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Organizers: Robert Murphey (murphey@eglin.af.mil)
Panos Pardalos (pardalos@ufl.edu)
Sergiy Butenko (butenko@ufl.edu)

ABSTRACTS

Cooperative UAV Control

SIVA S. BANDA & PHILLIP R. CHANDLER
Flight Control Division
Air Force Research Laboratory (AFRL/VACA)
Wright-Patterson AFB, OH 45433-7531
siva.banda@wpafb.af.mil, chandler@wpafb.af.mil

Abstract

The objective of this effort is to develop a hierarchical distributed control system for teams of UAVs, specifically wide area search munitions. The functions under development, and which are to be integrated, include: cooperative search, cooperative classification, cooperative attack, and cooperative damage assessment. The hierarchy has three levels of decomposition, with the top team level performing resource allocation using market techniques, the middle sub-team level coordinates cooperative tasks, and the lower vehicle level performs trajectory and cost generation. The system is completely decentralized, fault tolerant, and the on-line optimal decision capability accounts for large uncertainty, thereby not limiting the distributed system to a rigid set of actions.

Collective Vision Using Volume Holographic Optical Elements

George Barbastathis[1] and Arnab Sinha
MIT Mechanical Engineering
[1]gbarb@MIT.EDU

Abstract

Collective Vision is a method of cooperative image gathering by multiple Sensing Agents (SAs) scattered in the vicinity of a target. The task is simplified by designing the physical interface of the SAs to take into account the demands of the problem. For example, for tasks requiring excellent 2D resolution on a reflective target, we have designed a new class of optical imaging instruments, called volume holographic telescopes. These instruments, used cooperatively among several SAs, yield resolution of 1cm at a distance of 1km in all three directions. This result is supported by theoretical analysis and experimental data. In this talk, we review the operation of volume holographic telescopes and describe our preliminary work towards optimizing the image acquisition process for moving targets, uneven terrains, etc.

On the Construction of Virtual Backbone for Ad Hoc Wireless Network

SERGIY BUTENKO[1], XIUZHEN CHENG[2], DING-ZHU DU[2], PANOS PARDALOS[1]
[1]*Industrial and Systems Engineering*
University of Florida
[2] *Computer Science and Engineering*
University of Minnesota-Twin Cities
butenko@ufl.edu, cheng@mail.cs.umn.edu, dzd@cs.umn.edu, pardalos@ufl.edu

Abstract

Ad hoc wireless network is featured by dynamic topology. There is no fixed infrastructure as compared with wired network. Every host can move to any direction at any speed. This characteristic puts special challenges in routing protocol design. Most existing well-known routing protocols use flooding for route construction. But, flooding suffers from the notorious *broadcast storm problem* which causes excessive *redundancy, contention* and *collision* in the network. One solution to overcome this problem is to compute a virtual backbone based on the physical topology, and run any existing routing protocol over the virtual backbone. In our study, the virtual backbone is approximated by a *minimum connected dominating set (MCDS)*. We compute a spanning tree with as many leaves as possible. All the non-leaf nodes form a CDS. The performance of our algorithm is witnessed by simulation result and theoretical analysis.

Coupling in UAV Cooperative Control

Phillip R. Chandler & Corey J. Schumacher
Flight Control Division
Air Force Research Laboratory (AFRL/VACA)
Wright-Patterson AFB, OH 45433-7531
chandler@wpafb.af.mil, Corey.Schumacher@wpafb.af.mil

Abstract

The presentation addresses complexity and coupling issues in cooperative decision and control of distributed autonomous UAV teams. In particular, the recent results obtained by the inhouse research team are presented. Hierarchical decomposition is implemented where team vehicles are allocated to subteams using set partition theory. Results are presented for single assignment and multiple assignment using network flow and auction algorithms. Finally, the fundamental problem of generating trajectories or costs for sequences of tasks is addressed. Simulation results are presented for wide area search munitions where complexity and coupling are incrementally addressed in the decision system, yielding enhanced team performance.

