Michigan-AFRL Collaborative Center in Control Science
MACCCS (MAX)

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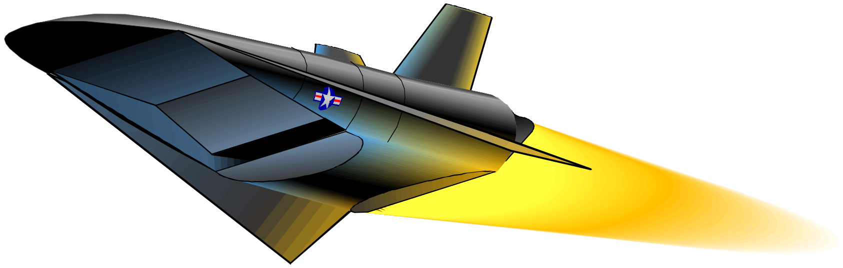
August 9, 2010

Michigan/AFRL Collaborative Center in Control Science (MACCCS, or MAX)

- An ongoing partnership between:
  - The University of Michigan, Ann Arbor
  - The Massachusetts Institute of Technology, and
  - The Control Science Center of Excellence in the Air Force Research Laboratory’s Air Vehicles Directorate
  - The ONR
  - The Boeing Company
  - The Ohio State University
- Initial focus:
  - Modeling and control of hypersonic vehicles
  - Cooperative control of unmanned air vehicles
  - New areas: Human factors, Flapping wing MAV
- Center team:
  - Anouck Girard (UM)
  - Carlos Cesnik (UM)
  - James Driscoll (UM)
  - Emilio Frazzoli (MIT)
  - Nadine Sarter (UM)
  - Missy Cummings (MIT)
  - Andrea Serrani (OSU)

  Corey Schumacher (Team Lead, AFRL)
  Michael Bolender (Team Lead, AFRL)
  David Doman (Team Lead, AFRL)
  AFRL Center of Excellence Team

Hypersonic Vehicles



- Development of simple low-order models that can characterize the main aerothermoelastic effects coupled with propulsion in a 6 DOF flight dynamics simulation of HSV
- Determination on how to appropriately modify vehicle configuration to improve dynamic controllability without compromising vehicle performance

Cooperative Control of Unmanned Air Vehicles

- Supervision and control for collaborative heterogeneous systems
  - Mixed-initiative operations
- Dynamic mission planning
  - Provably efficient, scalable and robust

Collaboration Plan

- Regular visits, including summer visits
- Formal yearly reviews
- Student-run 6-month reviews
- Seminar series
  - Control and Aero Seminars at UM and MIT
- Scientist in residence
  - Tal Shima, Summers of 2008, 2009, 2010
- Foreign-national post-doctoral researchers and graduate students travel to various universities

Hypersonic Vehicle (HSV) Modeling

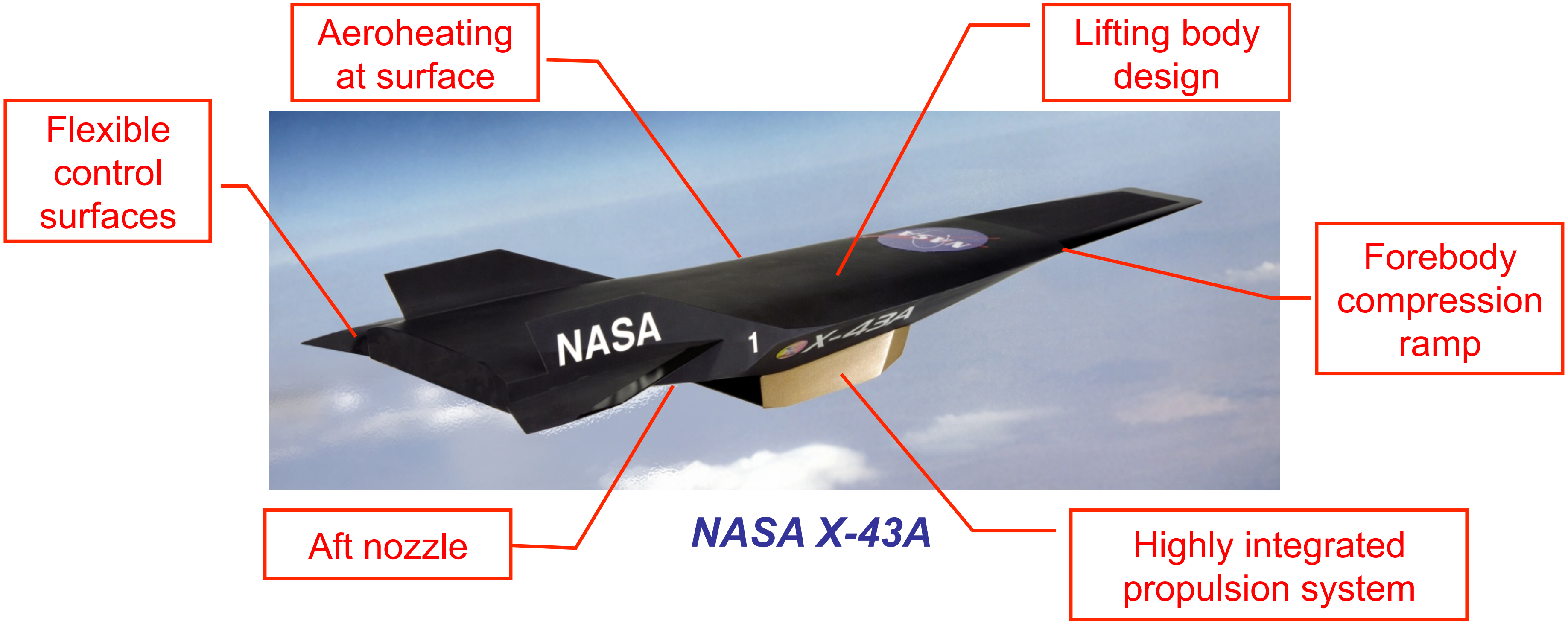
U of M Faculty: Carlos Cesnik, Jim Driscoll

Graduate students: Nathan Falkiewicz, Scott Frendreis, Derek Dalle, Torstens Skujins, Sean Torrez

AFRL collaborators: Mike Bolender (team leader), David Doman, Mike Oppenheimer

Hypersonic Aerothermoelasticity Overview

- Complex coupling between multiple disciplines is exhibited in hypersonic flight
- Control simulation and vehicle design require low-order models that are computationally efficient and possess a low number of states



Aeroheating at surface

Lifting body design

Flexible control surfaces

Forebody compression ramp

Aft nozzle

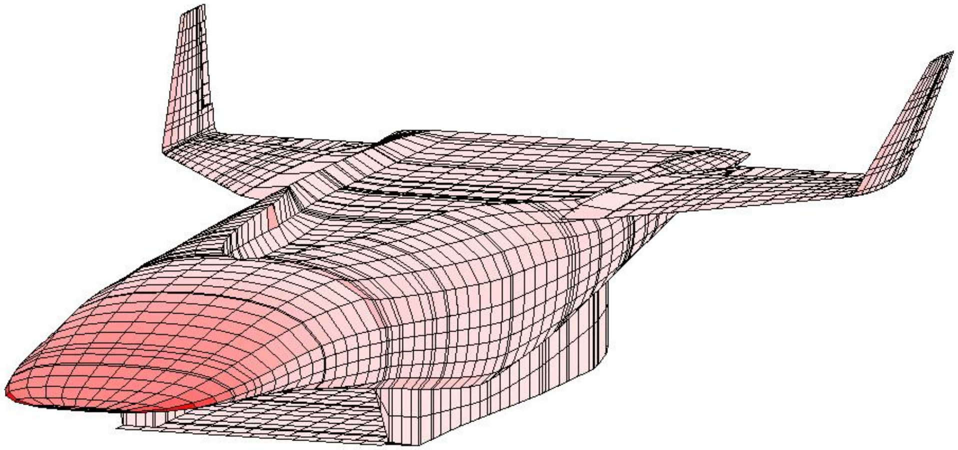
Highly integrated propulsion system

NASA X-43A

Coupled physics require interdisciplinary modeling approach

Hypersonic Vehicle Flight Dynamics Modeling

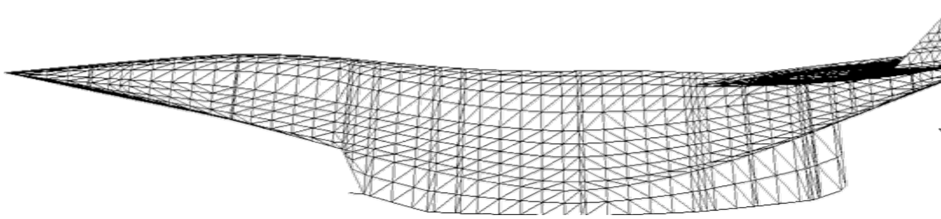
- Create 3D hypersonic vehicle simulation framework for design and evaluation of flight control
- Multiphysics approach: coupled flight dynamics, aerodynamics, elasticity, thermal effects, propulsion system
- Incorporate fundamental (FM) and reduced-order (ROM) models into simulation framework



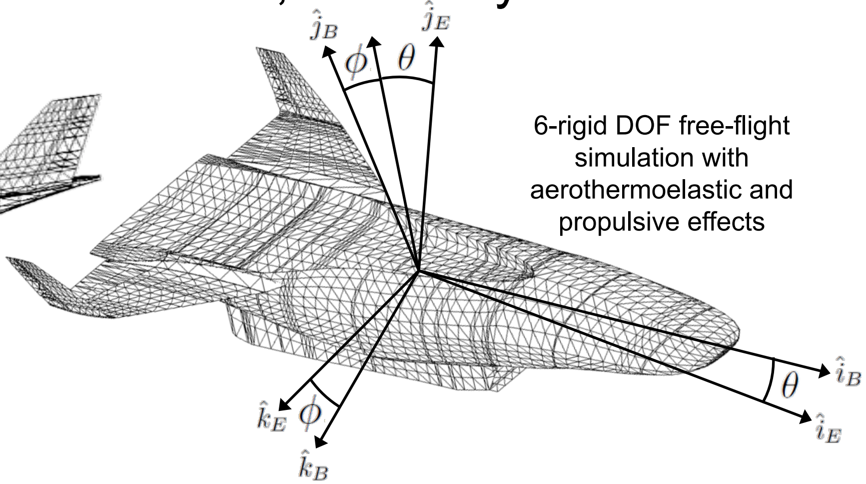
Sample Hypersonic Vehicle Configuration

CE Simulation Framework and ROM Integration

- Rigid body framework (steady aerodynamic FM and ROM, 1D scramjet)
- Flexible vehicle framework (modal representation, unsteady aerodynamics, 1D scramjet)

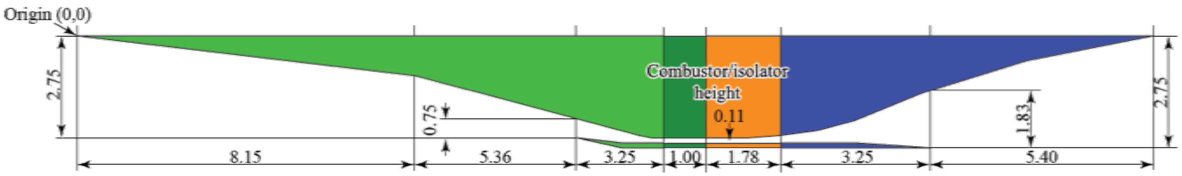


Hypersonic vehicle geometry (original grid from VSI) undergoing 1st longitudinal beam-bending mode deformation



6-rigid DOF free-flight simulation with aerothermoelastic and propulsive effects

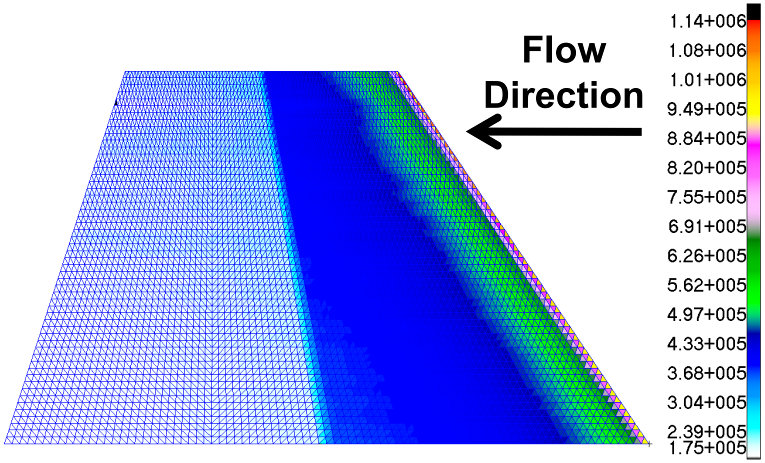
- Integration of scramjet model being developed by Driscoll's group (UMich) to replace simple 1D scramjet FM.



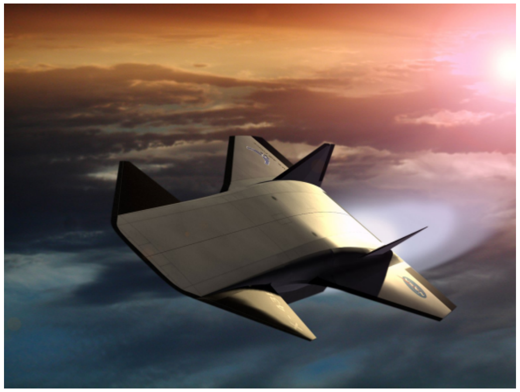
Scramjet flowpath proposed by Torrez, Dalle, and Driscoll, 2010 Joint Propulsion Conference

Reduced-Order Aerothermoelastic Models

- Due to high speed, time varying heat flux exists at vehicle surface
- Results in heat being conducted through internal structure → *need to know detailed heat path to determine local temperatures*
- Temperature-dependent Modulus and thermal stress modifies stiffness
  - Change in stiffness affects structural frequencies and mode shapes
  - Alters vehicle dynamics/controllability and control surface effectiveness

