aerial munitions during the attack phase of a mission against ground targets. It is assumed that sensor information from multiple munitions is available to refine an estimate of the target location. Based on models of the munition dynamics and sensor performance, munition trajectories are designed that enhance the ability to estimate the target location. The problem is posed as an optimal control problem using a cost function based on the variances in the targetlocation estimate. These variances are computed by fusing the individual munition measurements in a weighted least squares estimate. Numerical solutions are found for several examples both with and without considering limitations on the munitions field of view. These examples show large reductions in target-location uncertainty when these trajectories are used compared to other naively designed trajectories. This reduction in uncertainty could enable the attack of targets with greater precision using smaller, cheaper munitions.

Out-of-Order Sigma-Point Kalman Filtering for Target Localization using Cooperating Unmanned Aerial Vehicles

Gregory L. Plett, Dimitri Zarzhitski, and Daniel J. Pack

Department of Electrical and Computer Engineering, United States Air Force Academy

This paper outlines progress in research to develop a cooperative target localization method based on multiple autonomous unmanned aerial vehicles (UAVs) that are outfitted with heterogeneous sensors. The current focus of the research includes (1) optimizing the trajectories of the UAVs to place them at desired locations at desired times to capture target characteristics and (2) intelligently fusing measurements taken by multiple sensors to accurately estimate the position and velocity of a target. In this paper, we present our efforts on the second item as a preliminary but necessary step in the overall task. We might consider addressing this problem using some form of Kalman filter; however, a complicating factor in the present application is that sensor readings arrive out-of-sequence to the sensor-fusion process due, for example, to non-deterministic latency in the interand intra-UAV communication channels. We address this problem by developing an out-of-order sigma-point Kalman filter (O3-SPKF).

The particular solution of our interest to the broader problem of target localization must address a number of challenging requirements: (a) covert/passive sensing means must be used; (b) the dynamic characteristics of the target are unknown; (c) the target is episodically mobile; and (d) the target is intermittently occluded from particular sensing mechanism(s). The cooperative method proposed in this paper plays an important role in our larger overall goal to develop a multiple cooperative UAV system that can autonomously search/detect and localize multiple targets. Our solution addresses these requirements using a flight of small autonomous UAVs with heterogeneous sensing capabilities. Multiple autonomous UAVs offer certain advantages over other conventional sensor platforms: they offer robustness in the presence of a loss of members, they can quickly search a large area; they operate using a decentralized but cooperative control algorithm, requiring minimal human intervention; and they are small and relatively inexpensive, allowing quick and easy deployment.

Cooperative Rendezvous Between Active Autonomous Vehicles

Yechiel J. Crispin and Marie E. Ricour

Department of Aerospace Engineering, Embry Riddle University

The rendezvous problem between two autonomous vehicles is formulated as an optimal cooperative control problem with terminal constraints. Traditionally, optimal control problems have been solved by seeking solutions which satisfy the first order necessary conditions for an optimum. Such an approach is based on a Hamiltonian formulation, which leads to a difficult two-point boundary-value problem. We propose a different approach in which the control history is found directly by a genetic algorithm search method. The main advantage of the method is that it does not require the development of a Hamiltonian formulation and consequently, it eliminates the need to deal with an adjoint problem, which usually leads to a difficult two-point boundary-value problem in nonlinear ordinary differential equations. This method has been applied to the solution of two different rendezvous problems where the direction of the thrust is used as the control. The first problem is a cooperative rendezvous problem between two active autonomous vehicles moving in an underwater environment. We take into account the effects of gravity, thrust and viscous drag and treat the rendezvous location as a terminal constraint. The second problem is a cooperative rendezvous problem between two spacecraft with continuous low thrust, starting from two different points on the same circular orbit and meeting at a rendezvous point on a circular orbit of larger radius.