The Caltech Multi-Vehicle Wireless Testbed: Initial Implementation

LARS CREMEAN, JASON MELTZER, BEN LEE AND RICHARD MURRAY
MC 104-44
California Institute of Technology
Pasadena, CA 91125
lars@caltech.edu

Abstract

The Caltech Multi-Vehicle Wireless Testbed is a platform for the investigation of solutions to various challenges in coordinated control of vehicle formations. The testbed consists of a number of vehicles, a vision system that emulates a global positioning system by broadcasting the states of the vehicles, a command system that generates the forces necessary to regulate about a position or track about a trajectory, and methods of communication with and between vehicles.

The vehicles are driven by one-way high-powered ducted fans on a relatively smooth floor, resulting in an underactuated second-order dynamical system with constained actuation authority. Results from this system should be generalizable to systems in higher dimension of the same class, e.g. formation flight of unmanned aerial vehicles or formation flight of satellites.

Here we give a thorough introduction to our testbed, describe the methods by which we achieve closed-loop control, outline some controller designs, present some preliminary control results for the local stabilization of one vehicle about various trajectories, and discuss extensions to coordinated control of multiple vehicles.

Communication and Sensory Networks for Formation Control

Aveek Das, Vijay Kumar[1], John Spletzer, and Camillo Taylor
[1]kumar@cis.upenn.edu

Abstract

In formation control tasks, a group of agents must maintain constraints on relative separation and orientation while traversing toward a goal. We model the required communication and sensing as a directed graph and analyse the effect of this graph on the stability and performance of the cooperative control task. Experimental results are demonstrated using a team of robots using vision based control.

Biologically Inspired Guidance Sensor Systems for Cooperating Autonomous Air and Space Vehicles

JOHNNY H EVERS
Laboratory Task Manager
AFRL/MNGN
(850) 882-2220 x3330

BELINDA KING
AFOSR Program Manager
AFRL/NM
belinda.king@afosr.af.mil

Abstract

The thrust of this AFOSR Cooperative Control Theme project is to develop prototype configurations of biologically-inspired sensory, processing, and control functions that will yield wide field-of-regard spatial awareness for cooperating autonomous air vehicles. We will conduct closed loop experiments on the prototype configurations in the AFRL/MNG Kinetic Kill Vehicle Hardware-in-the-Loop Simulation facility (KHILS) and the NASA Langley UAV Test Bed. The goal is to lay a technical foundation for development of future air vehicles that have the capability to operate cooperatively in congested, high uncertainty environments.

Real-Time Marbles: A Scheme for Adaptive Distributed Resource Allocation

Martin Frank
Information Sciences Institute
University of Southern California
frank@isi.edu

Abstract

The problem of coordinating cooperative attacks in uncertain battlespaces by swarms of smart munitions and UCAVs is a hard resource allocation and optimization problem. A distributed algorithm must decide who should attack which targets (resource allocation), as well as maximize the effectiveness of the allocation (optimization). In addition, the system must rapidly adjust the plans to a changing environment, and do so in a distributed way.

I will present our Real-Time Marbles effort, in which we are investigating a particular class of distributed resource allocation schemes that can (1) compute good solutions from scratch and, more importantly, (2) adjust the solution within given time bounds as resources and tasks appear, change, and disappear. We propose to fully implement this class of negotiation schemes over the next two years; they will then satisfy the following properties: Distribution, Cooperation, Adaption rather than Recomputation of Solutions, Fault-Tolerance, Domain-based Task Valuation, Lack of Inflation, Ever-Fluctuating Prices, and - particularly - Sensitivity to Real-Time Constraints.