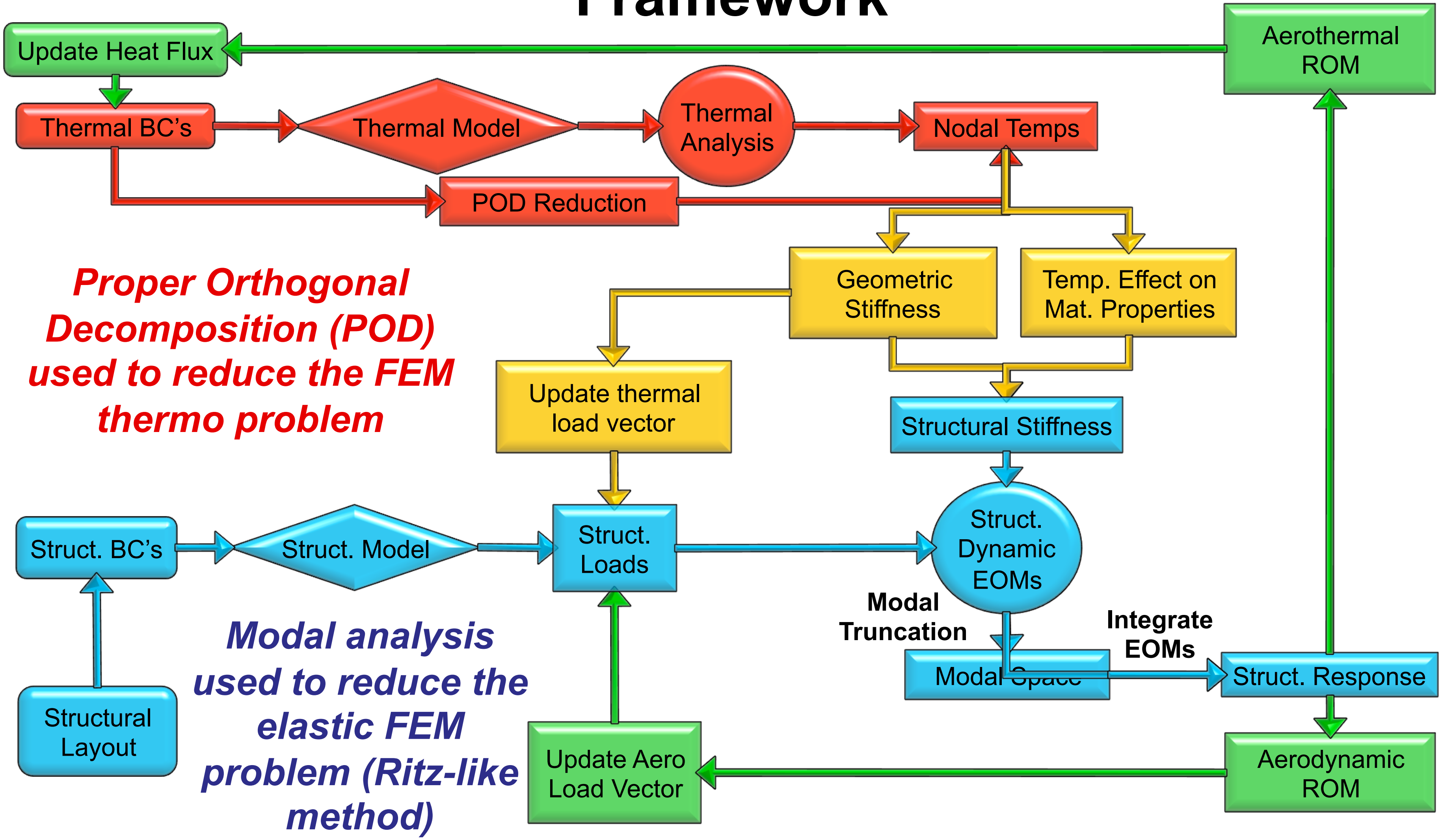


Heat Flux [W/m^2] on Bottom Surface of Airfoil at α = 6°



Rendition of NASA X-43B

Aerothermoelastic Reduced-Order Modeling (ROM) Framework



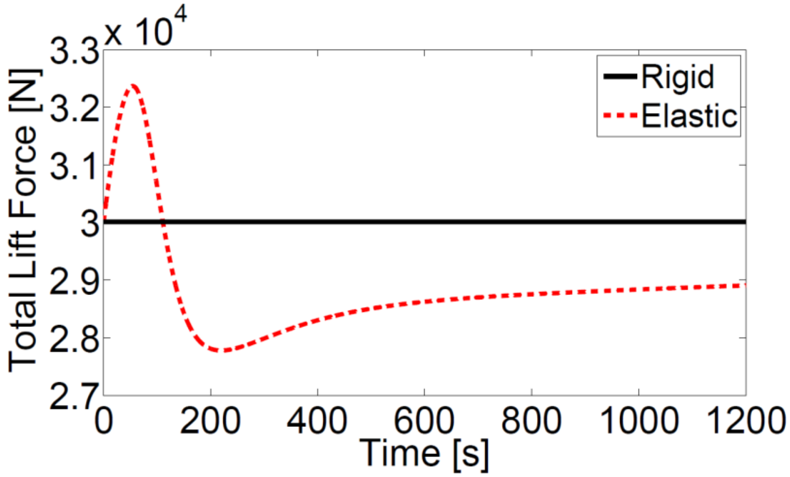
Proper Orthogonal Decomposition (POD) used to reduce the FEM thermo problem

Modal analysis used to reduce the elastic FEM problem (Ritz-like method)

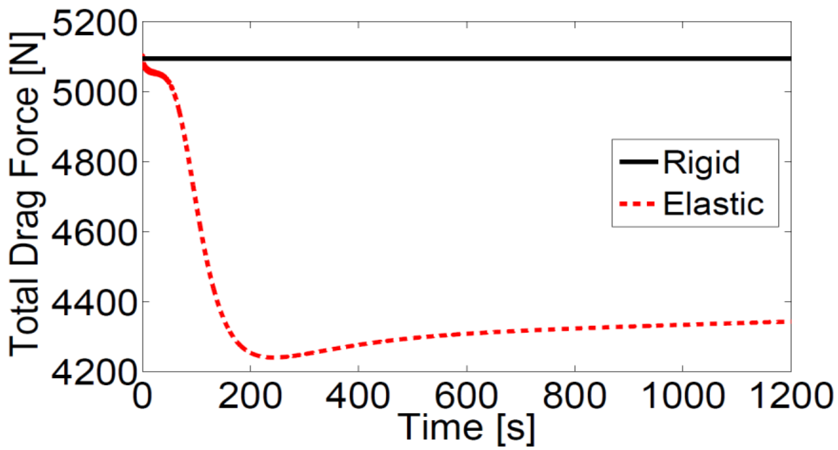
Aerothermoelastic solution using POD (thermo), Ritz modes (structural dynamics), kriging (aeroheating), and piston theory (unsteady aero) has been developed

Sample Aerothermoelastic Results: Cruise Trajectory

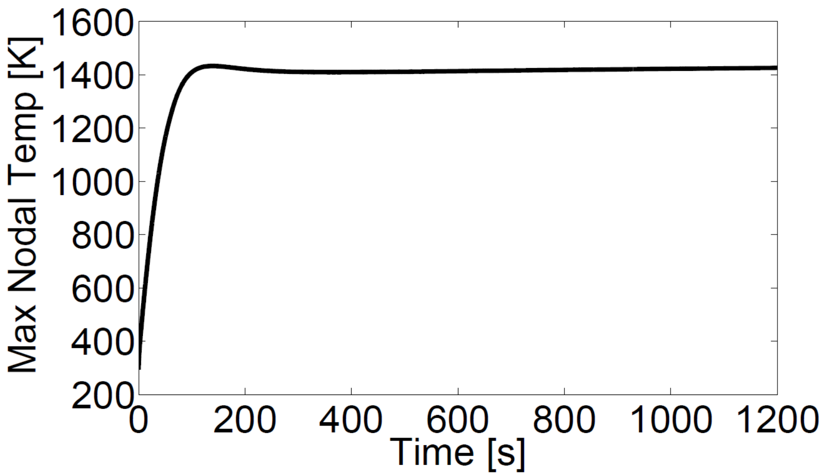
- Total lift/drag and maximum nodal temperature plotted vs. time for all-movable control surface
- Flight conditions: Altitude = 26 km, M_∞ = 8, α = 3º, T_0 = 293 K
- Iterative routine determined AoA needed to match lift of elastic wing to that of rigid wing



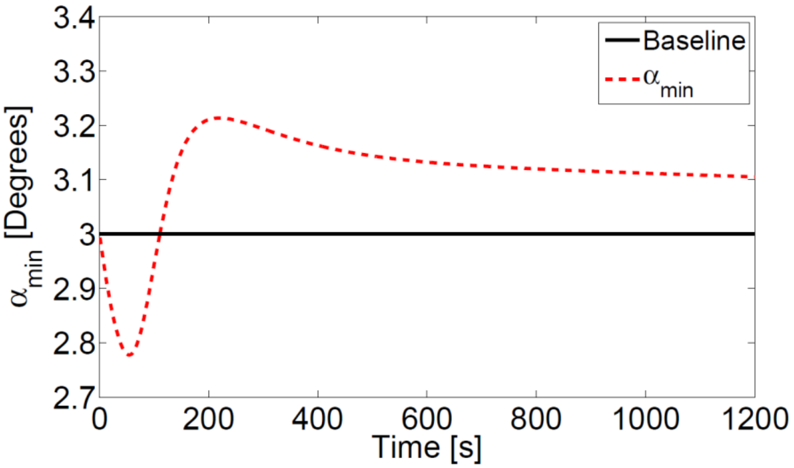
Lift vs. time, Max difference = 8%



Drag vs. time, Max difference = 17%



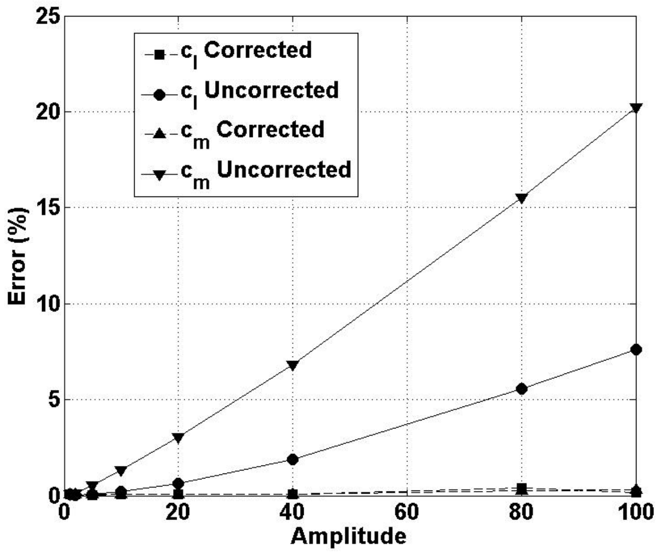
Max nodal temperature vs. time



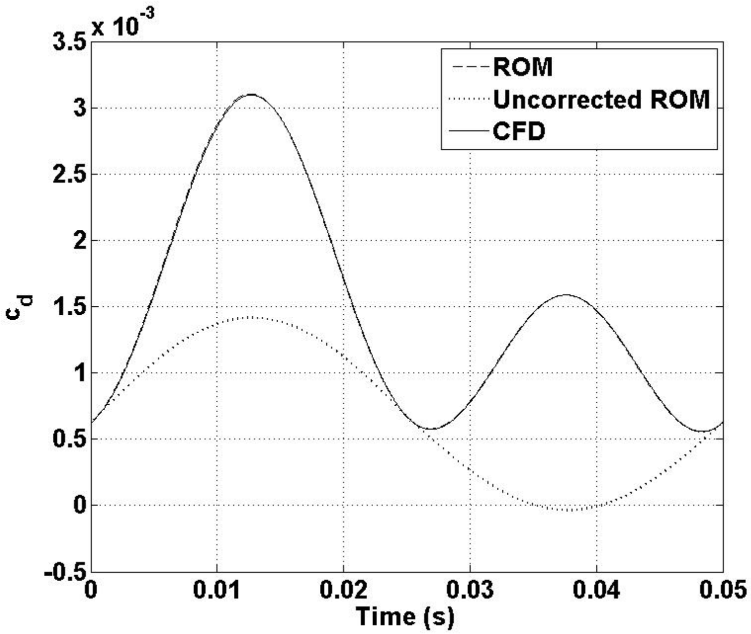
α needed to match $L_{elastic}$ to L_{rigid}

Aerodynamic Reduced-Order Model

- Goal: develop computationally-inexpensive ROM for unsteady aero which is applicable over wide range of parameters and modal input amplitudes
- Convolution-based ROM supplemented with nonlinear correction factor
- Modal inputs given to airfoil; lift, drag, and moment coefficient responses tracked
- Corrected ROM shows good agreement with CFD results and significant improvement over uncorrected ROM
- General method valid over range of 2-D and 3-D vehicle geometries



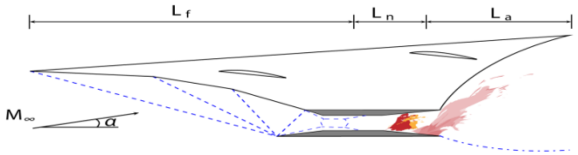
Correction factor improvement



ROM, CFD lines very close to each other

A control-oriented reduced-order model of a ramjet-scramjet propulsion system

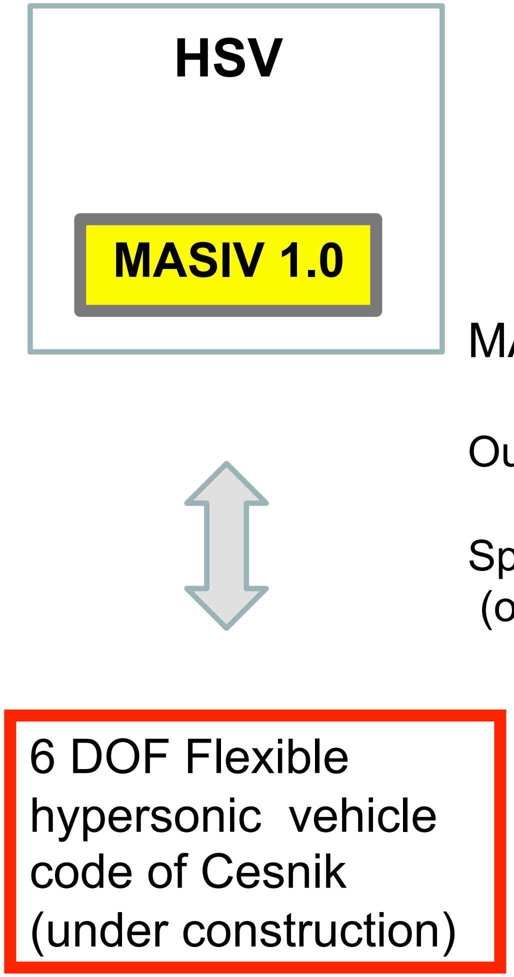
J.F. Driscoll, Sean Torrez, Derek Dalle, U. of Michigan



Goals:

1. Improve the Doman-Bolender AFRL propulsion model for a HSV (develop a ROM that adds complex chemistry, dissociation, inlet shock interactions to compute thrust, moments in <1 sec) ✓
2. Integrate this ROM into the AFRL HSV trim code ✓
3. Validate / determine accuracy by comparisons to high fidelity CFD ✓
4. Combine propulsion ROM with new 6 DOF flexible vehicle ROM of Cesnik (in progress)
5. Include ram-to-scram transition (in progress)

HSV and MASIV Software – distribution controlled by M. Bolender AFRL/RBCA



HSV

MASIV 1.0

HSV Hypersonic vehicle code (AFRL, Doman, Bolender):
Output: trim, stability analysis, transfer functions
Input: X-43 vehicle dimension, Mach number, altitude
Trim code computes: AoA, elevon angle, ER, Lift, Drag

MASIV Propulsion code – “Michigan-AFRL Scramjet in Vehicle” code embedded within HSV

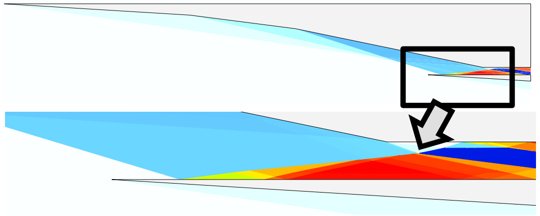
Output: provides wall pressures on panels for forces, moments and thrust to HSV to trim vehicle

Speed: 1 sec / “iteration” X 1000 iterations = 17 min/trim
(one standard PC, “iteration” = one AoA, elevon angle, ER)

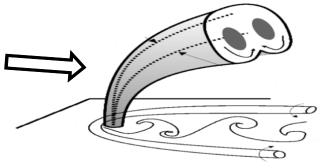
6 DOF Flexible hypersonic vehicle code of Cesnik (under construction)

Currently being mated to both HSV and MASIV
-vehicle bending changes inlet shock pattern, capture area
- lift, drag, engine thrust coupled to bending

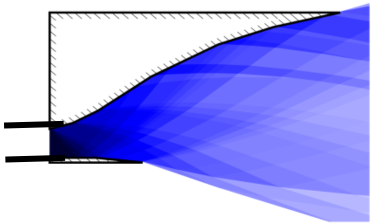
Our MASIV propulsion ROM has three components



Inlet ROM:
20 -100 shock interactions



Combustor ROM:
Fuel mixing,
finite-rate chemistry



Nozzle ROM
multiple waves
determine lower
boundary

Trim requirement: HSV code determines fuel Equiv. Ratio, AoA, elevon angle

Control variables: (CR) inlet contraction ratio– vary x location of cowl leading edge
(θ_{cowl}) inlet cowl ramp deflection angle
(ε_1) fraction fuel injected at location 1 vs. 2 – varied during ram-scram

Design variables: inlet wall panels, nozzle wall panels: lengths and angles
number of fuel injectors, injector diameters, locations,
fuel type (hydrogen or ethylene complex chemistry)