Multi-Cumulant Control for Zero-Sum Differential Games: Design-Performance-Measure Statistics and State-Feedback Paradigm

Khanh D. Pham

Air Force Research Laboratory, Space Vehicles Directorate

The paper presents an extension of cost-cumulant control theory over a finite horizon for a class of stochastic zero-sum differential games wherein the evolution of the states of the game in response to decision strategies selected by two players from sets of admissible controls is described by a stochastic linear differential equation and a standard integral-quadratic cost. A direct dynamic programming approach for the Mayer optimization problem is used to solve for a multi-cumulant based solution when both players measure the states and minimize the first finite number of cumulants of the standard integral-quadratic cost associated with this special class of differential games. The innovative decision-making paradigm is proposed herein to provide not only a mechanism in which the conflicting interests of noncooperative players can be optimized, but also an analytical tool which is used to provide a complete statistical description of the global performance of the stochastic differential game.

Swarm Intelligence for Formation Flight with Autonomous UAVs

Harish Mukhami, Jonathan Pikalek, Karl Altenburg, and Kendall E. Nygard

Department of Computer Science and Operations Research, North Dakota State University

We consider cooperative control procedures for surveillance search missions in which multiple autonomous UAVs establish a formation and maintain offset distances from each other using swarm intelligence techniques. We present an approach to cooperative following of waypoints and the executing of turns and maneuvers that utilizes local communication and sensors, maintains formations, and avoids conflict among the UAVs.

Unmanned Vehicle Navigation based on Peano-Cesaro Fractal Sweep

Jacob Yadegar, Junxian Wang, Harish Chandra,
Joseph Yadegar and Abhishek Tiwari

UtopiaCompression Corporation

We present a planar coverage strategy for autonomous vehicles for exploration and goal search applications avoiding obstacle collision. Our strategy is based on space filling Peano-Cesaro binary triangular fractal sweep and the associated Sierpinski tour approach. A Sierpinski tour is generated by joining the centers of the Peano-Cesaro tiles in the order they are visited using directed edges. The nodes of the Sierpinski tour can be regarded as waypoints for autonomous vehicle navigation. In addition to the Sierpinski tour for global coverage, we also employ local potential field based method to circumvent obstacles. It can be proven that the proposed planar coverage strategy can explore any part of the planar region to any level of resolution while providing navigation path very close in tour length to the optimal path. Furthermore, the time complexity of the algorithm is of the order nlogn, where n is the number of tiles visited. We illustrate our technique using simulation examples under irregular geometry of the planar region with irregular obstacles randomly distributed in the navigation region.

Virtual Leader Based Formation Control of Multiple Unmanned Ground Vehicles (UGVs): Control Design, Off-line Simulation and Real-time Experiment

Wenchuan Cai, Liguo Weng, Ran Zhang, Mingjin Zhang, and Y. David Song

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Closed formation control for multiple unmanned ground vehicles (UGVs) is studied in this work. The leading-following strategy with a virtual leader is applied to coordinate the whole formation group so that only local information is sufficient for every UGV to maintain close formation. Error-shaping memory-based control is designed for formation path tracking. The salient feature of this approach lies in its simplicity in design and implementation, and no need for detailed information on external disturbances and uncertainties. The performance of the proposed method is verified via real-time experiment on various formation operations. Some of the results are illustrated here. More detailed videos of the real-time experiment results will be presented at the conference.

Contact Point Selection for the Swarm Manipulation Problem

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In this paper we consider the problem of N autonomous tug boats, cooperating to move a large disabled surface ship. We discuss two sub-problems: (1) the problem of each tug selecting its optimal contact location along the hull of the disabled ship; and (2) the problem of each tug selecting its push force to steer the disabled ship along a desired trajectory. Both problems are addressed in a distributed framework - it is assumed that each tug must act independently, with limited knowledge of the actions of the other tugs.

The contact point selection problem is formulated by optimizing a distributed version of a classical grasp quality function from the robotics literature. We seek the configuration that allows the swarm to apply the largest net force/torque to the disabled ship without exceeding any one tugs thrust constraints. Since each tug must select its contact location with limited knowledge of the position of other tugs, we maximize the objective function under the assumption of the worst case scenario. Ultimately the problem is formulated as a min-max-min problem and solved via sequential quadratic programming. We give a geometric interpretation of the solution and offer insight into the game theoretic nature of the problem.

