# Full-day Workshop: Decision Making Algorithms for Unmanned Vehicles

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## I. Rationale

This workshop is focused on disseminating recent advances in the area of decision making algorithms for Unmanned Vehicles (UVs). Small autonomous UVs are seen as an ideal platform for many military applications such as monitoring targets, mapping a given area, aerial/road surveillance and civil applications such as search and rescue missions, reconnaissance, fire monitoring etc. The main advantage of using these vehicles is that they can be used in situations where a manned mission is dangerous and/or is not possible. Even though there are several advantages in using small UVs, these vehicles have resource constraints due to their limited computational and sensing capabilities. To successfully realize a mission involving UVs, one has to optimally use the available resources often in the presence of uncertainty, motion and sensing constraints, and possibly adversarial action. This workshop brings together practitioners from the academia and the Air Force Research Lab (AFRL), to provide a complete picture of the challenges behind UVs mission planning, specification, scheduling and real-time optimization. The talks in this workshop will discuss open problems, touch upon various issues in the area of UV decision making, provide practical solutions for some of the underlying problems and also illustrate the theoretical background behind the techniques. In particular, the talks will focus on the following topics:

1) An overview of UV decision making problems under uncertainty
2) Constrained motion planning algorithms for a collection of UVs
3) Approximation algorithms for UVs with resource and motion constraints
4) Role of information in dynamic games involving UVs and adversaries
5) Approximate linear programming methods for stochastic dynamic programs and its application to UVs
6) Intruder isolation and capture on a road network using partial and delayed information

During the course of the workshop, example problems illustrating the above topics and the corresponding solution techniques will also be covered. A simulation software (in MATLAB) which implements the latest decision making algorithms and all the presentations will also be provided to the attendees during the workshop.

## II. Proposed Schedule

- **Introduction** (8.30 am - 8.45 am)

- **Autonomy and Decision Making under Uncertainty** (8.45 am - 9.30 am)
  *Speaker: Phil Chandler*
  Air Force Research Laboratory, Dayton, Ohio.

- **Combinatorial Motion Planning for a Collection of Unmanned Vehicles** (9.30 am - 10.30 am)
  *Speaker: Dr. Swaroop Darbha*
  Texas A & M University, College Station, Texas.

- **Break** (10.30 am - 10.45 am)

- **Approximation Algorithms for Unmanned Vehicles with Resource Constraints** (10.45 am - noon)
  *Speaker: Dr. Sivakumar Rathinam*
  Texas A & M University, College Station, Texas.

  (This presentation also includes a tutorial on how to use our simulation software)

- **Informational Issues in Dynamic Games** (1 pm - 2 pm)
  *Speaker: Dr. Meir Pachter*
  Air Force Institute of Technology, Dayton, Ohio.
- **Approximate Dynamic Programming and its Application to a UAV Perimeter Patrol** (2 pm - 3 pm)
  *Speaker: Dr. Krishna Kalyanam*
  Air Force Research Laboratory, Dayton, Ohio.
- **Break** (3 pm - 3.30 pm)
- **Optimal Minimax Pursuit Evasion on a Manhattan Grid** (3.30 pm - 4.30 pm)
  *Speaker: Dr. Pramod Khargonekhar*
  University of Florida, Gainesvile, Florida.

## III. Presentation Abstracts

**UAVs: Autonomy and Decision Making under Uncertainty**

*Phil Chandler*

There have been many advances in aerospace systems in recent years, but none more of a game changer than unmanned air vehicles. These vehicles have enabled a new era in battlefield persistence and surveillance. Key enablers in this capability are long haul and high bandwidth communications; advanced sensors including high-resolution day/night full motion video; and increased automation of task planning and execution. The objective for these vehicles is to be operated less as remotely piloted vehicles, but more as vehicles that have an increasing level of autonomy. Recent advances in autonomy include collision avoidance, air-to-air refueling, automated terminal area operations, and integration into the national air space.

This presentation will emphasize recent progress, using three examples, in on-line decision making under uncertainty, cooperative control of multiple vehicles, and the integration of man and machine. Persistent patrol is the $first$ example; of a scenario dominated by stochastic alerts and false alarms. The on-line controller must decide which alerts to service next (and how long to service them) to maximize the overall quality of service. The controller, by modeling the uncertainty, is not myopic and can account for expected future alerts. The $second$ example is a road surveillance problem motivated by the search for dangerous roadside objects e.g., IEDs. Multiple vehicles autonomously distribute the surveillance workload via a decentralized approach. The $third$ example problem is the guaranteed capture of an intruder on a road network leading to a protected zone. Here, UVs monitor a road network instrumented with Unattended Ground Sensors (UGS); so as to detect and subsequently capture an intruder traveling on the road. This is a partial and delayed information scenario with the formidable difficulties that arise out of dual control. Some long-term research challenges in achieving autonomy are also highlighted in the presentation. The presentation concludes with a brief commentary on problems associated with false information (deception) and adversarial action (games).