Our inlet ROM – solves Euler eqns in < 0.5 sec

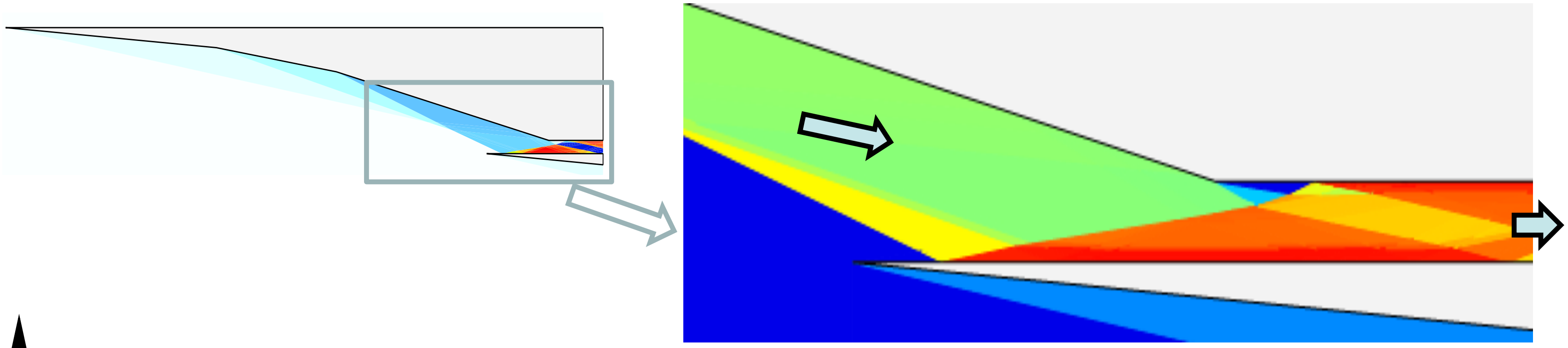
Shocks: assume 2-D, exact oblique shock relations with real gas properties
(c_p, γ not constant)

Expansions: discretize continuous fan into 2-4 waves

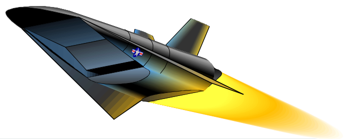
Use exact Riemann equations for each wave interaction (20 to 100 in each inlet)

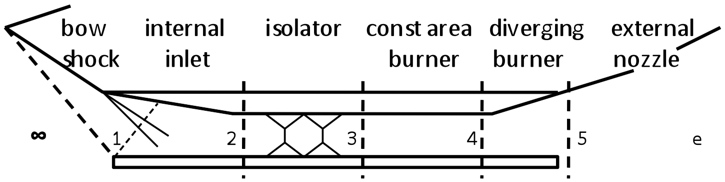
Boundary layers: displace wall by displacement thickness computed by
standard supersonic formula

Validation: high fidelity CFD++ solutions agree with our ROM to 6%



Our Combustor ROM solves 8 ODEs in < 1 sec





Fuel can be added anywhere

Area is variable

Wall friction, wall heat transfer

Heat is added by combustion

Real gas properties

Fast solution to ODEs

Obtain reaction rates (ω_i) from our turbulent combustion model with complex dissociation chemistry

Conserv. mass

$$\frac{1}{\rho}\frac{d\rho}{dx} = \frac{1}{\dot{m}}\frac{d\dot{m}}{dx} - \frac{1}{U}\frac{dU}{dx} - \frac{1}{A}\frac{dA}{dx} \tag{1}$$

momentum

$$\frac{1}{U}\frac{dU}{dx} = \frac{-1}{\gamma\ M^2}\left(\frac{1}{p}\frac{dp}{dx} + \frac{2\gamma M^2 C_f}{D} + \frac{\gamma M^2(1-\varepsilon)}{\dot{m}}\frac{d\dot{m}}{dx}\right) \tag{2}$$

$$\frac{1}{p}\frac{dp}{dx} = \frac{1}{\rho}\frac{d\rho}{dx} + \frac{1}{T}\frac{dT}{dx} - \frac{1}{\overline{\overline{MW}}}\frac{d\overline{MW}}{dx} \tag{3}$$

$$\frac{d\,\overline{MW}}{dx} = -\overline{\mathrm{MW}}^2\ \sum_i\left(\frac{1}{MW_i}\frac{dY_i}{dx}\right) \tag{4}$$

$$\frac{d\dot{m}}{dx} = \sum_i \frac{d\dot{m}_{i,added}}{dx} \tag{5}$$

energy

$$\frac{dT}{dx} = \frac{1}{c_p}\left\{\frac{dh_{RP}}{dx} + \left[h_{0,s,added} - h_{0,s}\right]\left[\frac{1}{\dot{m}}\frac{d\dot{m}}{dx}\right] - \frac{2C_f\, c_p\,(T_{aw} - T_w)}{\mathrm{Pr}^{2/3}\ A} - \mathrm{U}\ \frac{dU}{dx}\right\} \tag{6}$$

$$\frac{dY_i}{dx} = \frac{\omega_i\, MW_i\, A}{\dot{m}} + \frac{1}{\dot{m}}\frac{d\dot{m}_{i,added}}{dx} - \frac{Y_i}{\dot{m}}\frac{d\dot{m}}{dx} \tag{7}$$

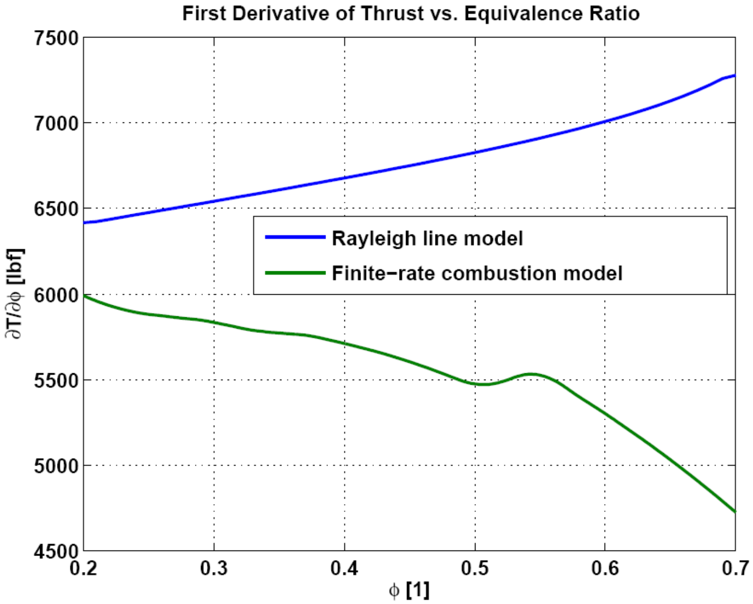
$$\omega_i = \frac{dC_{Q_i}}{dt} = \sum_j \left[\, k_{f,j}\ (\nu_{ij}'' - \nu_{ij}')\ \prod_i C_i^{\nu'_{ij}}\right] \tag{8}$$

Our improved propulsion ROM predicts very different control derivatives than simple AFRL ROM of Doman

Sensitivity of forces, moments to control variables:
Force = thrust control variable = fuel-air equivalence ratio

- Previous model of Bolender et al. - compared to our new engine model with real gas effects (non-constant specific heat and dissociation)
- Thrust sensitivity decreases with increasing equivalence ratio

∂(Thrust) / ∂ (fuel-air equivalence ratio)



fuel-air equivalence ratio

What is the shift in pole/zero location due to new propulsion model ?

- Elevon – to – flight path angle transfer function
- Significant changes in real poles and transmission zeros
- Short period dynamics change the most

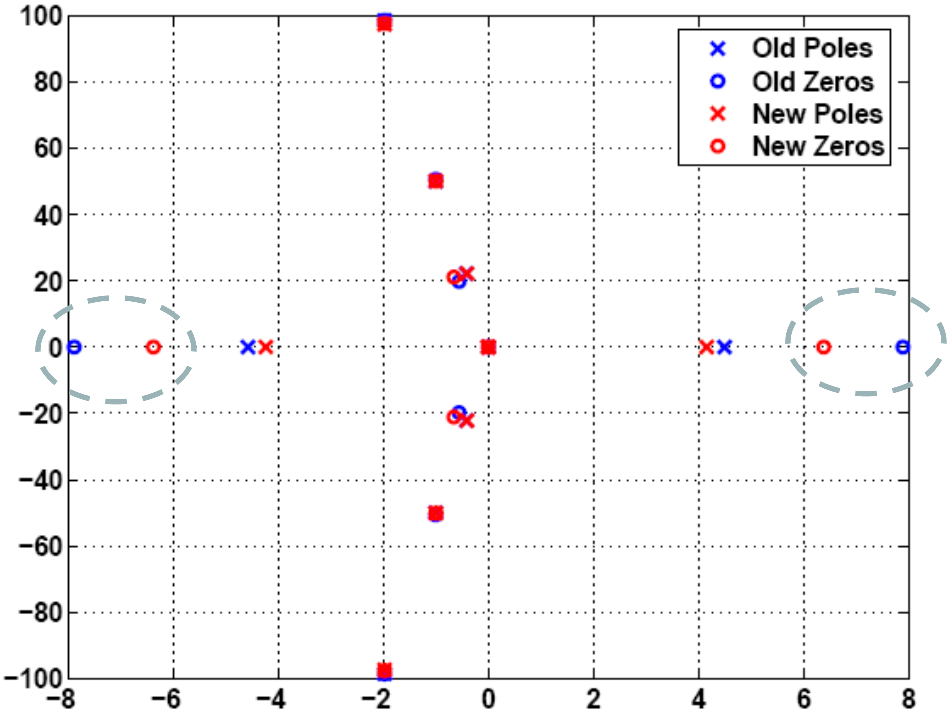


Figure 8. Pole-zero Map of Open-loop Dynamics at Mach 8, 85,0000 ft

Publications to date:

1. “Reduced Order Modeling of Turbulent Reacting Flows With Application to Scramjets”, S. M. Torrez, J. F. Driscoll, M. Ihme, M. L. Fotia, to appear, J. of Propulsion & Power, 2010.
2. “Reduced-Order Modeling of Two-Dimensional Supersonic Flows with Applications to Scramjet Inlets”, D. J. Dalle, M. L. Fotia, J. F. Driscoll, to appear J. Prop. Power, 2010
3. “A Scramjet Engine Model Including Effects of Precombustion Shocks & Dissociation”, SM Torrez, D. Micka, J. F. Driscoll, MA Bolender, DB Doman, M Oppenheimer, AIAA Paper 2008-4619
4. “Shift of the Poles and Zeros of a Hypersonic Vehicle Due to Variations in the Scramjet Engine Model”, SM Torrez, JF Driscoll, MA Bolender, DB Doman, M Oppenheimer, AIAA Paper 2008-4619
5. “Flight Dynamics of Hypersonic Vehicles: Effects of Improved Propulsion Modeling”, SM Torrez, JF Driscoll, MA Bolender, DB Doman, AIAA Paper 2009-6152
6. “Scramjet Engine Model MASIV: Role of Finite-Rate Chemistry and Combustor-Isolator Interactions”, SM Torrez, JF Driscoll, D Dalle, DJ Micka, M Fotia, AIAA Paper 2009-4939.
7. “Preliminary Design Methodology for Hypersonic Engine Flowpaths”, S. M. Torrez, J. F. Driscoll, Derek J. Dalle, M. L. Fotia, AIAA Paper 2009-7289.

Collaborative Control of UAV

Faculty: Anouck Girard (UM),
Emilio Frazzoli (MIT)

Post-doctoral researchers:
Weilin Wang (UM), Ketan Savla (MIT)
Graduate students: Baro Huyn, Justin Jackson,
Sertac Karaman, Tom Temple

MACCCS: Recent progress at MIT

- Incremental sampling-based algorithms for online mission planning
  - Temporal logic specifications
  - Optimal planning
  - Pursuit-evasion differential games

- Dynamical queueing methods for humans-in-the-loop systems
  - Modeling
  - Experimental validation

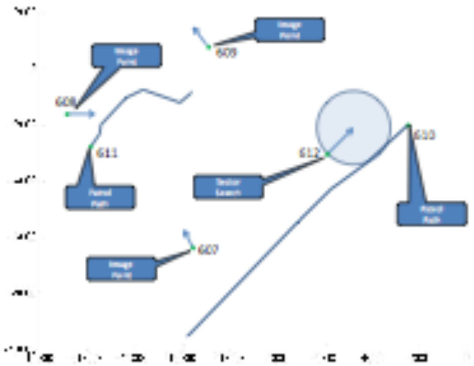
- Mission planning under uncertainty
  - Persistent patrol
  - Search and service on road networks

Incremental sampling-based algorithms for online mission planning

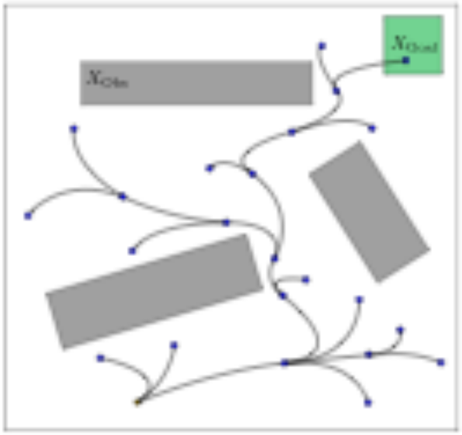
- **Objective:** on-line computation of "efficient" mission plans (i.e., task assignment, task sequencing, control policy) for multiple dynamical systems, subject to **physical** and **logical** constraints.

- Provably hard problems (e.g., PSPACE-hard)
  - Heuristics: **not** complete, **not** optimal
  - Abstraction methods: resolution complete/optimal, but **poor scalability**

- Incremental sampling-based methods:
  - Main idea: Build a sequence of abstractions that provably converges to a model containing the (optimal) solutions.
  - Anytime algorithms: Very fast computation of a solution + guaranteed convergence to optimal solutions
  - Computational efficiency: local computations

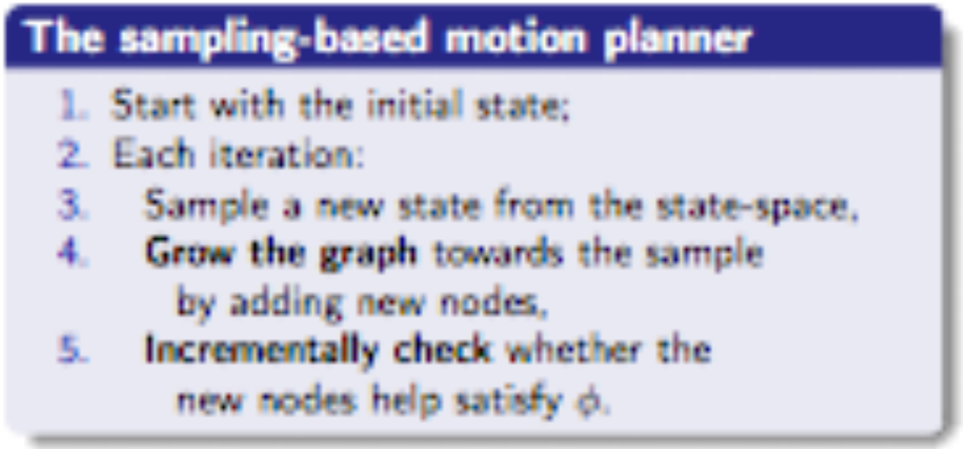


[Kingston, Rasmussen, et al., '09]



The Rapidly-exploring Random Graph (RRG) algorithm

- Basic idea:



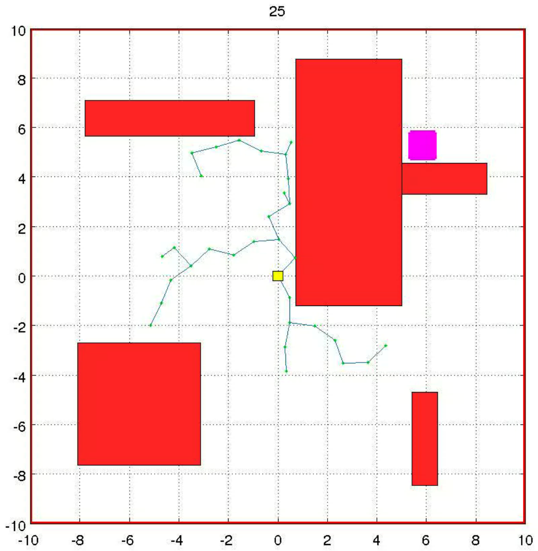
The sampling-based motion planner

1. Start with the initial state;
2. Each iteration:
3. Sample a new state from the state-space,
4. **Grow the graph** towards the sample by adding new nodes,
5. **Incrementally check** whether the new nodes help satisfy ϕ.