In order to evaluate contact point selection in a dynamic sense, a position/orientation tracking control strategy is developed for a given swarm configuration. Specifically, a unidirectional thrust controller is developed that forces the disabled vessel to track a desired position/orientation trajectory under the assumption that the tugs can only exert a unidirectional (i.e., pushing) force on the disabled vessels hull. Simulation results are expected to provide further quantification of a selected swarm configuration during a dynamic maneuver. In addition, an experimental apparatus has been developed in which to provide further verification of a configurations performance.

Real-time optimal time-critical target assignment for UAVs

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In the literature including our previous work [1], one can find the so-called ‘‘basic’’ UAV target assignement mission in which ‘‘m’’ UAVs with a capacity limit ‘‘q’’ visit ‘‘n’’ targets in a cooperative manner (and return to their departure points) such that the cost incurred by UAV's travel is minimized. In our previous work, we proposed a mixed integer linear program (MILP) formulation which exactly solves the problem, as well as four alternative MILP formulations which are computationally less intensive (and therefore suited for real-time purposes) yet yield a theoretically guaranteed sub-optimal solution. In this present work, we further consider ‘‘timing constraints’’ imposed on some ‘‘p’’ of the targets, so-called ‘‘prime targets’’. This consideration is often required for scenarios in which prime targets must be visited in a pre-defined time interval, and mathematically results in the addition of several integer linear constraints to the previous MILP formulation and subsequently making the problem computationally intractable. In this work, we propose a novel procedure of adding these cumbersome timing constraints to the previous MILP formulation, in order to avoid increasing too much comutational cost under practically valid assumptions. We further show that the proposed procedure still guarantees the previously claimed theoretical solution quality associated with the basic mission. Extensive numerical simulations are given to support our claims.

References

[1] Y. Kim, D. W. Gu. and I. Postlethwaite. Real-time optimal mission scheduling and flight path selection, Submitted to IEEE Transactions on Automatic Control.

Second-order Cone Programming Techniques for Coordinating Large-Scale Robot Teams in Polygonal Environments

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In this paper, we present an online optimization approach for coordinating a large-scale robot team. Specifically, we investigate the problem of moving a formation from an initial shape/pose to an objective shape/pose while minimizing the total distance that the robots must travel subject to workspace constraints. By leveraging results from statistical shape analysis, we formulate a higher-level representation where the objective pose is modeled via a linear constraint set that embeds the relative position, orientation, and scale of the formation. With this representation, we show that when the workspace is convex, optimal solutions to the resulting motion planning problem can be obtained through second-order cone programming (SOCP) techniques. Furthermore, we show that the problem has a theoretical complexity of $O(k^{1.5}m^{1.5})$, and can be solved in $O(km)$ time in practice or in linear time with the number of robots m and the number of convex constraints k used to model the workspace.

For the case where the workspace is not convex but can be modeled as a polygonal environment, we present a hybrid optimization approach. In the discrete phase, an optimal path C_p over an appropriate tessellation of the workspace is generated first. This path specification serves as input to the continuous optimization phase, where model predictive control techniques are used to find optimal trajectories over C_p for the formation while also guaranteeing against collisions with obstacles and the workspace boundaries. The problem is again solved as a SOCP with a theoretical running time of $O(l^{3.5}m^{1.5})$, and $O(l^3m)$ in practice where l corresponds to the length of the optimization horizon. Note the running time again scales linearly with the number of robots m.

These results are verified through extensive simulations, which show our optimization approach to be suitable for the "real-time" coordination of large-scale robot teams (e.g., 100s to 1000s of nodes) and over multiple horizon steps.