Multiset Graph Partitioning

William W. Hager and Yaroslav Krylyuk
Department of Mathematics
University of Florida, Gainesville, FL 32611
hager@math.ufl.edu

Abstract

Local optimality conditions are given for a quadratic programming formulation of the multiset graph partitioning problem. These conditions are related to the structure of the graph and properties of the weights. This work was supported by the National Science Foundation.

Coordination and Control for Cooperating UAV's

Jonathan How
MIT
jhow@MIT.EDU

Abstract

This paper presents results from ongoing research on the guidance and control of fleets of cooperating UAV's. A key challenge for these systems is to develop an overall control system architecture that can perform optimal coordination of the vehicles, evaluate the overall system performance in real-time, and quickly reconfigure to account for failures or new targets. The fleet coordination includes trajectory optimization, task assignment, and resource allocation which, for many vehicles, obstacles, and targets, are very complicated optimization problems. As such, several centralized and distributed methods of solving this fleet coordination problem will be compared in this paper. The centralized approach gives the global minimum-time solution to the combined assignment and path planning problem, which is solved as a mixed-integer linear program (MILP). Binary variables are used to encode the discrete decisions involving collision avoidance (obstacle and vehicle) and task assignment (waypoint and final time selection). The paper will also discuss techniques developed to distribute the trajectory cost generation, which is the most computationally intensive aspect of this problem. This approach generates the costs for various trajectory options using distributed platforms and then solves a centralized assignment problem. The cost calculations can be performed using smaller MILP's or graph searches. Numerous heuristics can be used to eliminate unfavorable waypoint permutations prior to the cost calculations, which further reduces the computational effort. Several examples will be used in the paper to compare the performance and computational effort of these approximate solution techniques with the global optimal solutions from the centralized method.

Decentralized Optimization, with Application to Multiple Aircraft Coordination

Gokhan Inalhan, Duvsan Stipanovic and Claire J. Tomlin
Department of Aeronautics and Astronautics
Stanford University, Stanford, CA 94305
ginalhan,dusko,tomlin@stanford.edu

Abstract

A feature of multiple aircraft systems is that information is distributed throughout the system. Particularly, each aircraft may have a good idea of its own state and intent, as well as that of its closest neighbors, however it may have very little or no information about aircraft far away from itself. To account for this distribution of information, a centralized control paradigm may be used, in which information about each aircraft is sent to a central control unit which processes this information, makes decisions about the required actions of each vehicle, and transmits this information back to the aircraft. With the centralized control paradigm, however, comes delays associated with information transmission and processing which restricts the kinds of operations permitted by multiple aircraft systems.

We are interested in designing multiple aircraft control systems which are much more flexible and responsive than the centralized paradigm allows. We would like aircraft to have more responsibility over their own path planning and control routines; and thus would like a decentralized control paradigm in which each aircraft transmits its own information to a neighborhood, receives information about the aircraft in its neighborhood, and plans a path for itself accordingly.

Thus, the paradigm should allow for multiple decision makers, multiple objectives, and must treat inter-vehicular constraints. Such a scheme would be natural in many applications of Unmanned Aerial Vehicles (UAVs), from distributed sensing, imaging, and reconnaissance, for civilian (agriculture, weather sensing) and military purposes, in which autonomous operation with limited ground support is desired. Of particular importance to military applications, the replacement of traditional complex aircraft fighter systems with an array of simpler and lower-cost UAVs improves flexibility and offers a high degree of redundancy and reconfigurability in the event of a vehicle failure. In this work, we present a decentralized optimization methodology for a general class of nonlinear discrete-time dynamic systems with multiple decision makers. Specifically, we apply this methodology to a multiple aircraft system, with kinematic aircraft models and separation requirements between the aircraft. A decomposition method is presented for local dynamic models subject to global state constraints. We show how Nash solution properties are conserved under this decomposition. Penalty methods are utilized to generate merit functions for local optimization (at each decision maker).