- Incrementally refine a discrete model of the dynamics by building a graph (vs. a tree) of feasible trajectories
- Incrementally check whether such model contains a plan satisfying the specification
- Both of these operations can be performed efficiently
- **Theorem**: (Under some technical assumptions) the RRG algorithm generates a feasible trajectory satisfying the specifications, if one exists, with probability approaching one as the number of samples goes to infinity.

Optimal planning and RRG

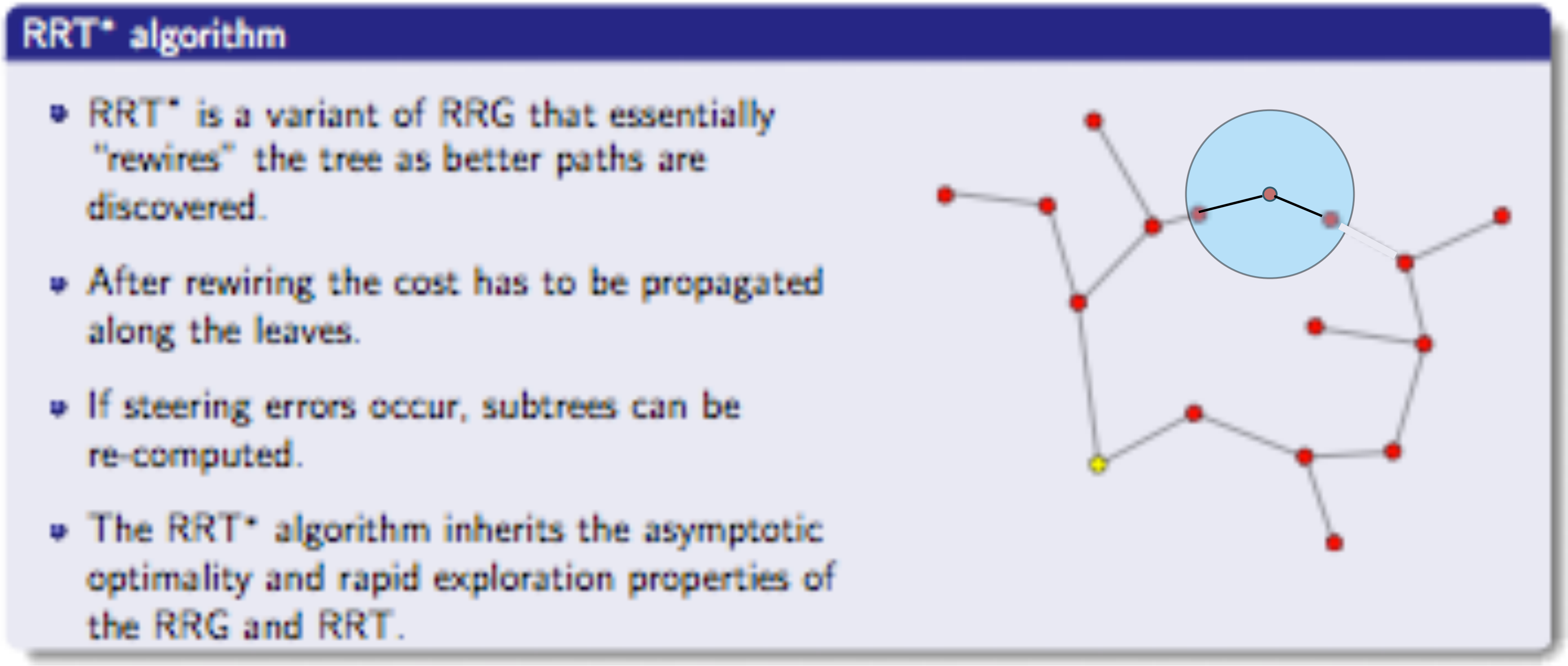
- In some applications, it is important to find an optimal path to a goal, not only a feasible path.
- **A negative result**: state-of-the-art sampling-based algorithms such as RRT converge to optimal solutions with probability 0!
  - Focus on nearest neighbor provides good exploration features, at the expense of optimality.



- The RRG algorithm makes connections to all nodes within a ball of volume O(log(n)/n). *(where n is the number of nodes in the RRG.)*
- **Theorem**: (under some technical assumptions) the best feasible trajectory in the RRG provably approximates optimal solutions as the number of samples goes to infinity.
- The proof relies on novel connections between motion planning and the theory of Random Geometric Graphs [Penrose ’03].
- **Theorem:** The computational cost of RRG is within O(1) of the computational cost of RRT.

RRT*: a tree version of RRG

- In some instances, it is convenient to maintain a tree structure as opposed to a graph structure. *(e.g., in the presence of process noise, non-exact planner, etc.)*



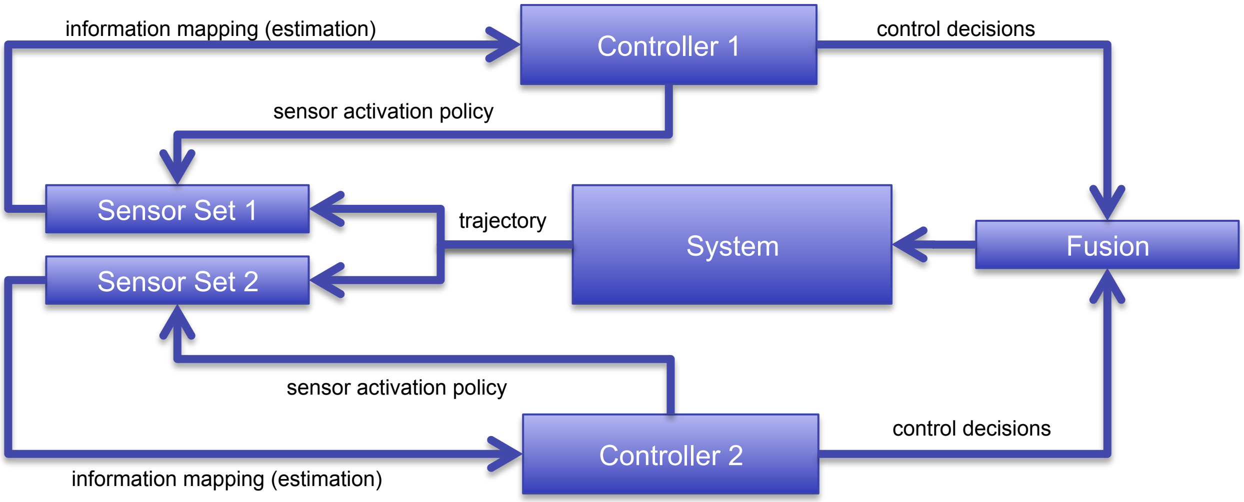
RRT* algorithm

- RRT* is a variant of RRG that essentially "rewires" the tree as better paths are discovered.
- After rewiring the cost has to be propagated along the leaves.
- If steering errors occur, subtrees can be re-computed.
- The RRT* algorithm inherits the asymptotic optimality and rapid exploration properties of the RRG and RRT.

- *Best Open Source Code Award at Robotics, Science and Systems, 2010.*

Information Acquisition and Dynamic Observations in Distributed Systems

- Our problem formulation is informational
  - Problems about when and which pieces of information are needed
  - Trajectories that look the same must followed by the same information acquisition decision
  - Information must be sufficient for correct decision-making in control or fault diagnosis



Information Acquisition and Dynamic Observations in Distributed Systems

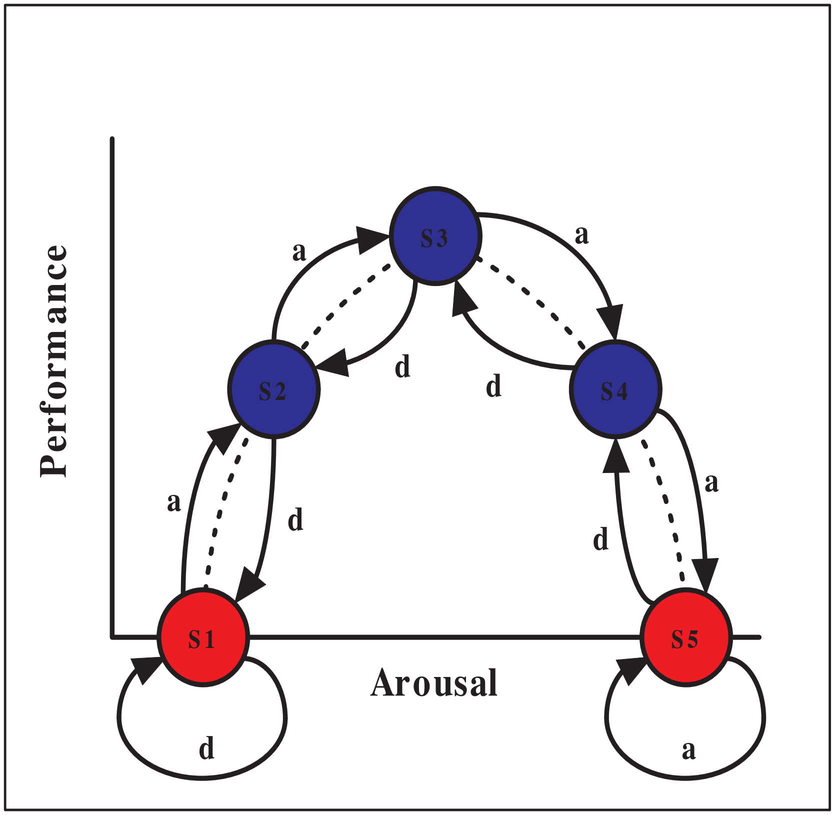
- Two important properties in Dynamic Observations
  - Coobservability answers the question of whether or not agents are able to collect sufficient information to make correct control decisions
  - Codiagnosability concerns identifying trajectories that contain unobservable fault events
  - Developed algorithms to reduce the problem of coobservability to the problem of codiagnosability in dynamic observations
- Efficient algorithms are developed which are provably optimal
  - Minimizing information acquisition in distributed control
  - Similar problems are solved for event diagnosis
  - Extensions for computing all minimal solutions and dealing with stochastic models
  - Online version for centralized control
  - Extension to infinite solution domain of language
- Research on other topics
  - Developed a stochastic approximation algorithm when optimum solution is not unique and applied it for optimizing human performance

Recent Journal Articles

- W. Wang, S. Lafortune, F. Lin, and A. R. Girard "*Minimization of Dynamic Sensor Activation in Discrete Event Systems for the Purpose of Control*", November 2010, IEEE Transactions on Automatic Control
- W. Wang, A. R. Girard, and C. Gong "*Computing all Minimal Sensor Activation Policies*", accepted by IEEE Transactions on Automatic Control, 2010
- W. Wang, S. Lafortune, A. R. Girard, and F. Lin "*Optimal Sensor Activation for Diagnosing Discrete Event Systems*", July 2010, Automatica
- W. Wang, A. R. Girard, "*An Online Approach for Optimizing Sensor Activation in Supervisory Control*", accepted by Automatica, 2010
- W. Wang, A. R. Girard, S. Lafortune, and F. Lin "*On Codiagnosability and Coobservability with Dynamic Observations*", under revision, IEEE Transactions on Automatic Control

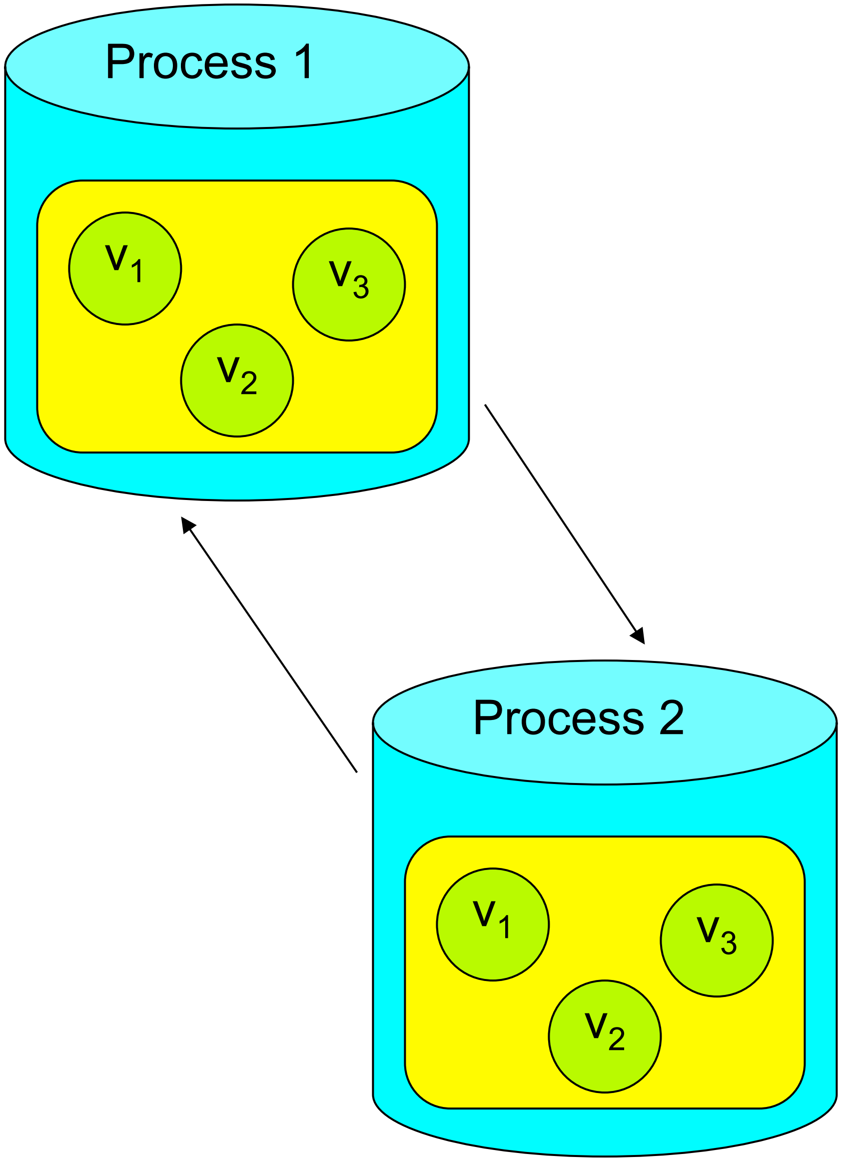
Discrete Event Modeling of Heterogeneous Human Operator Teams in Classification Tasks

- A team of operators on a monitoring task duty that demands classification decisions.
- A stream of images taken by a team of UAVs are transmitted to the operators
- Operator team: Mixture of two levels of expertise (novice and expert).
- How to model the operator and how to exploit the team?
    - Study of operator modeling and supervisory controller using Discrete Event Systems