An Analysis and Solution of the Sensor Scheduling Problem

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The optimal placement of sensors is a significant problem in surveillance, search, and tracking, with applications ranging from sea to space. In this paper, we focus on a class of mobile sensors with a limited sensing range. Sensors with these characteristics could include loitering munitions, undersea or underground robots, or satellites with a focused sensor footprint. The wide-spread development of low-flying unmanned air vehicles and air-delivered munitions with extended flight times provides the opportunity for these platforms to serve as intelligence, surveillance, and reconnaissance (ISR) assets, pulling information from the battlefield into the global information grid. This paper provides tools for the analysis of these types of systems.

We consider a problem in which the objective is for a single sensor to maintain an estimate of a dynamic physical attribute (e.g., position) of multiple sites (targets). This research builds on our previous work, in which we investigated probabilistic strategies for the motion of the single sensor among the sites. In this paper, we focus on deterministic methods to schedule the sensor's motion. A deterministic approach overcomes one disadvantage of probabilistic motion: with any random motion strategy, there is nonzero probability that a particular site will not be visited at all in any finite time horizon.

First, we build an optimization model for the sensor scheduling problem, associating with each site a fixed and a variable cost of information not obtained by the sensor. More specifically, a fixed penalty of not visiting a certain site is incurred for each time step in which the sensor is away from the site. In addition, a variable cost is incurred for each time unit that has passed since the sensor's last visit to that site, providing ever-increasing motivation for the sensor to visit a neglected site. The objective function in our model minimizes the maximum penalty incurred for a sensor schedule defined over a finite time horizon. We show that the problem is NP-Hard.

Second, exploiting the structural properties of the problem, we note that the problem is closely related to the pinwheel scheduling problem arising in the context of scheduling computer and telecommunication systems in real-time. Using the results obtained for the pinwheel scheduling problem in the existing literature, we develop a lower bound on the objective function of the sensor scheduling problem.

Third, in considering possible solution methods to the problem, we show that existing methods developed for the scheduling of just-in-time manufacturing systems can be adapted to the sensor scheduling problem. The worst-case performance analysis reveals that a solution to the problem can be constructed such that the objective function value is not more than twice the lower bound. This result motivates the development of efficient heuristic solution methods which also have worst-case performance guarantees.

Fourth, we develop two computationally efficient constructive heuristics for the sensor scheduling problem. The first is a greedy approach equipped with a look-ahead feature. The second is an alternative greedy approach that dynamically sets a deadline to visit each site and then selects the site with the earliest deadline for the sensor's next move. Both approaches are computationally very efficient and can be used in real time. Finally, we design and conduct an extensive computational study to test the performance of the proposed heuristics. The results from the computational study show that the methods are also effective; i.e., they yield near-optimal solutions to the problem.

An Adaptive Sequential Game Theoretic Approach to Coordinated Mission Planning For Aerial Platforms

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Coordinated mission planning is one of the core steps to effectively exploit the capabilities of cooperative control of multiple UAVs. In this paper, we develop an effective team composition and tasking mechanism and an optimal team dynamics and tactics algorithm for mission planning under a hierarchical adaptive sequential game theoretic framework. Our knowledge/experience based static non-cooperative and non-zero games are used for team composition and tasking to schedule tasks at the mission level and allocate resources associated with these tasks. The dynamic adaptive sequential game model is used for team dynamics and tactics to assign targets and decide the optimal salvo size for each aerial platform to achieve the minimum remaining platforms of red and the maximum remaining platforms of Blue at the end of a battle. A simulation software package has been developed to demonstrate the performance of our proposed algorithms.

Cooperative Control of Multiple Agents and Search Strategies

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Multiple agent control problems have proven difficult to solve using classical control methods partly because first, in non-cooperative problems different agents may disagree about what constitutes ‘‘optimality’’ and second, even when agents cooperate, an optimal solution may be computationally unsolvable. Satisficing solutions present an alternative approach based on a procedurally rational decision methodology using a geometrical approach. In problems which are inherently ‘‘rationality limited’’, a perspective frequently encountered in multiple agent problems, procedurally rational strategies are required. We discuss mathematical aspects of the unified game theory (UGT) and theory of the control structures (TCS). We analyze a game as a hierarchical structure. It is assumed that each agent can be described by a fiber bundle. We also present a design mechanism for generating multi-agent satisficing strategies that not only performs well in cooperative problems, but also allows agents to make decisions with partial information in competitive environments. We demonstrate the power of the satisficing solution methodology for cooperative control problems regarding many-target search. An appropriate search strategy for the whole system can be embodied: hierarchical, coordinated or cooperative. Geometrical and computational aspects of many-target search problems are considered.