We define a global cost function in terms of local cost functions, and we show how local cost function decrease causes this global cost function to decrease. We develop an iterative algorithm involving local optimization and message passing between decision makers, which emulates a block Gauss-Seidel iteration for this global cost function. This process involves a bargaining scheme on the global plan for all the vehicles. We discuss the robustness of our numerical methods under asynchronous data communication and communication loss, and demonstrate our solution with several numerical examples.

Research supported by the ONR MURI F33615-99-C-3014.

Search Allocation, Classification, and Attack Decision Algorithms for Cooperative Wide Area Search Munitions

LtCol David R. Jacques
Assistant Professor of Aerospace Engineering
Department of Aeronautics and Astronautics
Air Force Institute of Technology
2950 P Street, Suite 201C
WPAFB, OH 45433
David.Jacques@afit.edu

Abstract

This paper will discuss recent results in the area of cooperative behavior and control of autonomous vehicles. For the dynamic search allocation problem, a simple Kalman filter has been used to model the uncertainty associated with target motion. This allows the propagation in time of a target location distribution function. For a given distribution function, classical operations research methods can be used to formulate and solve the search allocation problem, but it now must be done dynamically. Further, the increasing tendency to false alarm when searching expanding areas ultimately limits how much the search area can be expanded. In the area of cooperative classification, recent investigations have highlighted scenarios where cooperative classification can degrade the overall system effectiveness, and these scenarios can be characterized in terms of Autonomous Target Recognition (ATR) performance and warhead lethality. In keeping with (Robert) Murphey's law, "Thou shalt not do anything cooperatively that will degrade the performance of the nominal (non-cooperative) system", this suggests that cooperative classification will require a scheme to insure graceful degradation under certain scenarios. Finally, a new cooperative attack decision logic based on probabilistic outcomes of search and attack has been developed. This approach explicitly considers the perceived benefit of continuing to search vs. the probability of the desired outcome if an attack is initiated. A framework for combining the results from search allocation, classification and attack into an overall approach to cooperative behavior will be proposed.

Route Algorithm for Autonomous Vehicles in Adversarial Environments

Myungsoo Jun and Raffaello D'Andrea
Cornell University
mj73@cornell.edu

Abstract

In the path planning problem in adversarial environments, the top priority is, of course, to complete the given mission – to arrive at the target within a given time – and the next priority should be safety of vehicles. While many papers provided path planning algorithm for autonomous vehicles, most of them were most focused on collision avoidance or optimal path generation with respect to fuel consumption and time traveled. In adversarial environments, however, the safety of vehicles should be put in higher priority than fuel consumption and time traveled. In this paper, we propose an algorithm to plan a path from the origin to the target by detouring highly hazardous area. We assume that the region of interest consists of n cells and a priori surveillance gives some information on the probability of enemy appearance in each cells. We transform the map of cells with probability to weighted digraph and convert the problem into shortest path problem in weighted digraph. We find a shorted path in the digraph by using Bellman-Ford algorithm. Thereby, we get a sequence of cells that shows a safe route to the target.

Automatic Synthesis of Controllers for Distributed Assembly and Formation Forming

Eric Klavins
Postdoctoral Scholar
Computer Science Department
California Institute of Technology
klavins@cs.caltech.edu

Abstract

We consider the task of assembling a large number of self controlled parts (or robots) into copies of a prescribed assembly (or formation). In particular, we introduce a way to synthesize, from a specification of the desired assembly, local controllers to be used by each part which, when taken together, have the global effect of assembling the parts. We pay careful attention to the time and space complexity of the synthesis procedure, showing that the size of the representation of the synthesized controller is polynomial in the size of the specification and that the computational power needed by the controller is low. More details can be found at http://www.cs.caltech.edu/ klavins/rda/.