Discretized Y-D law with event-driven transitions

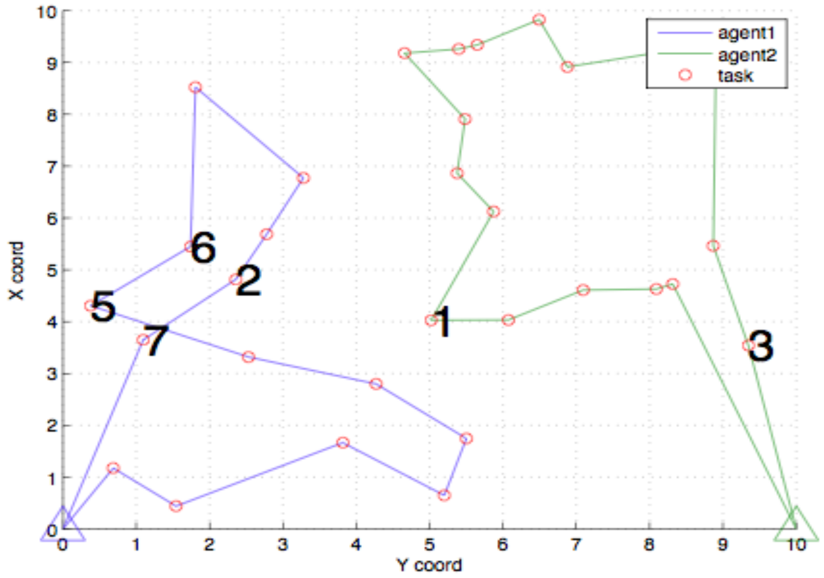
Distributed Constrained Scheduling

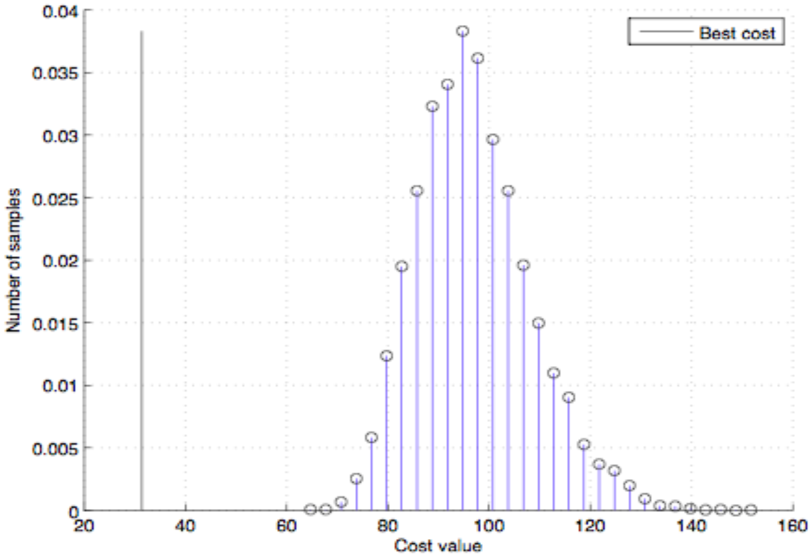


- Distributed weak commitment search applied to scheduling problem
- Supports constraint satisfaction
- Extension to multi-variable case, accounts for assignment and timing
- Implemented over unreliable communication network

Solution Quality Measurement For Task Assignment Problems

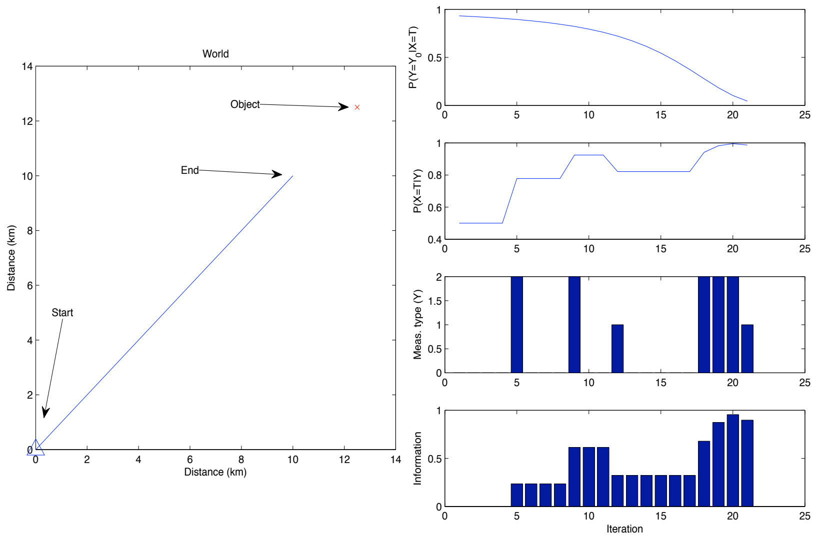
- Developed an effective measurement of solution quality
- Applicable to many constrained, nonlinear task assignment problems
- Non-Gaussian statistical characterization of combinatorial problems
- Independent of problem solving approach used





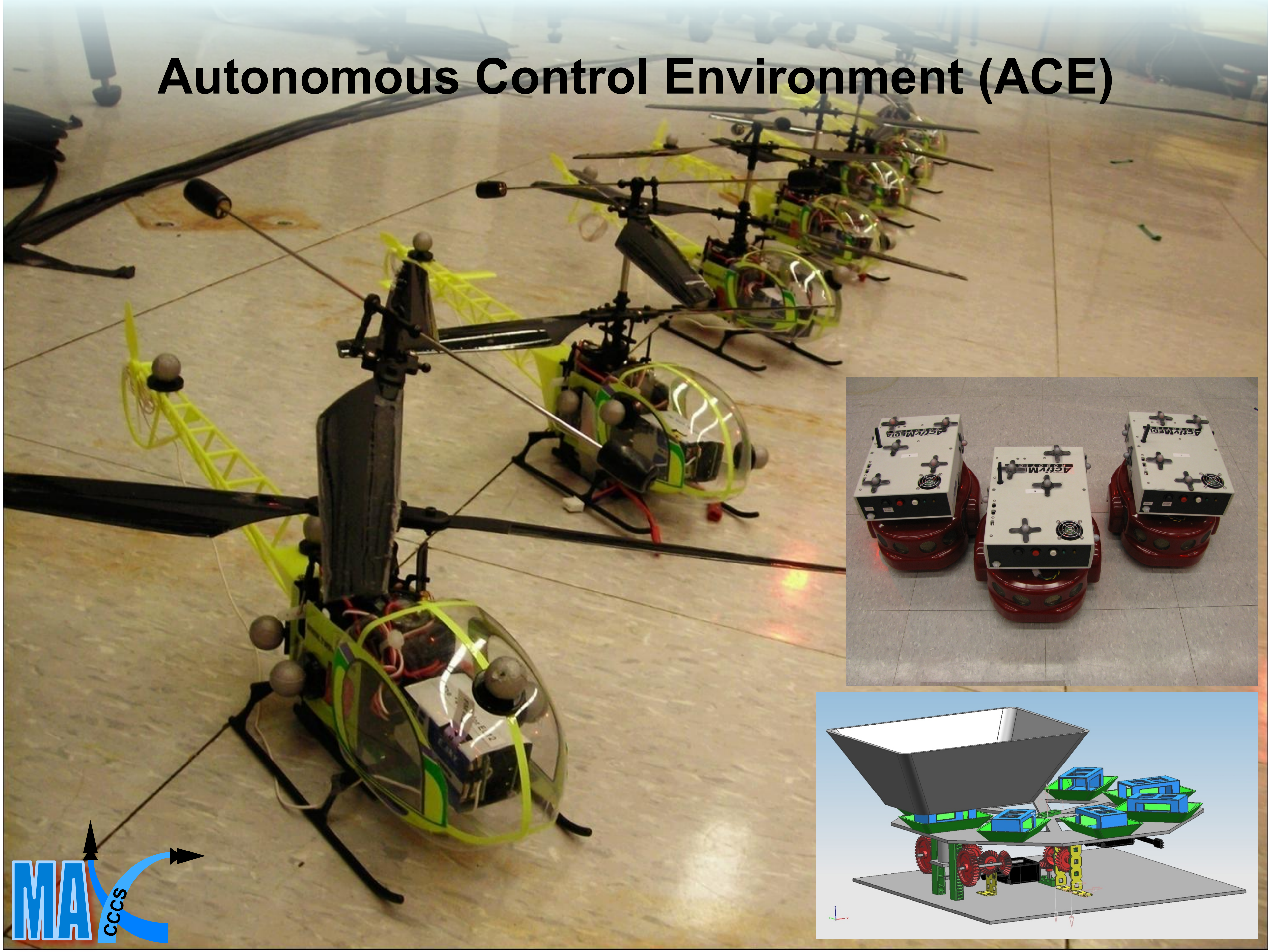
Optimal Path Planning with Bayesian Classification

- Friend-finding problem
  - Large hall (museum or train station) crowded with people
  - You're looking for your friends
  - You have myopia (the closer you get, the better you can see)
  - Don't have much time to search the entire hall
- Need to come up with a path such that you can distinguish your friends from others
  - Knowing the cost for misclassifying, what is the optimal path that guarantees correct classification?



Example path and Bayes classifier results

Autonomous Control Environment (ACE)



Human Factors

Faculty: Nadine Sarter (UM),
Missy Cummings (MIT)

Post-doctoral researchers:
Luca Bertuccelli (MIT)

Supporting Re-planning and Timesharing in UAV Control (UM IOE – THInC Lab)

- Attentional demands on UAV operators can be expected to increase dramatically
- UAV operators need to timeshare between numerous tasks, such as monitoring overall mission health, searching for/ identifying targets in UAV video feeds, and re-planning when necessary
- Our goal: Support operators in performing these tasks in parallel through the design of human-centered displays and multimodal attention guidance

Research Activities (2009-2010)

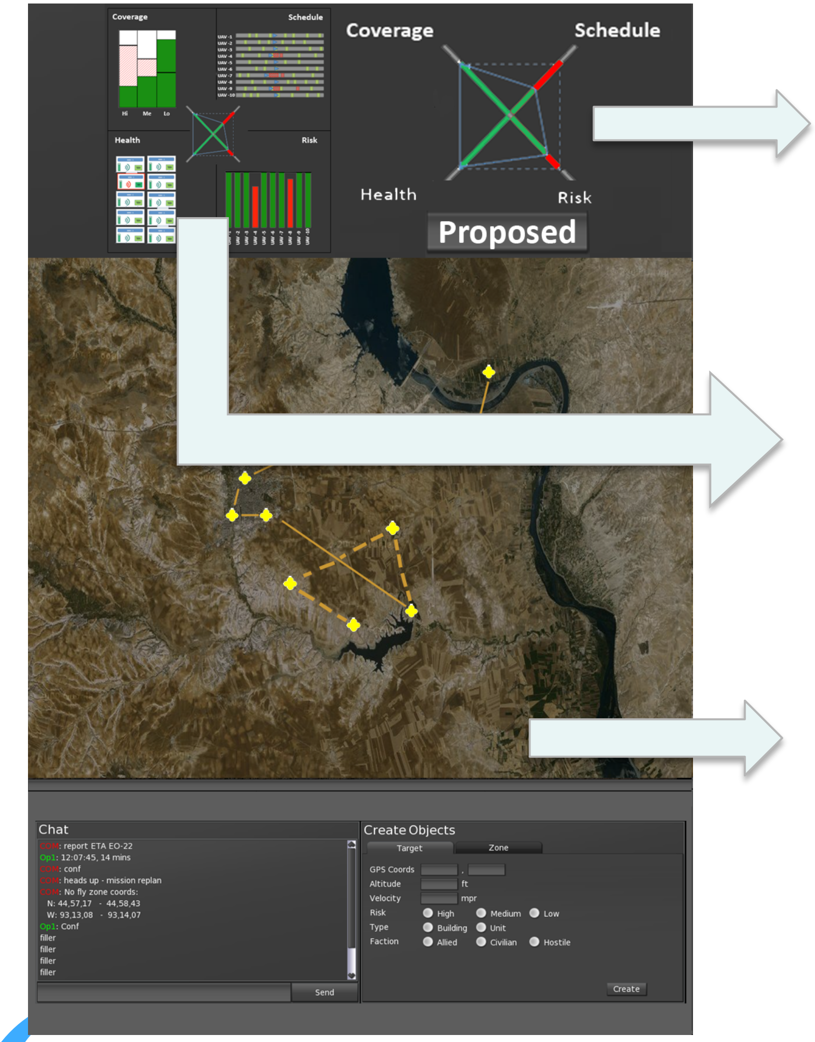
- Developed a re-planning and monitoring interface that is distributed across three large display screens:
  - Center: includes top-down map of the area to be surveyed and overall current mission health/status information
  - Right side: video/sensor data from each of 10 UAVs
  - Left side: supports mission re-planning and implementation/evaluation of new plan

Re-planning   Map and Mission Health   UAV Video Feeds

COM: report ETA EO-22
Op1: 12:07:45, 14 mins
COM: conf
COM: heads up - mission replan
COM: No fly zone coords:
N: 44,57,17 - 44,58,43
W: 93,13,08 - 93,14,07
Op1: Conf
filler
filler
filler
filler

- Change Target-5 Status
- Add Target - 14
- Modify Target - 2
  - Risk Status changed: Medium -> High
  - Flower loitering Established
- Recall UAV -1

Re-planning Screen



Chat

COM: report ETA EO-22
Op1: 12:07:45, 14 mins
COM: conf
COM: heads up - mission replan
COM: No fly zone coords:
N: 44,57,17 - 44,58,43
W: 93,13,08 - 93,14,07
Op1: Conf
filler
filler
filler
filler

Create Objects

GPS Coords ,
Altitude ft
Velocity mpr
Risk ○ High ○ Medium ○ Low
Type ○ Building ○ Unit
Faction ○ Allied ○ Civilian ○ Hostile

Configural display showing deficiencies related to schedule and risk but good coverage and UAV health

Detailed modifiable data on four areas related to mission health: coverage, schedule, UAV health, and risk

Top-down view, showing current (solid line) and possible revised (dashed line) UAV flight path

Developing Operator Models for Visual Search Task

Luca F. Bertuccelli and Missy Cummings
Humans and Automation Laboratory
MIT, Dept of Aeronautics and Astronautics
{lucab, missyc}@mit.edu

Introduction to developing operator models

- **Objective**: develop integrated human-machine systems for information–gathering missions
  - Human is a high level supervisor overseeing mission
  - Issues: workload, fatigue, human error, human variability

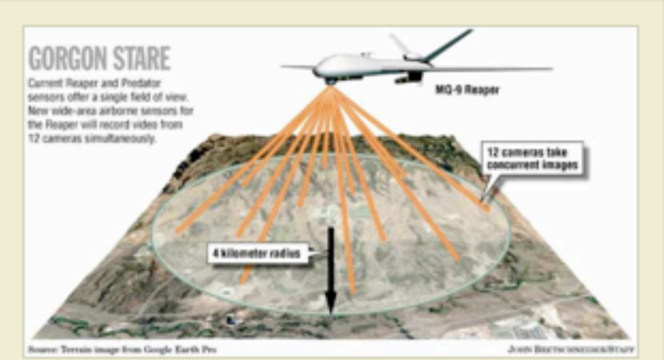
- **Problem/opportunity**: We live in a sensor-rich environment with operators inundated with data
  - How do operators handle visual search in imagery from multi- or heterogeneous sensor sources? Can **relook** at images

Military Is Awash in Data From Drones

By CHRISTOPHER DREW
Published: January 10, 2010

HAMPTON, Va. — As the military rushes to place more spy drones over Afghanistan, the remote-controlled planes are producing so much video intelligence that analysts are finding it more and more difficult to keep up.