Distributed Cooperative Optimization

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Often times in a social system, individuals working together in a cooperative way can solve hard problems beyond the capability of any individual in the system. Cooperative optimization is a newly discovered general optimization method inspired by cooperation principles in social systems. It is based on a cooperative system of multiple agents working together in cooperative ways to solve a hard optimization problem. It first breaks a problem into a number of sub-problems of manageable sizes and complexities. Following that, it assigns each sub-problem to an agent in the system and ask all the agents to solve the sub-problems in a cooperative way instead of independently. The cooperation is achieved by asking the agents to compromise their solutions with their neighbors. Solution compromising is done through adjusting each agent's objective based on its neighbors solutions. When all the agents in the system resolve conflicts in their solutions via solution compromising, the system reaches a consensus solution. For a certain class of cooperative optimization algorithms, a consensus solution must be the global optimal one, guaranteed by theory.

Cooperative optimization has demonstrated outstanding performances in solving real-world problems and has an established theoretical foundation. It knows whether a solution it found is a global optimum and which direction is more promising than others for finding a global optimum. With some very general settings, a cooperative optimization algorithm has a unique equilibrium and converges to it with an exponential rate regardless initial conditions and insensitive to perturbations. The insights we gained at studying cooperative optimization might help us to apply the cooperation principle to understand or solve more generic decision optimization problems arose from fields like neurosciences, business management, political management, and social sciences. This talk presents some recent technology advances and theoretical discoveries in cooperative optimization, including a cooperative decoding algorithm for HDTV and the discovery of quantum dynamics as a special case of cooperative optimization for the energy minimization of (sub)atomic systems.

On Some Characteristics of the Distribution of Hamming Distance Values between Solutions of Multidimensional Assignment Problem

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The Multidimensional assignment problem (MAP) can be viewed as an extension of the linear assignment problem (LAP). Many interesting applied problems in such practical areas as data association, resource allocation, air traffic control, surveillance, and others can be modeled as MAP.

Although LAP can be solved using polynomial time algorithms, the MAP is known to be generally NP-hard. This can be proved using a reduction of the matching problem in three-dimensional space. In fact, as a result of the great complexity of the problem, only moderate sized instances of the MAP can be solved routinely at the moment. As a matter of fact, previous studies had clearly demonstrated that the expected number of local minima is exponential with respect to the dimensions of MAP.

Since the majority of the exact and heuristic algorithms developed for this challenging problem are based on various types of local neighborhood search, the performance of these algorithms depends rather substantially on the relative "location" of local minima with respect to the global solution. Because each solution of an MAP instance can be represented as a collection of permutations, we employ Hamming distance as a measure of the relative location of any given solution with respect to the global optimum.

In our previous study, we focused our attention on the correspondence between the value attained at a local minimum (solution fitness) and its relative location to the global minimum (Hamming distance). Whereas, the focus of the present study is shifted to the distribution of values of Hamming distance between two solutions in general, and the expected value in particular. First, the distribution is analyzed analytically, and then the results are confirmed experimentally.

Error Analysis for Image-Based Geo-Location

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Unmanned air vehicles are often fitted with cameras to provide image data for target, or feature tracking. However, the errors associated with the geo-location of a point in an image frame may be difficult to quantify. The purpose of this paper is to investigate the errors associated with geo-location in a static setting with a standard, uncalibrated, commercial off-the-shelf (COTS) camera. Standard practice is to use a process known as bundle-adjustment to calibrate individual cameras for proper image referencing. This is a time consuming process, and requires high overhead to maintain. We desire to establish the severity, and characteristic tendencies of errors in a standard COTS camera. This will allow reasonable judgments to be made on whether individual camera calibrations are required to facilitate reasonable geo-location. The errors will be studied with respect to range, azimuth, and elevation using physically surveyed points for both targets and camera position as truth data for analysis.