On Computational Control Theory for Optimality Condition of Cooperative Agents

Victor Korotkich and Galina Korotkich
Faculty of Informatics and Communication
Central Queensland University
Mackay, QLD 4740, Australia
v.korotkich@cqu.edu.au, g.korotkich@cqu.edu.au

Abstract

Is it possible to have a general optimality condition specifying when cooperative agents as a whole show their best performance for a particular problem? This question has significant applied and fundamental interest.

Recent results of extensive computational experiments give strong facts to believe that such condition exists and can be formulated in terms of a concept of structural complexity. The experiments are made with 100-10000 agents for a number of classes of combinatorial optimization problems and by using robot soccer simulators.

In the experiments the structural complexity of agents is monotonically increased by a control parameter to see how their performance to solve repeatedly the same problem changes. A remarkable result is found for all problems tested. Namely, performance of the agents for each problem unimodally peaks at some point in an interval as their structural complexity increases. Hence, the structural complexity of a problem can be defined.

The experiments give considerable computational evidence to formulate a general optimality condition: the agents show their best performance for a particular problem when their structural complexity equals the structural complexity of the problem.

In the paper we show that the optimality condition leads to the development of computational control theory. It is needed to get the condition in an optimal way as the structural complexity of a problem cannot be known in advance. In particular, simulations prove that the distribution of results shown by the agents evolves in time according to an equation, when the optimality condition takes place. It is also found that the parameter controlling their structural complexity affects the shape of the distribution in a certain way. These facts constitute the basis of the theory.

Dynamics and Control of Agile Formations

P. S. Krishnaprasad
Department of Electrical and Computer Engineering
&Institute for Systems Research
University of Maryland
College Park, MD 20742
krishna@Glue.umd.edu

Abstract

In this joint project with Timothy Horiuchi and Dimitrios Hristu-Varsakelis, we are exploring a variety of aspects of cooperative control, including the use of synthetic potentials and dissipation, languages for hybrid control (with local trajectory optimization using biologically inspired pursuit strategies and wireless communication management in formations), continuum limits for formations, and neurobiologically inspired algorithms (related to bat-sonar for localization and for communication in swarms). We provide an overview of the goals and approaches of our research program, followed by in-depth discussion of selected items where we have made significant progress. This research is supported by AFOSR BAA 2001-2 Theme 1 Grant No. F496200110415, and by a grant from National Aeronautics and Space Administration under NASA-GSFC Grant No. NAG5-10819.

Robust Decision Making: Addressing Uncertainties in Distributions.

P. Krokhmal[1], R. Murphey[2], P. Pardalos[3], S. Uryasev[1] and G. Zrazhevski[1]
[1]*Risk Management and Financial Engineering Lab,*
Department of Industrial and Systems Engineering, University of Florida, USA
[2] *Air Force Research Laboratory, Eglin AFB Florida, USA*
[3] *Center for Applied Optimization,*
Department of Industrial and Systems Engineering, University of Florida, USA
krokhmal@ufl.edu

Abstract

This paper develops a general approach to risk management in military applications that involve uncertainties in information and distributions. The risk of loss, damage, or failure is measured by a Conditional Value-at-Risk (CVaR) measure. Loosely speaking, CVaR with the confidence level estimates the risk of loss by averaging the possible losses over the worst cases $(1-\alpha)100\%$ (e.g., 10%). As a function of decision variables, CVaR is convex and therefore can be efficiently controlled/optimized using convex or (under quite general assumptions) linear programming. The general methodology was tested with several stochastic Weapon-Target Assignment (WTA) problems. It is assumed that the distributions of random variables in the WTA formulations are not known with certainty. The total cost of a mission (including battle damage) was minimized, while satisfying operational constraints and ensuring destruction of all targets with high probabilities. The risk of failure of the mission (e.g., targets are not destroyed) is controlled by constraints constructed using the CVaR measure. The case studies conducted show that there are significant qualitative and quantitative differences in solutions of deterministic WTA and stochastic WTA problems.