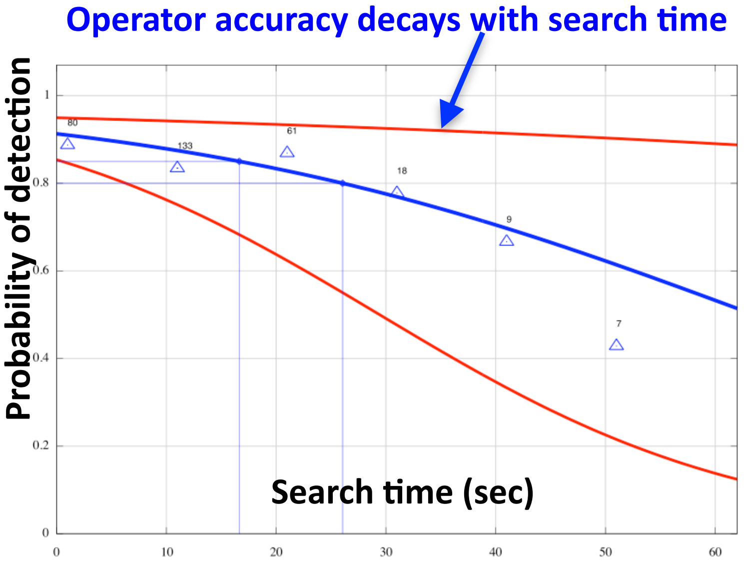
NY Times, Jan 2010



Gorgon Stare project for Reaper

Previous work shows potential in providing relooks

- Previous experimental work showed that operator performance can degrade with time
  - Setting: sequential search with image and task ambiguity
  - Sources of degradation:
    - Operator may be unsure or too busy with other tasks
    - Fatigue

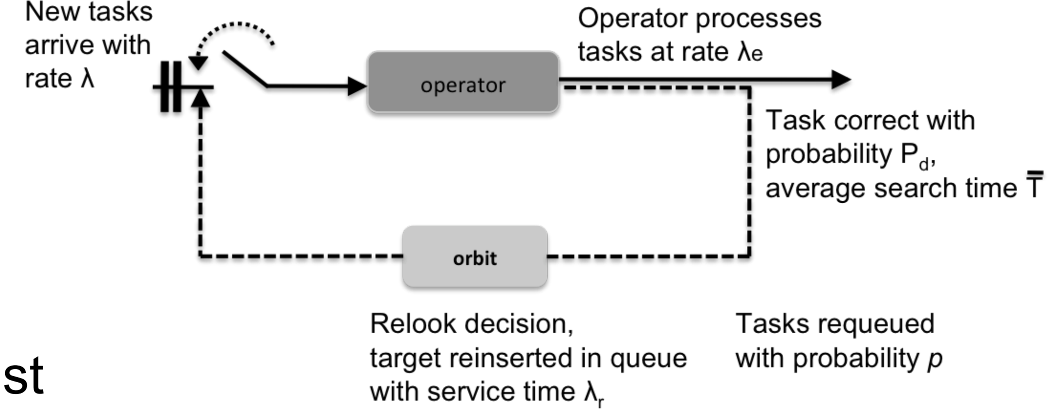


Operator accuracy decays with search time

- Hypothesis: “**Relooking” at tasks later can be beneficial to operators in multi-UAV supervisory mission**
- Approach: Retrial queueing framework
  - Note: this has been previously attempted, but in the context of single UAV, use of Automatic Target Recognition and only a second look

A retrial queueing model to the relook problem

- Queueing operator model extended to account for the possibility of relooks
  - Operator skips difficult tasks, reinserted in task list



New tasks arrive with rate λ

Operator processes tasks at rate λe

operator

Task correct with probability P_d, average search time $\bar{\bar{T}}$

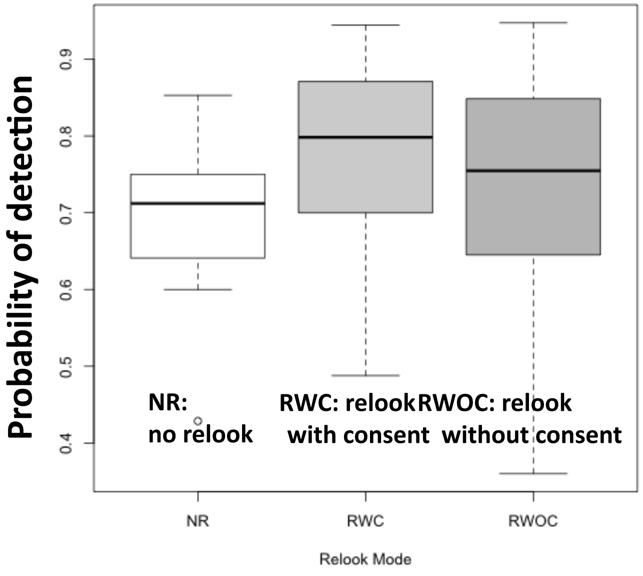
orbit

Relook decision, target reinserted in queue with service time λ_r

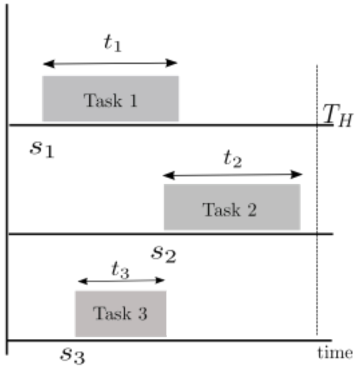
Tasks requeued with probability *p*

- Three different experimental conditions tested with humans in the loop: no relook (NR), automation only (RWOC), automation assisted (RWC)
  - Performance improves by using relooks
  - Relooks may result in possible increase in workload

Probability of detection for different relook modes



Previously we showed how to replan but not plan



- In our current work we are investigating how effective operators are at scheduling heterogeneous search tasks w/algorithm help

- Decision support system directs operator's attention using a scheduling algorithm
  - Assumes operator maximizes accumulated reward (sum of target values)
  - Can pose as an integer program
  - Algorithm presents a list of tasks to operator

$$\max_x E\left[\sum_j R_j \sum_i x_j^i\right]$$

$$s.t. \quad \sum_i x_j^i \le 1 \ \forall i, \quad \sum_i x_j^i \le 1 \ \forall j$$

$$c_{i-1} - \sum_j p_j x_j^i \le c_i \ \forall i$$

$$\sum_j \left(p_j + r_j\right) x_j^i \le c_i \ \forall i$$

$$c_i \le T \ \forall i$$

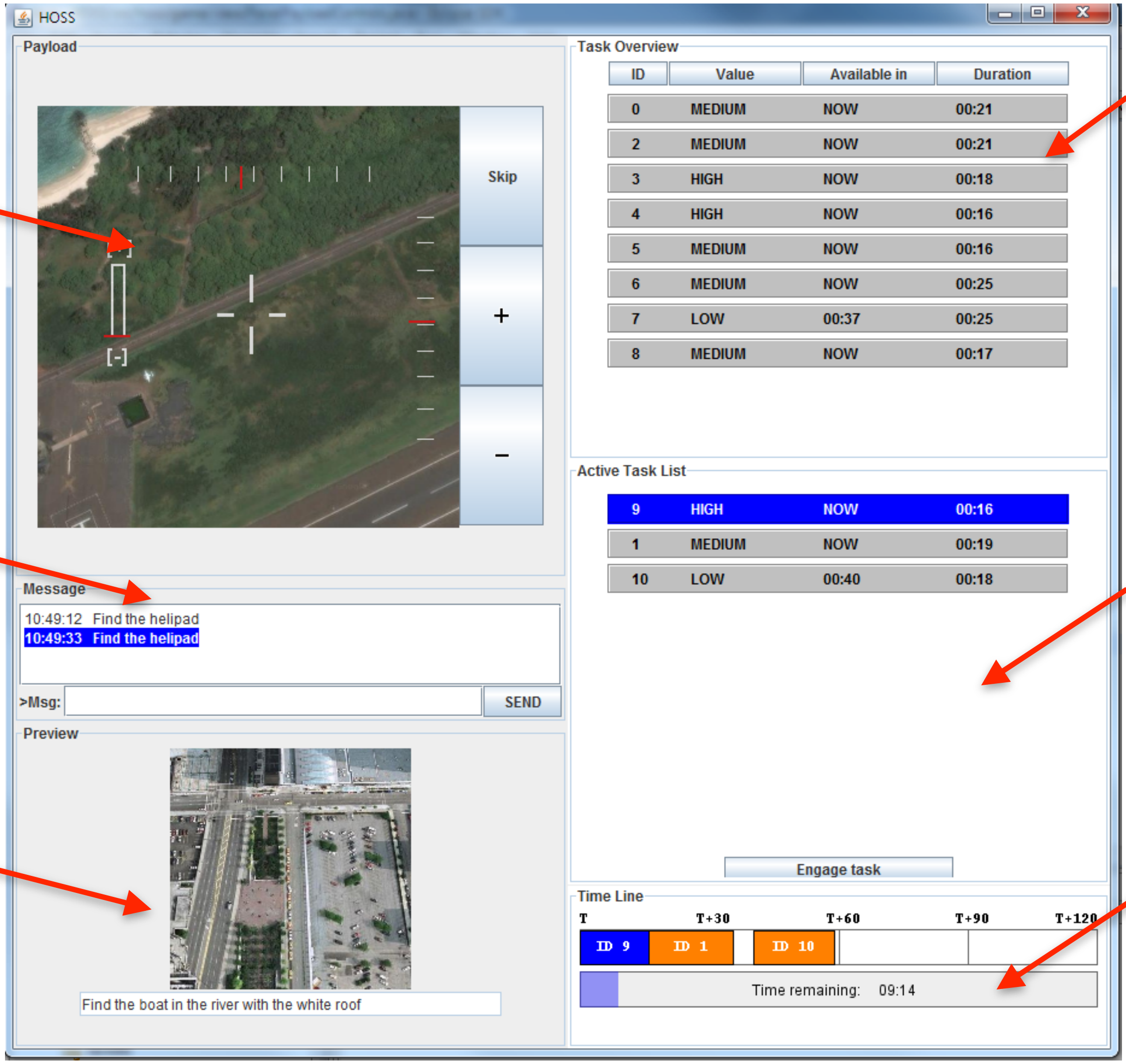
- **Research question:** does operator performance improve with this algorithm support? How does operator performance change if a "preview" of the search task is shown to operator?

Scheduling Support via novel interface

Image payload pane displays the image in which operator needs to search and identify the target

Chat box tells operator what to search for and updates operator with relevant information

Preview pane provides a small view of other tasks, along with description of task



Task Overview

ID	Value	Available in	Duration
0	MEDIUM	NOW	00:21
2	MEDIUM	NOW	00:21
3	HIGH	NOW	00:18
4	HIGH	NOW	00:16
5	MEDIUM	NOW	00:16
6	MEDIUM	NOW	00:25
7	LOW	00:37	00:25
8	MEDIUM	NOW	00:17

Active Task List

9	HIGH	NOW	00:16
1	MEDIUM	NOW	00:19
10	LOW	00:40	00:18

10:49:12 Find the helipad
10:49:33 Find the helipad

Find the boat in the river with the white roof

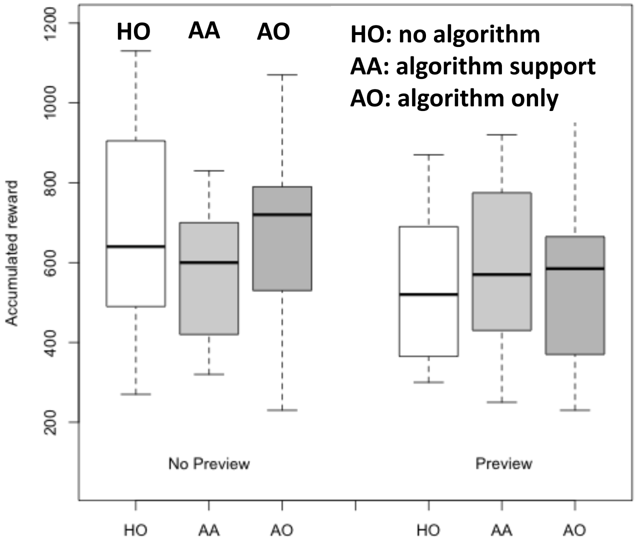
Time remaining: 09:14

Task Overview Pane contains list of all remaining tasks that need to be searched by the operator

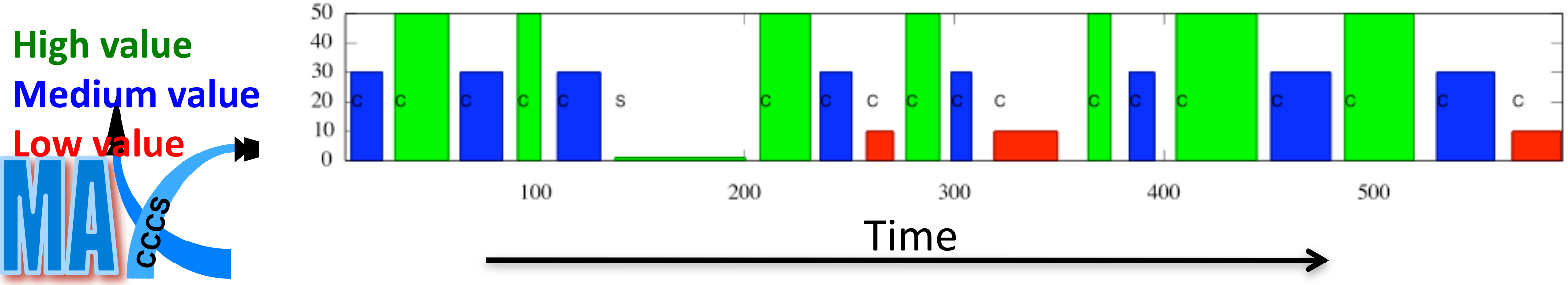
Operator drags tasks from Task Overview pane to Active Task List pane – engages the first task to initiate the search

Timeline provides temporal awareness during the course of the mission

Preliminary results



- Overall, operators do well in terms of accumulated reward (sum of target values)
  - Providing a preview seems to be a distraction, more analysis needs to be performed
- Can gain significant insight into operator decision strategies by analyzing their time-series preferences
  - When do they do high-value tasks? Do they do shorter duration tasks first? How do operators schedule?



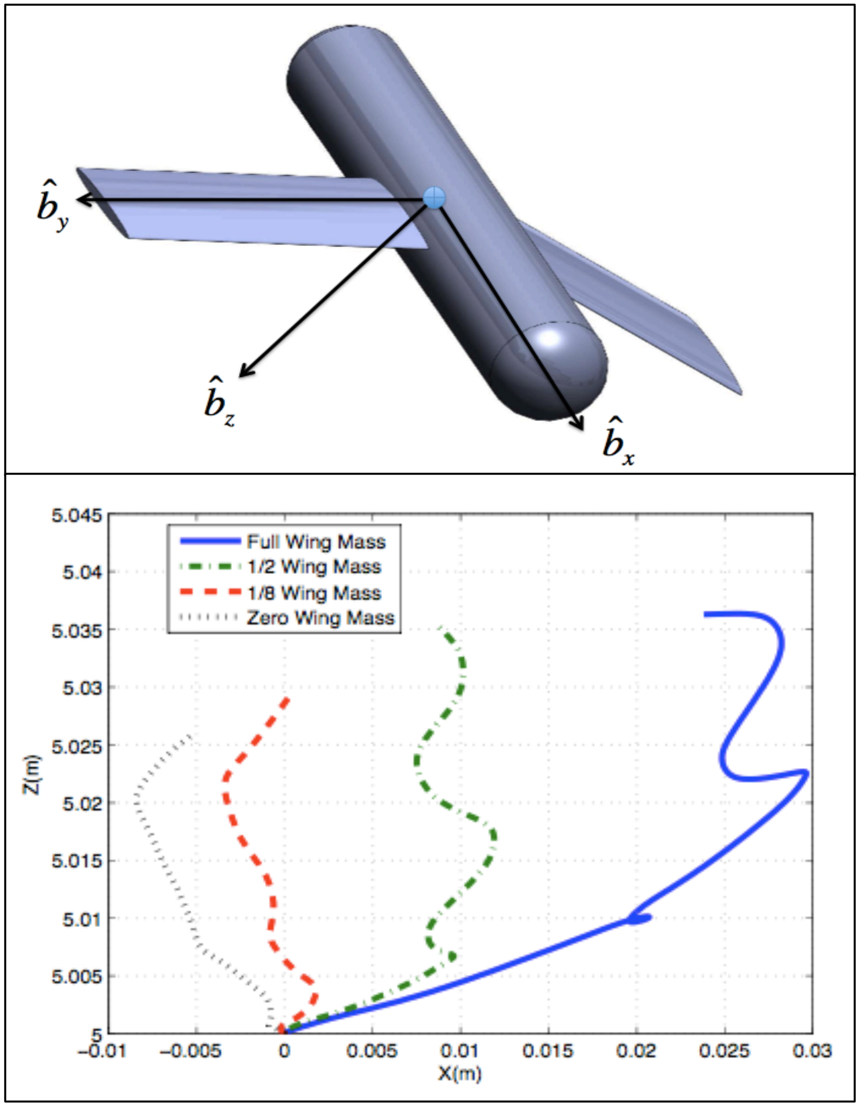
Flapping Wing MAVs

Faculty: Anouck Girard (UM),
Andrea Serrani (OSU)