Decentralized Extremum-Seeking Control of a Cooperative Team of Nonholonomic Vehicles to Form a Communication Chain

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Cooperative electronic chaining is the formation of a linked communication chain using a team of mobile vehicles, acting as communication relays in an ad hoc network, that maximizes the end-to-end throughput of the chain while allowing the end nodes of the chain to move independently in an unknown, dynamic environment. Electronic chaining utilizes the fact that with networked mobile vehicles, the quality of the link is directly influenced by the motion and location of the vehicles within the radio propagation environment, and thus controlling the motion of the vehicles can influence the performance of the network. The specific motivation of this work is maintenance of a solid high-quality connection from a ground station to a single remote unmanned aircraft (UA), which would otherwise be out of communication range, using the cooperation of other possibly heterogeneous UA teammates.

A decentralized extremum seeking (ES) controller, which is an adaptive model free controller, is presented for electronic chaining to control the location of a mobile communication relay based on received signal strength as opposed to relative position alone because a communication chain that seeks to maximize a link performance metric such as bandwidth or end-to-end delay does not necessarily form a linear, evenly spaced formation of the nodes. The factors that determine the final formation of an optimal communication chain is dependent upon numerous system and environmental factors such as environmental RF noise, including jamming, different vehicle communication capabilities, vehicle performance constraints, and possible terrain effects that are all very difficult to accurately predict and completely model prior to deployment of a UA team.

This paper will present an ES controller that has been specifically designed for use with teams of unmanned aircraft that present unique performance constraints on the ES controller. Of importance to this work is the individual aircraft speed range and turning rate performance constraints as these two directly influence the responsiveness and convergence of the communication chain to an optimal formation. Because an aircraft must maintain a minimum, nonzero, flight speed and has bounded turn rate, this paper will present bounds on the loop feedback in the ES controller along with bounds on the dither signal so that the path the UA is to track by an onboard autopilot system is within the performance abilities of the UA.

A Game Theoretic Formulation of the Dynamic Sensor Allocation Problem

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This paper presents a view of cooperative control using the language of learning in games. Specifically, we look at the cooperative control problem of dynamic sensor allocation for enemy submarine tracking. First, we formulate the sensor allocation problem as a noncooperative game where the decision makers are the sensors. In this setting, each sensor is assigned a local objective or utility function and is given the ability to autonomously alter its position and sensing activity in real time. We demonstrate that by designing the sensors utility functions appropriately, the sensor allocation problem can be modeled as a potential game. Furthermore, we illustrate that by implementing an appropriate learning algorithm for potential games, in which each sensor selfishly seeks to maximize its own utility, one can guarantee that the sensors will collectively operate efficiently. Furthermore, the distributed nature of the decision making in the sensor allocation game allows for robustness to communication failures, sensor failures, and environmental changes.

Recent Advances in Eavesdropping and Jamming Communication Networks

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We consider the problem of determining the optimal number and placement of eavesdropping/jamming devices in order to intercept/supress communication on a wireless telecommunication network. This problem is known as the `wireless network jamming problem` and is *NP-hard* in general. In this talk we review several recent advances including the development of integer programming formulations, heuristics, and bounds. Numerical results are provided which validate the theoretical results and demonstrate the effectiveness of the proposed procedures.

Path Planning with precedence constraints for a collection of Dubin's vehicles

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In this paper, we address the problem of motion planning of m vehicles through n targets in a plane. The motion of the vehicles satisfies a non-holonomic constraint, i.e., the yaw rate of the vehicle is bounded. Each target is to be visited by one and only one vehicle. The initial position and the heading of each vehicle and the position and the heading of each target are known. Also known are the precedence constraints on the order in which the targets much be visited. The objective of the Motion Planning Problem (MPP) we consider is to assign a sequence of targets for each vehicle to visit. The sequence of targets for each vehicle must satisfy the given precedence constraint. to find a feasible path for each vehicle that passes through the assigned targets at the specified heading angles with a requirement that each vehicle returns to its initial position and heading. to minimize the total distance traveled by all the vehicles.