Technologies Leading to Unified Multi-agent Collection and Coordination

Ronald Mahler
Lockheed Martin Tactical Systems,
3333 Pilot Knob Road, Eagan MN 55121
Ronald.p.mahler@lmco.com

Abstract

This presentation introduces a new project funded under the AFOSR Cooperative Control program. In this presentation, I will outline a proposed technical pathway to a feedback-connected unification of Multi-Agent Collection (i.e., distributed robust data fusion and interpretation) and Multi-Agent Coordination (i.e., distributed robust platform and sensor monitoring and control). The basis of our approach is twofold:

(1) a novel hybrid-systems control architecture that integrates the best of the current approaches; and

(2) a new statistical foundation for multisensor-multitarget problems called "finite-set statistics." Another presentation/paper at this workshop, "Mixed integer/LMI programs for low-level path planning" by R.K. Prasanth et. al., addresses a specific aspect of the Multi-Agent Coordination problem. In this presentation I will focus on Mult-Agent Collection. Finite-set statistics is a geometric, "engineering friendly" formulation of point process theory that also integrates expert-systems approaches often regarded as heuristic (fuzzy logic, Dempster-Shafer, rule-based inference) under a single probabilistic (in fact Bayesian) paradigm. I will summarize finite-set statistics and outline how we intend to apply it to the problem of unifying Multi-Agent Collection and Multi-Agent Coordination.

Reactive GRASP with Path Relinking for Channel Assignment in Mobile Phone Networks

CARLOS OLIVEIRA
University of Florida
oliveira@ufl.edu

Abstract

The Frequency Assignment Problem (FAP) is NP-Hard, and arises in radio transmission networks. It plays an important role in cellular mobile networks, where the goal is to minimize the total system interference. In this paper, a metaheuristic to solve the cellular FAP is proposed, based on GRASP (Greedy Randomized Adaptive Search Procedure). Enhancements to GRASP, like Reactive GRASP and Path Relinking, are also proposed, and computational results are reported.

Optimal Trajectories for Cooperative Classification

MEIR PACHTER[1] AND JEFFREY HEBERT[2]
[1]*Professor, Dept. of Electrical and Computer Engineering*
Air Force Institute of Technology
[2]*Captain, U.S. Air Force*
Meir.Pachter@afit.edu, Jeffrey.Hebert@afit.edu

Abstract

A projected role for uninhabited air vehicles is to classify and autonomously attack time critical targets. This includes identification and classification of targets, as well as battle damage assessment after an attack. Presented in this paper is a strategy for designing optimal trajectories for these missions. First the problem of determining optimal look angles for automatic target recognition/classification is addressed. Next, minimum time trajectories for a vehicle with a constant turning radius are investigated. Lastly, the two concepts are combined and an algorithm for performing cooperative classification and/or battle damage assessment involving more than one air vehicle, is presented.

Cooperative Control of Physical Processes, Geometrical Structures, and Optimization

Panos M. Pardalos
Center for Applied Optimization and ISE Department
University of Florida
pardalos@ufl.edu

Vitaliy A. Yatsenko
Scientific Foundation of Researchers and Specialists on
Molecular Cybernetics and Informatics
yatsenko@ise.ufl.edu

Abstract

Nowadays the development of the geometric theory of controlled structures makes it possible to extend the concept of cooperative control of complex systems. This report provides a short introduction to the methods devised over recent decades to explore cooperative control. We stress the role of two disciplines that have modified our outlook on cooperative control. The first is global optimization, and the second discipline is the modern geometric theory of dynamical systems. This report presents a new geometric concept of cooperative control of open active physical systems. A geometric structures of an information-dynamical system such as a the human brain, a neural networks and a dynamical cellular automatons are considered. A structural description of the dynamical properties of physical processes within the framework of the Yang-Mills fields, symmetry and optimization formalism is proposed. Principles of optimal interaction between the controlling medium and the complex object are formulated as specific cooperative control problems.