**Combinatorial Motion Planning for a Collection of Unmanned Vehicles**

*Dr. Swaroop Darbha*

This presentation will focus on the combinatorial motion planning problem of allocating tours for a collection of vehicles. 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. Given a set of targets and the yaw rate constraints on the vehicles, the problem is to assign each vehicle, a sequence of targets to visit, and to find a feasible path for each vehicle that passes through the assigned targets with a requirement that the vehicle returns to its initial position. The heading angle at each target location may not be specified. The objective function is to minimize the sum of the distances traveled by all the vehicles. This presentation will present an overview of the available methods and the latest developments for both the single and the multiple vehicle case.

**Approximation Algorithms for Routing a Team of Heterogeneous Unmanned Vehicles**

*Dr. Sivakumar Rathinam*

Heterogeneity of UVs is an important issue that complicates the motion planning of UVs with motion constraints. It can arise in different ways: (1) Vehicles may be structurally heterogeneous, $i.e.$, they can be of different make and hence, the cost of traveling from one target to another may depend on the employed vehicle, or (2) Vehicles may be functionally heterogeneous, $i.e.$, vehicles are identical structurally, but each vehicle may have a different suite of sensors which imposes some restrictions on the targets that may be visited by each vehicle and vice-versa. The underlying combinatorial problem is difficult because it embeds and couples two difficult combinatorial problems: (1) partitioning the set of targets that may be visited by each vehicle, and (2) sequencing the set of targets that may be visited by each vehicle.

In this presentation, we present novel approximation algorithms for constructing tours for a structural and functional heterogeneous collection of UVs. These algorithms will be based on rounding linear programs and primal-dual methods, and will disseminate the latest developments in this area.

**Informational Issues in Dynamic Games**

*Dr. Meir Pachter*

The state of affairs concerning dynamic games with incomplete information is not satisfactory. Upon reviewing the literature it quickly becomes apparent that there is an acute need to clarify critical conceptual issues. In this respect, the situation is not much different now than it was in 1971 when, Witsenhausen, in his IEEE Proceedings paper, made a similar observation. In this talk, a careful analysis of conceptual issues in dynamic games with incomplete information and decentralized optimal control is undertaken. Informational issues arising in stochastic dynamic games involving UVs and adversaries are addressed. The emphasis is on conceptual issues and gaining insight - we shall therefore exclusively focus on Linear-Quadratic Dynamic Games (LQDGs), which are more readily amenable to analysis. At the same time, LQDGs stand out as far as applications of the theory of dynamic games are considered. In particular, the talk will highlight the critical role of information in dynamic games that arise in UV decision making. Example scenarios such as pursuit of an intruder by UVs on a road network will be discussed.

**Approximate Dynamic Programming and its Application to a UAV Perimeter Patrol**

*Dr. Krishna Kalyanam*

This talk addreses the following problem: an Unmanned Aerial Vehicle (UAV) and a human operator cooperatively perform the task of perimeter surveillance. Alert stations consisting of Unattended Ground Sensors (UGSs) are located at key locations along the perimeter. Upon detection of an incursion in its sector, an alert is flagged by the UGS. A camera equipped UAV is on continuous patrol along the perimeter and is tasked with inspecting UGSs with alerts. Naturally, the longer a UAV dwells (loiters) at an alert site, the more information it gathers and transmits to the operator. The objective here is to maximize the information gained, and, at the same time, reduce the expected response time to an alert.

To determine the optimal patrol policy, one has to solve a Markov decision problem, whose large size renders exact dynamic programming methods intractable. So, we explore a state aggregation based approximate linear programming method to construct provably good sub-optimal policies instead. As a general result, it is shown that this approximate value function is independent of the non-negative cost function (or state dependent weights; as it is referred to in the literature) and moreover, this is the least upper bound that one can obtain, given the partitions. Furthermore, it is shown that the restricted system of linear inequalities also embeds a family of Markov chains of lower dimension, one of which can be used to construct a tight lower bound on the optimal value function. Finally, numerical results supporting the approximate method are also presented.

**Optimal Minimax Pursuit Evasion on a Manhattan Grid**

*Dr. Pramod Khargonekar*

This presentation focusses on the problem of finding an optimal control for a pursuer searching for a slow moving evader on a road network. The pursuer does not have the on-board capability to detect the evader and relies instead on Unattended Ground Sensors (UGSs) to locate the evader. We assume that all the intersections in the road network have been instrumented with UGSs. When an evader passes by an UGS location, it triggers the UGS and this time-stamped information is stored by the UGS. When the pursuer arrives at an UGS location, the UGS informs the pursuer if and when the evader passed by. When the evader and the pursuer arrive at an UGS location simultaneously, the UGS is triggered and this information is instantly relayed to the pursuer, thereby enabling "capture". In this presentation, we will outline the optimal strategy, provide a tight bound on the optimal number of steps to capture and show the main results.