Graduate students: Christopher Orlowski

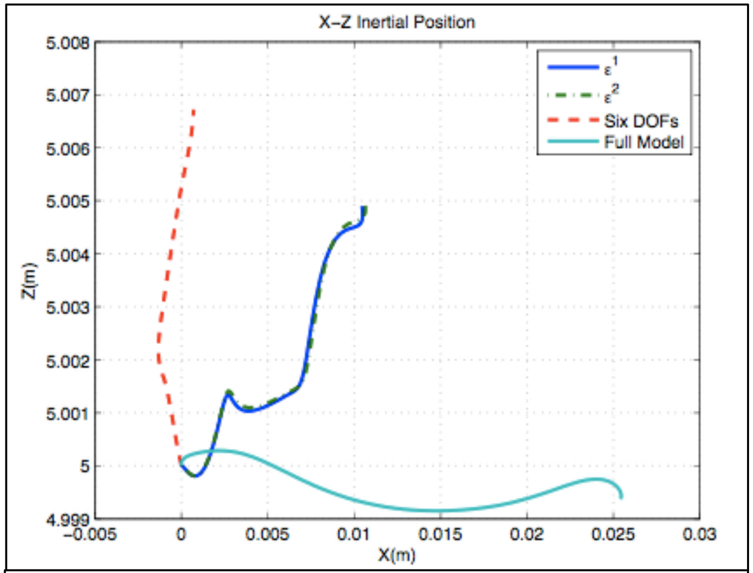
FWMAV
Dynamics, Stability and Control

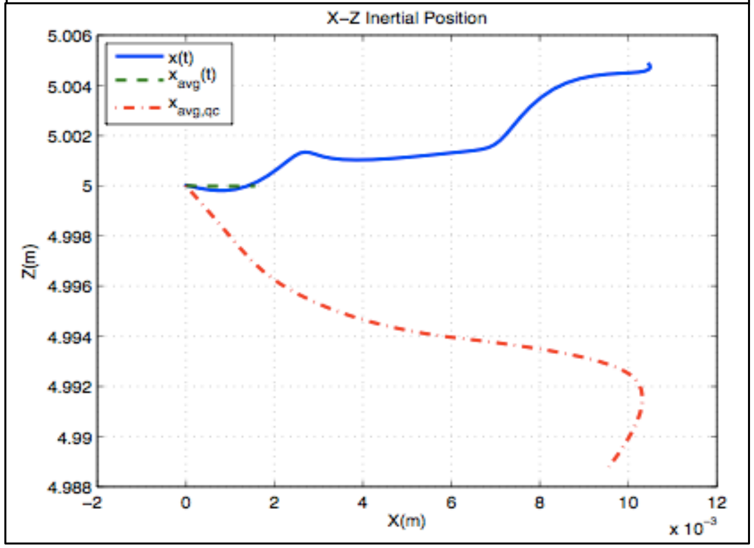
- Multi-body equations of motion for flapping wing micro-air vehicles (FWMAV)
  - Two wings (3DOF per wing)
  - Four wings
  - Two wings w/tail and/or control mass (for pitch control)
- Mass of wings important for dynamics, stability and control studies
  - Significant difference in behavior between multi-body model and standard aircraft model
  - Multi-body model approaches standard aircraft model as mass of wing decreases
  - Qualitative similarity in dynamic behavior with different aerodynamic models



FWMAV
Dynamics, Stability and Control

- Current/Future work : Approximation of nonlinear dynamics
  - Averaging theory
    - Treat the wings as a small perturbation "ε" on the standard (fixed-wing) aircraft equations
    - Local averaging methods are not accurate over a flapping cycle;
    - Proposed solution is to use averaging over quarter-cycles
  - Singular Perturbations
    - Treat central body as "slow" system and wings as "fast" system
  - Describing functions
    - Investigating use of describing functions for stability analysis in the vicinity of hover
    - May be used to describe both the aerodynamic inputs and mass effects of the wings





Contributions

- Proceedings
  - C. Orlowski, A. Girard, W. Shyy, “Derivation and Simulation of the Nonlinear Dynamics of a Flapping Wing Micro-air Vehicle,” EMAV 2009, Delft, Netherlands
  - C. Orlowski, A. Girard, W. Shyy, “Open Loop Pitch Control of a Flapping Wing Micro-Air Vehicle Using a Tail and Control Mass,” IEEE ACC 2010, Baltimore, MD
  - C. Orlowski, A. Girard, W. Shyy, “Four Wing Flapping Micro Air Vehicles – Dragonflies or Xwings?,” AIAA GNC 2010, Toronto, Ontario, Canada
- Recent work
  - C. Orlowski and A. Girard, “Modeling and Simulation of the Nonlinear Dynamics of Flapping Wing Micro-Air Vehicles,” Accepted for Publication in *AIAA Journal*
  - C. Orlowski and A. Girard, “Averaging of the Nonlinear Dynamics of Flapping Wing Micro Air Vehicles for Symmetrical Flapping,” Submitted to 2011 AIAA Aerospace Sciences Meeting

Center Highlights

- 15 conference papers presented in Year 1
- 5 journal papers and 26 conference papers in Year 2
- 9 journal papers and at least 22 conference papers in Year 3

- 14 graduate students funded in Year 3 (some partially)
- 8 undergraduate students funded partially
- 1 PhD student graduated (Andy Klesh, 2009).
- 2 post-doctoral fellows
- 1 scientist in residence

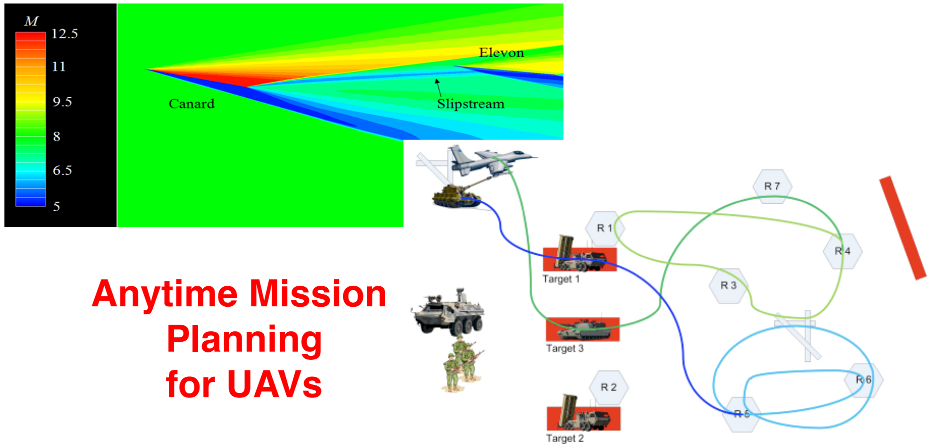
Leveraged Funding

- Leveraged funding:
  - $735K (3-years at UM) for a total of $1,242K (OSU + UM)--from NASA NRA
  - Students on DOD Fellowships: Driscoll, Girard (x2)
  - ONR Addition to MAX: $300,000 total (3 years and $100K/yr)
  - Boeing addition to MAX: $100K/yr (in second year)

- Papers, videos and presentations available from:
  - http://www.umich.edu/~arclab/max/

Michigan-AFRL Collaborative Center in Control Science
MACCCS (MAX)
University of Michigan, Anouck Girard

Canard/Elevon Interactions in HSV



Anytime Mission Planning for UAVs

Long-Term PAYOFF: Establish, sustain and amplify an internationally recognized center of excellence in control science research and education

OBJECTIVES:

1. Foster close interaction and joint efforts in MACCCS;
2. Address technical issues in the two concentration areas in close collaboration with AFRL/RBCA;
3. Identify emerging research issues and develop novel approaches to collectively elevate our competency and readiness level.

APPROACH/TECHNICAL CHALLENGES

1. Cooperative Control of Unmanned Air Vehicles (C2UAV): (i) supervision and control of cooperative heterogeneous systems (mixed-initiative operations); (ii) dynamic, sequential, combinatorial and/or stochastic mission planning.
2. 2. Air-Breathing Hypersonic Vehicle (ABHV): (i) development of simple low-order models that can characterize the main aerothermoelastic effects coupled with propulsion; (ii) determination on appropriately modifying vehicle configuration to improve dynamic controllability

FUNDING ($K)—Show all funding contributing to this project

	FY06	FY7	FY08	FY09	FY10
AFOSR Funds	0	50	500	500	500
AFRL	0	50	570	500	500
Leveraged					
NASA	0	0	250	250	250
Boeing	0	0	0	100	100
ONR	0	0	0	100	100

TRANSITIONS

- 63 conference, 14 journal publications

STUDENTS, POST-DOCS

7 professors, 2 post-docs (partial), 14 graduate students

LABORATORY POINT OF CONTACT

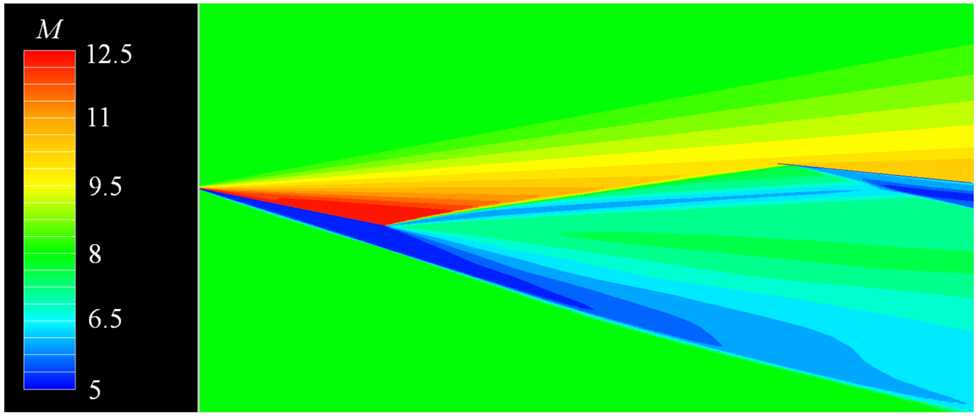
Dr. Schumacher, AFRL/RBCA, WPAFB, OH

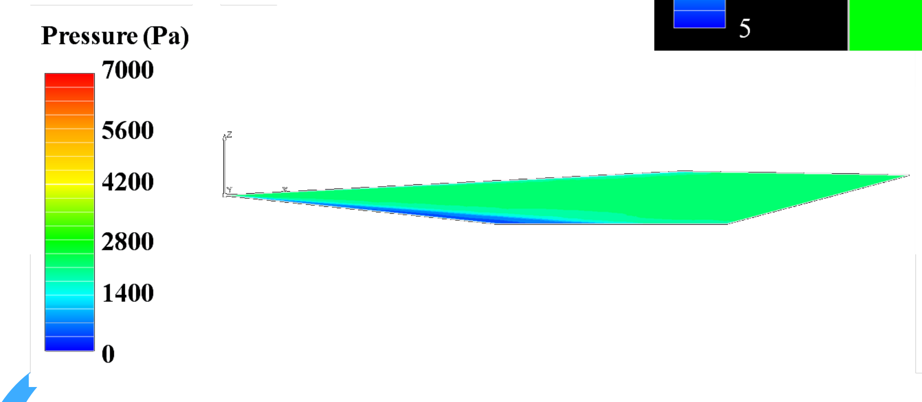
Backup slides

Hypersonic Aerodynamics Modeling

- More accurate and general steady and unsteady representation of the hypersonic flow for arbitrary vehicle geometry is being studied
- Resulting ROM will be integrated with aerothermoelastic framework to replace piston theory for 3-D vehicle
- Creation of unsteady reduced-order models from convolution with CFD-based step response

Study of control surface interaction in hypersonic flow





Modeling of pressure on 3-D hypersonic vehicle

Sampling-based motion planning

- State-of-the-art algorithms for robotic motion planning (e.g., RRTs, [LaValle & Kuffner, ’01]) rely on sampling techniques to achieve probabilistic/ resolution completeness
- Field-proven in major robotic applications (e.g., MIT entry to the 2007 DARPA Urban Challenge)

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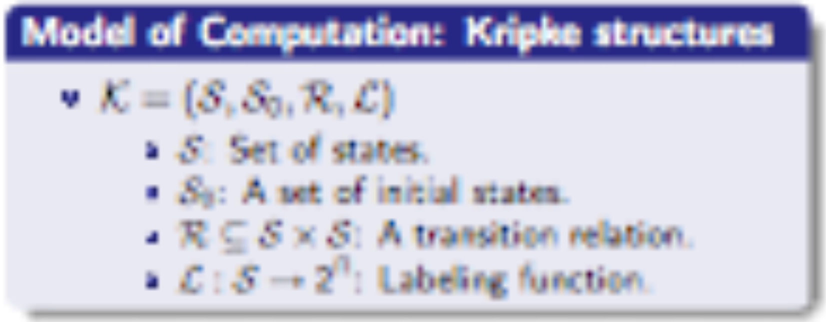
- These algorithms work only for very simple specifications, e.g., ***Eventually*** *reach the goal,* ***always*** *avoiding obstacles*

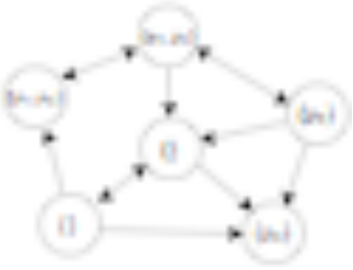
Deterministic Fragment of the modal mu-calculus: Definitions



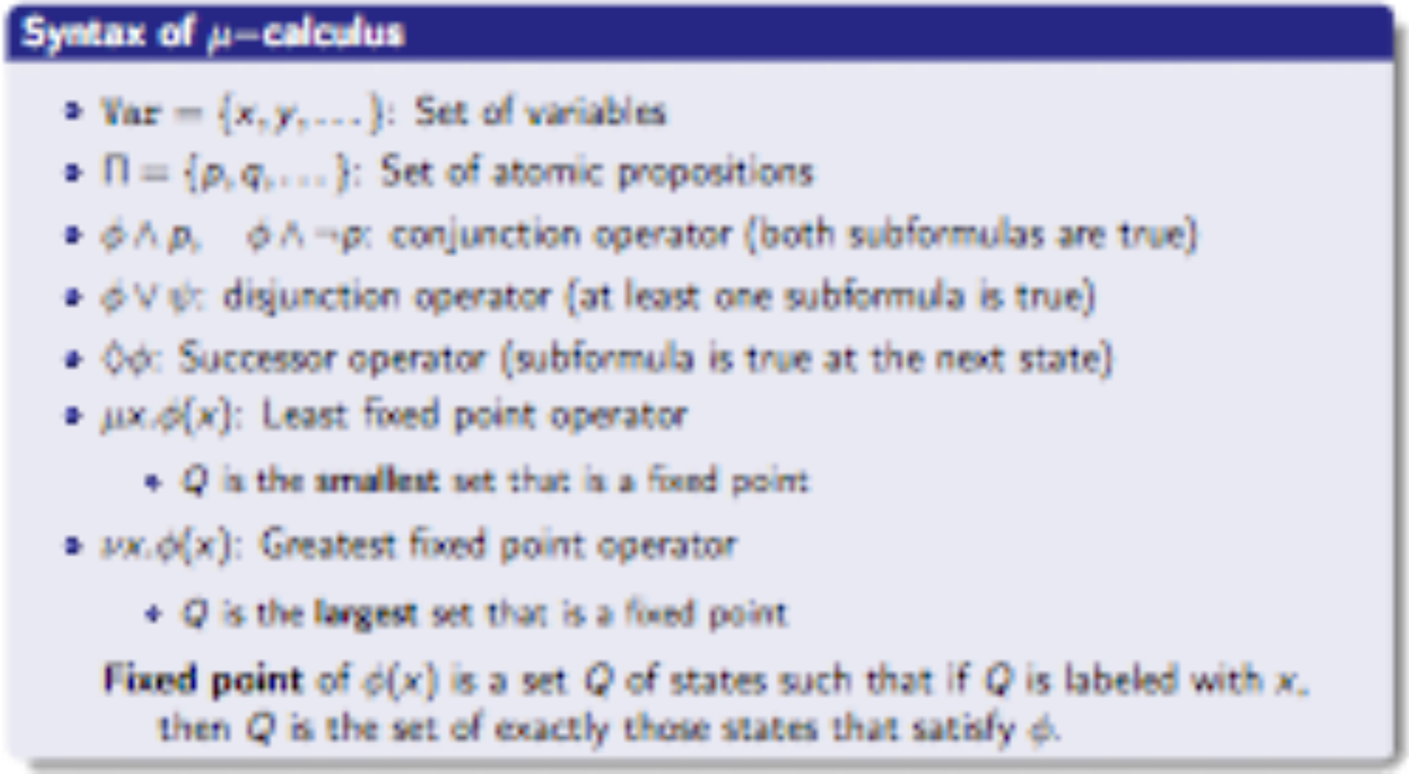
Model of Computation: Kripke structures

- $\mathcal{K} = (\mathcal{S}, \mathcal{S}_0, \mathcal{R}, \mathcal{L})$
  - $\mathcal{S}$: Set of states.
  - $\mathcal{S}_0$: A set of initial states.
  - $\mathcal{R} \subseteq \mathcal{S} \times \mathcal{S}$: A transition relation.
  - $\mathcal{L} : \mathcal{S} \rightarrow 2^{\Pi}$: Labeling function.