Approach Angles to Multiple Targets

Eduardo Pasiliao
AFRL/MNGN
eduardo.pasiliao@eglin.af.mil

Abstract

The paper formulates a model to simulate the possible paths for an airborne agent through multiple target locations requiring visitations. For our studies, we assume that the targets are immobile and the search agent turns with a fixed minimum radius and travels in a two-dimensional frame. The problem is primarily to find an optimal target visitation sequence. However, in order to calculate the length of the travel path through a given visitation sequence, we need to manipulate the approach angles to the target locations. The optimal approach angle for any single target is dependent on the approach angles to the other targets immediately before and after its place in the visitation sequence. Changing the approach angle through a target location could dramatically affect the optimal approach angle to every other target. An approach angle through a target is considered optimal if its assignment results in the shortest travel route for the agent.

Cooperative Control for Autonomous Air Vehicles

K. Passino, M. Polycarpou, D. Jacques, M. Pachter, M. Mears,
P. Chandler, M. Baum, Y. Liu, , M. Flint, Y. Yang
The Ohio State University
2015 Neil Avenue
Columbus, OH 43210-1272 USA
passino@ee.eng.ohio-state.edu

Abstract

In our team's project we are developing and evaluating the performance of strategies for distributed coordination and cooperative control of autonomous air vehicles that seek to gather information about a dynamic target environment, evade threats, and coordinate strikes against targets. We are applying the approach to the autonomous munitions problem. In this talk, we will overview project progress in the following areas: (i) a generic approach for distributed learning and planning for cooperative control, (ii) the use of dynamic programming methods and limited look-ahead policies for cooperative control, (iii) search theory based methods, (iv) behavioral rules approach to cooperative control, and (v) stability analysis of vehicular swarm cohesion mechanisms for the multidimensional and mobile case.

Sweep Optimization for Wide Area Search and Attack with Cooperative Entities

HENRY PFISTER
AFRL/MNGN
pfister@eglin.af.mil

Abstract

The coverage of an area for search by cooperative airborne entities is dependent on planning the imaging sweep operations. This is a difficult multi dimensional search problem with geometric constraints on sweep tiling, uncertain target locations, and complex cooperation strategies between search entities. The goal of the entire area search process is to maximize the detection and attack of targets of interest at unknown locations in the minimum time.

In general the search area can be characterized by the possibility of finding a target at any location that depends on prior information with uncertainty in time and place. An optimization algorithm is presented to determine a set of search sweeps for imaging operations that can maximize the possibility of target detection. Sweeps are constructed using a two dimensional dynamic programming approach with an embedded Lagrange multiplier to control the sweep length. The optimization process is made computationally efficient by the use of a unique sums matrix to evaluate sweep increment stages in the optimization process.

A simulation of the wide area search process using the optimized sweeps is executed with both cooperative and independent entities using various search and attack strategies and target location scenarios to gather performance data. This data provides a comparison of employing a sweep optimization versus a fixed pattern search in order to estimate relative measures of performance such as value of targets located, time to target attack, and area coverage efficiency. In general, the sweep optimization using cooperative entities out performs combinations of pattern searches and independent entities.

Groups of Unmanned Vehicles: Differential Flatness, Trajectory Planning, and Tracking Control

Stephen T. Pledgie, Yongxing Hao, Armando M. Ferreira, Sunil K. Agrawal, and Robert Murphey
Mechanical Systems Laboratory, Department of Mechanical Engineering
University of Delaware,
Newark, DE 19716, USA
agrawal@me.udel.edu

Abstract

This paper addresses the problem of trajectory planning and tracking control of groups of unmanned vehicles. The trajectory planner is aimed at satisfying the dynamic equations and constraints. The planner builds on two features of the group: (i) state equations for each member are differentially flat, and (ii) inequality constraints have special structures due to proximity constraints between members. Under these assumptions, formations are made so that the dynamic equations and constraints are satisfied. The tracking controller is developed using the linear representation of the nonlinear but differentially flat system. The linear models are coupled using interconnection patterns that preserve the overall tracking cost while creating new, rich behaviors during tracking. Illustrative simulations of groups of unmanned ground vehicles in formations are presented. The results are also implemented on a laboratory facility with three unmanned ground vehicles.