## IV. Target audience and expected enrollment

Automation tools that account for strategic and tactical decision making involving UVs has received significant attention by the research community over the last decade. This workshop will outline the challenges, disseminate the most recent developments, and present some open problems in this research area. The interest in UV autonomy is expected to increase given the usefulness of UVs in civilian applications such as forest fire monitoring and remote sensing in agricultural and weather monitoring applications. Therefore, we expect this workshop to benefit practitioners from the industry and researchers from the academia including students. We expect a total enrollment of 25 participants.

## V. Biographical sketches of the presenters

**Phil Chandler** is the tech advisor for the Control Design & Analysis branch of the Air Force Research Lab (AFRL), Wright-Patterson Air Force Base. He received his B.S. and M.S. degrees from Wright State University. He was the principal architect of the Self Repairing Flight Control System advanced development program and recipient of the prestigious General Foulois award in 1994. He is currently researching autonomous control algorithms for unmanned combat aerial vehicles.

**Dr. Swaroop Darbha** received his Bachelor of Technology from the Indian Institute of Technology - Madras in 1989, M. S. and Ph. D. degrees from the University of California in 1992 and 1994 respectively. He was a post-doctoral researcher at the California PATH program from 1995 to 1996. He has been on the faculty of Mechanical Engineering at Texas A&M University since 1997, where he is currently a professor. His current research interests lie in the development of diagnostic systems for air brakes in trucks, development of planning, control and resource allocation algorithms for a collection of UAVs.

**Dr. Sivakumar Rathinam** is currently an Assistant Professor in Mechanical Engineering at the Texas A & M University, College Station. Prior to joining A & M, he was an associate research scientist at the University of California-NASA Ames Research Center. He received his Ph.D in Civil-Systems Engineering and M.S. in Electrical Engineering and Computer Science from the University of California in 2007 and 2006 respectively. He research interests include Motion Planning, Combinatorial Optimization, Air Traffic Control and Vision Based Control.

**Dr. Meir Pachter** is a Professor of Electrical Engineering at the Air Force Institute of Technology, Wright-Patterson AFB. Dr. Pachter received the BS and MS degrees in Aerospace Engineering in 1967 and 1969 respectively, and the Ph.D. degree in Applied Mathematics in 1975, all from the Israel Institute of Technology. Dr. Pachter held research and teaching positions at the Israel Institute of Technology, the Council for Scientific and Industrial Research in South Africa, Virginia Polytechnic Institute, Harvard University and Integrated Systems, Inc. Dr. Pachter is interested in the application of mathematics to the solution of engineering and scientific problems. His current areas of interest include military operations optimization, dynamic games, cooperative control, estimation and optimization, statistical signal processing, adaptive optics, inertial navigation, and GPS navigation. For his work on adaptive and reconfigurable flight control he received the AF Air Vehicles Directorate Foulois award for 1994, together with Phil Chandler and Mark Mears. Dr. Pachter is a Fellow of the IEEE.

**Dr. Krishnamoorty Kalyanam** received the B.Tech. degree in Mechanical engineering from the Indian Institute of Technology, Madras in 2000, and the M.S. and Ph.D. degrees in Mechanical engineering from The University of California at Los Angeles, in 2003 and 2005, respectively. In Oct 2005, he joined G.E. Global Research in Bangalore, India as a Research Engineer, where he worked on Train optimal control and Wind Farm Layout Optimization. In July 2009, he moved to the U.S. Air Force Research Laboratory (AFRL) as a National Research Council sponsored

Research Associate. In May 2011, he moved to the InfoSciTex Corporation in 2011 and is currently a in-house cooperative control research scientist at the Control Design & Analysis branch at AFRL, Wright-Patterson Air Force base, Ohio. His current research interests are in the cooperative control of autonomous air vehicles and the underlying stochastic optimal control methods.

**Dr. Pramod Khargonekar** has worked at the Universities of Florida, Minnesota, and Michigan. He was Chairman of the EECS Department and held the Shannon Chair at Michigan. He was Dean of Engineering and holds Eckis Professorship at Florida. He is a recipient of the NSF Presidential Young Investigator Award, the American Automatic Control Councils Eckman Award, the IEEE Baker Prize Award, the IEEE CSS Axelby Best Paper Award, the Hugo Schuck ACC Best Paper Award, and a Distinguished Alumnus and Distinguished Service Award from IIT Bombay. He is a Fellow of IEEE and is a Web of Science Highly Cited Researcher.