This MPP is a generalization of the Asymmetric Traveling Salesman Problem (ATSP) and is NP-Hard. We formulate MPP as an integer programming problem with both the Dantzig-Fulkerson-Johnson (DFJ) and Miller-Tucker-Zemlin (MTZ) constraints. By dualizing the MTZ constraints and a set of degree constraints on the vertices, we obtain lower bounds on the optimal cost of the motion planning problem. We embed these lower bounds in a Branch and Bound solver and present experimental results that finds the optimal solution for the motion planning problem. These results extend the well known Held-Karp algorithm available for the single TSP to the MPP.

Cooperative Formation Flying in Autonomous Unmanned Air Systems with Application to Training

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The study on unmanned air systems (UASs) has been one of the active research topics in recent years due to its wide application in practice. Current operational UASs operate standalone, independent of neighboring Unmanned Aircraft (UA) and are used primarily for reconnaissance. However UAS roles are expanding and will continue to increase to the point where UA swarms operate as cooperative autonomous units. This paper focuses on trajectory planning and cooperative flight formation, and a simulation platform for a group of unmanned aerial vehicles that carry out a series of missions is presented. The missions include planning the coverage search path, real-time trajectory generation, obstacle avoidance, and flight formation along a specified path, thus this simulation contains both individual and cooperative behavior.

Efficient Calculation of Multi-Sensor/Multi-Agent Entropic Maps

PAUL DEIGNAN

L-3 Communications

Just as cooperative control of intelligent agents may be organized about the optimization of a shared cost function, the cooperative control of intelligence–seeking agents may be organized about a functional quantification of a shared view of the environment to be identified. This shared view is empirically parameterized for distributed optimization with agent–based uncertainties carried forward free of model–dependent constraints. In this paper we propose the formulation of an entropy map as the object of distributed sensing and demonstrate how it might be efficiently calculated using a novel branch and bound technique based on entropic estimates. This technique is shown to significantly reduce the search space while maintaining global optimality of the resultant estimated entropy map.

On Designing Algorithms For Solving Multidimensional Assignment Problem: An AI/OR Approach

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The multidimensional assignment problem (MAP) is a combinatorial problem where elements of a variable number of sets must be matched, in order to find a minimum cost solution. MAP is a higher dimensional version of Linear Assignment Problem (LAP). The MAP has applications in a large number of areas, and is known to be NP-hard. These applications occur in the areas such as data association, target tracking, resource allocation, etc. Most of algorithms which have been developed or adapted for solving this problem (Simulated Annealing, Variable Neighborhood Search, GRASP, Genetic Algorithm, Greedy Local Search, some Branch and Bound methods etc.) use local search (greedy algorithms), partially or totally. Each of these algorithms has some parameters to be set to work efficiently. Furthermore depending on characteristics of the problem under study, they have different efficiencies timewise or solution quality-wise and it is the duty of the researchers to design or select proper algorithms to solve their MAPs. Despite differences between these methods, there are many commonalities between them which lead researchers to derive a framework for design and development of algorithms with the aim of saving time for designing these methods. Use of such a framework will allow algorithm designers to expedite development of new hybrid metaheuristics. Use of such a framework will allow algorithm designers to expedite development of new hybrid metaheuristics and algorithms. The main goals of such frameworks are designing algorithms faster using reusable components and easier hybridization. This is a promising research area which is going to be a rich research topic in the field of hybrid metaheuristics and combinatorial optimization. In this paper, using an AI/OR approach, a framework for developing hybrid algorithms for solving MAPs will be presented. Keywords: Multidimensional Assignment Problem, Metaheuristics, Heuristic, Algorithm, Framework, Optimization Software, Algorithm Development, Combinatorial Optimization, Global Optimization.