Network MFA

Aubrey B. Poore
Department of Mathematics
Colorado State University
Fort Collins, CO 80523
poore@math.colostate.edu

Abstract

The performance gain in using multiple frame assignments (MFA), formulated as multidimensional assignment problems, for tracking multiple targets using sensors on multiple platforms has been very significant over the last ten years. This approach to tracking has been developed for a centralized communication architecture; however, due to communication loading and single-point failures, a decentralized architecture is required. This presentation compares three different tracking and communication architectures in their ability to affordably preserve the quality of a near-optimal centralized architecture across a network of platforms while managing communication loading and achieving a consistent air picture on entities of interest for each platform.

Mixed Integer/LMI Programs for Low-Level Path Planning

R. K. Prasanth, J. D. Boskovic, R. K. Mehra and R. P. Mahler
prasanth@ssci.com

Abstract

Collision avoidance and trajectory generation problems are generally difficult to solve because the set of feasible solutions is non-convex, possibly infinite dimensional and defined in terms of an infinite number of constraints. Recent approximation methods use a finite dimensional parameterization of solutions and impose constraints on a finite grid in time. They result in large feasibility problems and are at best only sufficient. We show that there is no need to grid if the admissible trajectories are restricted to polynomials of degree no larger than a specified bound. A finite dimensional necessary and sufficient condition, whose size depends only the assumed degree bound, is derived in this paper. This condition is in general a mixed integer/LMI program, but turns out to be a LMI in many problems and approximation schemes. It is used to improve some existing trajectory generation methods, develop new approximation methods and solve a collision avoidance problem exactly. Our techniques clearly show how certain non-convex constraints arising in path planning can be converted to mixed integer/LMI constraints.

Biological and Silicon Modeling of Moving Target Detection in Insects

Patrick Shoemaker
Tanner Research, Pasadena, CA
pat.shoemaker@tanner.com

David O'Carroll
Dept. Physiology and Centre for Bioengineering
Adelaide University

Abstract

Although insects are relatively simple organisms compared to vertebrates, with nervous systems of limited size and complexity, they nonetheless do a remarkable job of controlling flight and other behaviors based on their low-resolution visual sense. Many flying insects detect and track small moving targets, both in pursuit of prey or mates, and in coordination of swarming flight. Intracellular recordings have now been made from neurons in the optical ganglia of odonates (several dragonfly species) and dipterans (a hoverfly), which respond selectively to small moving targets in the visual field. These cells are being studied and classified according to receptive field properties and possible interrelations. At the same time, we are attempting to model the processing that leads to these receptive properties, with the eventual goal of implementing similar processing in analog VLSI. We discuss preliminary progress and plans for this effort, as well as possible application to seekers and flight coordination in swarms of autonomous vehicles.

Optimal Sequential Allocation with Imperfect Feedback Information

Samuel Wu
samwu@biostat.ufl.edu

Abstract

A given number of bullets can be fired in an attempt to destroy a fixed number of targets. The probability of successfully destroying a target at each shot is known. The bullets will be fired in sequence and, after each shot is fired, there is a report on the state for the target just fired at. The reports are subject to the usual two types of errors: falsely claiming an intact target as destroyed and falsely claiming destroyed target as intact. The probabilities of these two types of errors are also known. The goal is to destroy as many targets as possible. In this talk we discuss the optimality of the myopic decision strategy that allocates each bullet as if it is the last one. We also give results on comparing different feedback systems. (This is joint work with Z. Max Shen, C. T. C. Mo, R. Chen and M. C. K. Yang.)