States



Labeling function



Syntax of μ–calculus

- Var = $\{x, y, \ldots\}$: Set of variables
- $\Pi = \{p, q, \ldots\}$: Set of atomic propositions
- $\phi \wedge p$, $\phi \wedge \neg p$: conjunction operator (both subformulas are true)
- $\phi \vee \psi$: disjunction operator (at least one subformula is true)
- $\Diamond\phi$: Successor operator (subformula is true at the next state)
- $\mu x.\phi(x)$: Least fixed point operator
  - Q is the **smallest** set that is a fixed point
- $\nu x.\phi(x)$: Greatest fixed point operator
  - Q is the **largest** set that is a fixed point

Fixed point of $\phi(x)$ is a set Q of states such that if Q is labeled with x, then Q is the set of exactly those states that satisfy ϕ.

Deterministic Fragment of the modal mu-calculus: Examples

- Reachability:
  $\mu x.(p_1 \vee \Diamond x)$

- **Safety**: $\nu x.(\neg q \wedge \Diamond x)$: Always avoid q.
- **Safely reach a region**: $\mu x.(\neg q \wedge (p \vee \Diamond x))$: Reach p, while avoiding q.
- **Reach a safe region**: $\mu x.((\nu y.(p \wedge \Diamond y)) \vee \Diamond x)$: Reach p and stay there thereafter.
- **Ordering**: $\mu x.(p \vee (q \wedge \Diamond x))$: Ensure p until q is attained.
- **Liveness**: $\nu y.\mu x.\Diamond((p \wedge y) \vee x)$: satisfy p infinitely often.

- Deterministic μ–calculus can be used to specify most (all?) meaningful linear-time properties.
- Automated translation is possible from, e.g., LTL.

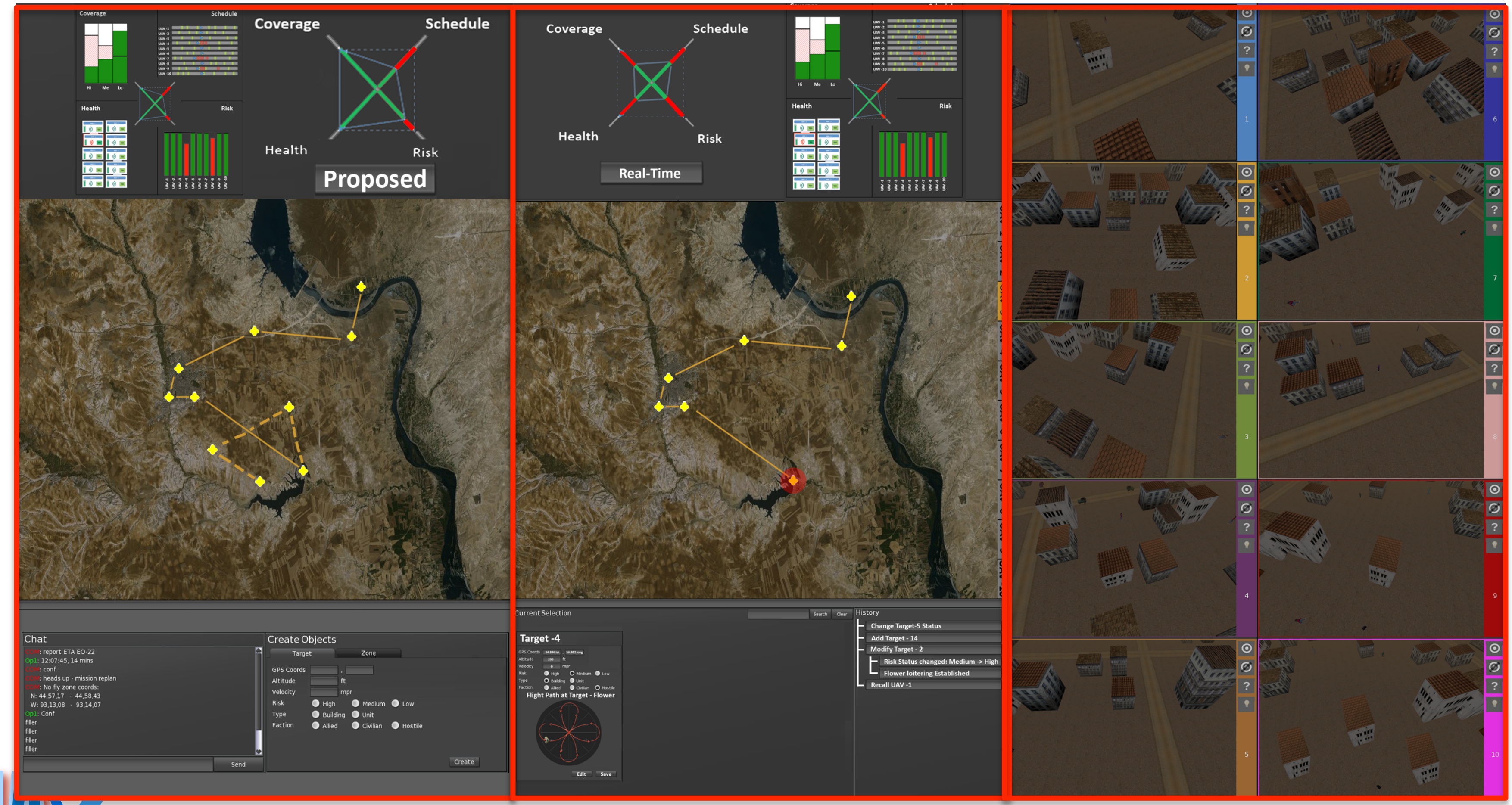
Conclusions

- Incremental sampling methods provide a very attractive class of algorithms for real-time motion planning applications, such as autonomous vehicles and robots.
  - Identified some drawbacks of state-of-the-art algorithms (RRTs) in terms of trajectory optimality.
  - New algorithms, such as RRG and RRT*, can provide asymptotically optimal trajectories at a minimal computational overhead on RRT (O(1)).
  - Algorithms such as RRG can also be used for real-time motion planning with temporal/logic specifications: in fact, it turns out that motion planning with μ-calculus specifications is not much harder than "standard" motion planning.
- Some current directions in this area:
  - Optimal planning with temporal/logic specifications.
  - Extensions to reactive cases
  - Extensions to differential games (e.g., pursuit-evasion games).
  - Extensions to cooperative control problems.

Overall Display Suite

(work in progress)

Re-planning　　Map and Mission Health　　UAV Video Feeds



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filler
filler
filler
filler

- Change Target-5 Status
- Add Target - 14
- Modify Target - 2
  - Risk Status changed: Medium -> High
  - Flower loitering Established
- Recall UAV -1

Next Steps

- Display suite will be finalized in August
- Pilot study on the effectiveness of the display suite will be conducted towards the end of August
- Iterative refinement of the displays will be performed based on findings from pilot study
- Final large-scale simulation study on re-planning and timesharing performance planned for Fall 2010

Logistical Updates

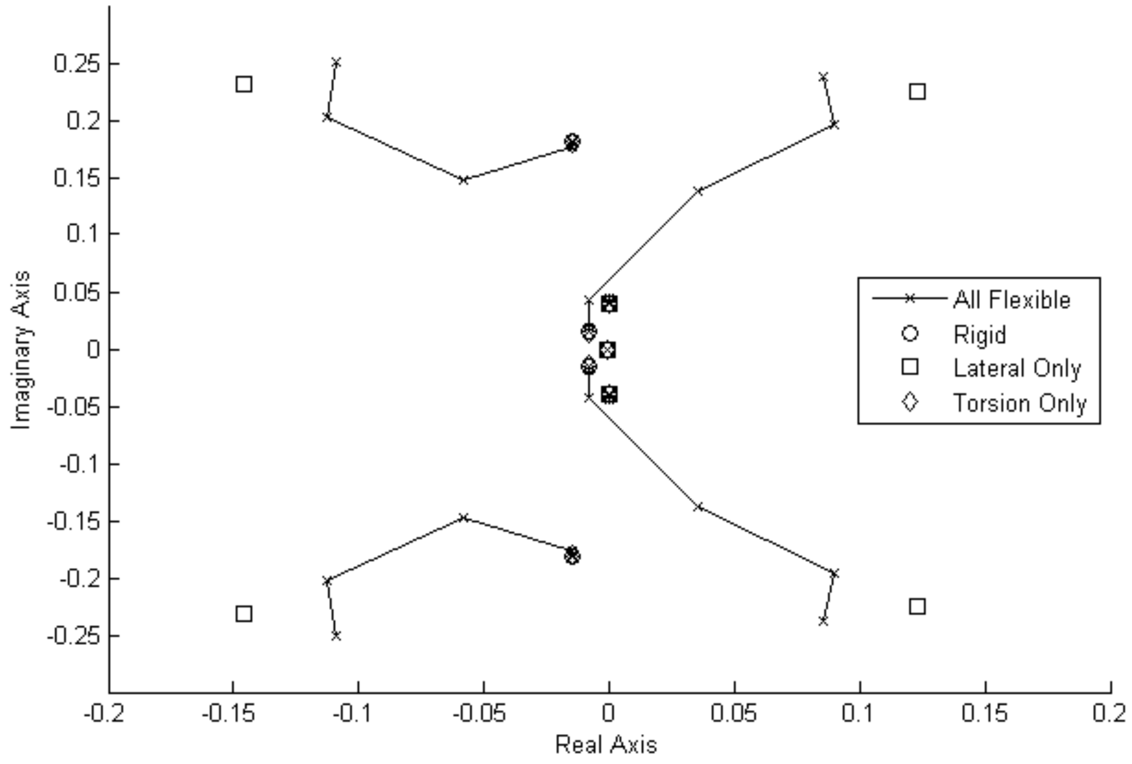
- Luca and Ketan co-chaired invited session at American Control Conference in Baltimore, June 30-July 02, 2010
  - “Human-in-the-loop control systems”
  - Attendees: Princeton, Michigan, MIT, BU, UCSB
  - Session proposal and overall session received **very positive** reviews

ACC
2010 – Baltimore

- Luca and Ketan will be co-teaching course on cooperative control at MIT in the fall of 2010
  - First time course offering at MIT that incorporates together vehicle routing, queueing models, and human supervisory control

Sample Study: Effect of Flexibility on Vehicle Stability

- Linearize EOMs about trim states
- Examine how rigid-body mode eigenvalues vary with stiffness
- Two additional cases: pure lateral bending and pure torsion



Lateral bending DOF responsible for unstable roll-spiral mode

Next Year – Research Plan:

1. Our ROM works well for low frequency (< 500 Hz) control applications:

   flight dynamics, vehicle bending

2. Integrate propulsion ROM into the flexible hypersonic vehicle ROM
3. Continue interaction with P. Friedmann – uncertainty analysis
4. Run CFD++ for high frequency (> 500 Hz) engine unstart
5. To model unstart with ROM: develop a POD set of "snapshot" CFD solutions

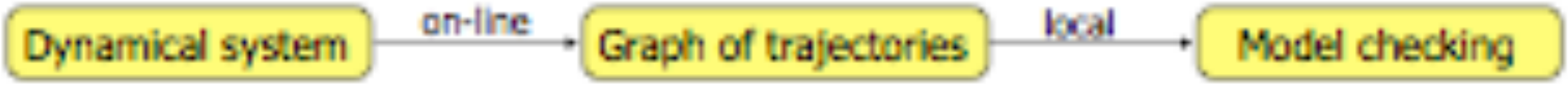
   for the isolator shock-boundary layer interaction

6. Add unsteady terms to our ROM to model unstart
7. Continue our leveraged experiments (DoD funding) for true validation

Sampling-based algorithms for temporal logic specifications

- IDEA: Combine
  - on-line sampling for dynamics discretization
  - incremental (local) model checking

- Use deterministic μ-calculus as underlying formal language:
  - Most expressive language for ω-regular properties
  - Det. μ-calculus models LTL (via exponential reduction), or interesting fragments of LTL (via polynomial reduction)
  - Det. μ-calculus can be efficiently checked incrementally, in polynomial time



Dynamical system

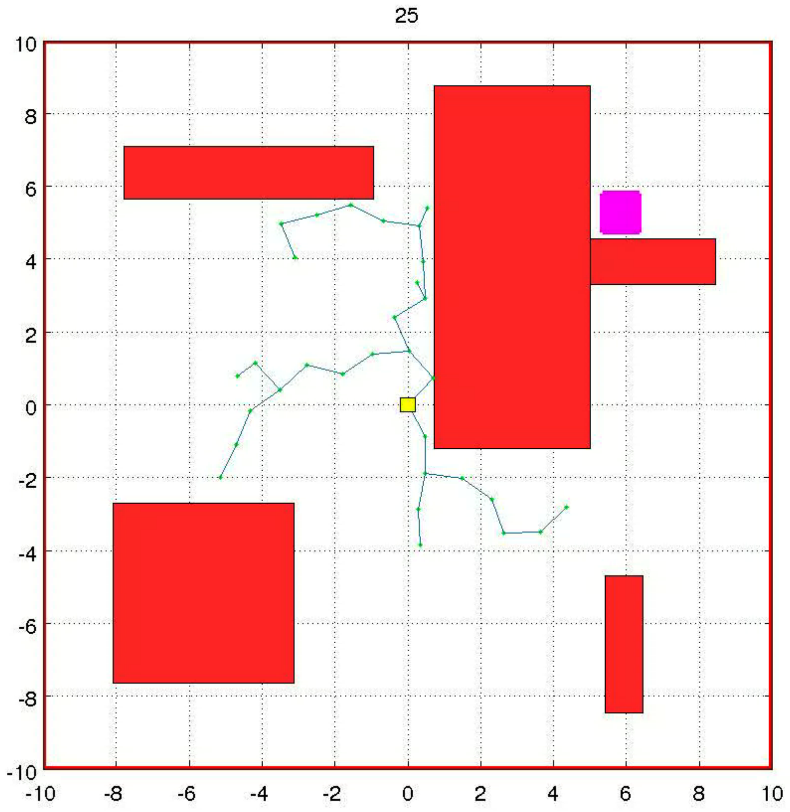
on-line

Graph of trajectories

local

Model checking

RRT* Simulations




Cost of the best path


Variance of the solution

- RRT is shown in RED, RRT* is shown in BLUE.


Relative computational cost

- RRT* provably converges to globally optimal solutions, with essentially the same computational complexity as RRT