Hybrid Control Synthesis
Real-Time Control Problems for UAV

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Problem: Design of Intelligent Control Architectures for Distributed Multi-Agent Systems

• An architecture design problem for a distributed system begins with specified safety and efficiency objectives for each of the system missions (surveillance, reconnaissance, combat, transport) and aims to characterize control, observation and communication.
  – Mission and task decomposition among different agents
  – Inter-agent and agent—mother ship coordination
  – Continuous control and mode switching logic for each agent
  – Fault management

• This research attempts to develop fundamental techniques, theoretical understanding and software tools for distributed intelligent control architectures with a model UAV as an example.
Fundamental Issues for Multi-Agent Systems

- Central control paradigm breaks down when dealing with distributed multi-agent systems
  - Complexity of communication, real-time performance
  - Risk of single point failure
- Completely decentralized control
  - Has the potential to increase safety, reliability and speed of response
  - But lacks optimality and presents difficulty in mission and task decomposition
- Real-world environments
  - Complex, spatially extended, dynamic, stochastic and largely unknown
- We propose a hierarchical perception and control architecture
  - Fusion of the central control paradigm with autonomous intelligent systems
  - Hierarchical or modular design to manage complexity
  - Inter-agent and agent–ship coordination to achieve global performance
  - Robust, adaptive and fault tolerant hybrid control design and verification
  - Vision-based control and navigation (to be covered in research but not central focus of this grant)
Autonomous Control of Unmanned Air Vehicles

- **UAV missions**
  - Surveillance, reconnaissance, combat, transport

- **Problem characteristics**
  - Each UAV must switch between different modes of operation
    - Take-off, landing, hover, terrain following, target tracking, etc.
    - Normal and faulted operation
  - Individual UAVs must coordinate with each other and with the mothership
    - For safe and efficient execution of system-level tasks: surveillance, combat
    - For fault identification and reconfiguration
  - Autonomous surveillance, navigation and target tracking requires feedback coupling between hierarchies of observation and control
Research Objectives: Design and Evaluation of Intelligent Control Architectures for Multi-agent Systems such as UAVs

Research Thrusts

- Intelligent control architectures for coordinating multi-agent systems
  - Decentralization for safety, reliability and speed of response
  - Centralization for optimality
  - Minimal coordination design
- Verification and design tools for intelligent control architectures
  - Hybrid system synthesis and verification (deterministic and probabilistic)
- Perception and action hierarchies for vision-based control and navigation
  - Hierarchical aggregation, wide-area surveillance, low-level perception

Experimental Testbed

- Control of multiple coordinated semi-autonomous BEAR helicopters
Methods

- **Formal Methods**
  - Hybrid systems (continuous and discrete event systems)
    - Modeling
    - Verification
    - Synthesis
  - Probabilistic verification
  - Vision-based control

- **Semi-Formal Methods**
  - Architecture design for distributed autonomous multi-agent systems
  - Hybrid simulation
  - Structural and parametric learning
  - Real-time code generation
  - Modularity to manage:
    - Complexity
    - Scalability
    - Expansion
Hybrid Multiagent Control Architectures

- **Coordinated multi-agent system**
  - Missions for the overall system: surveillance, combat, transportation
  - Limited centralized control
    - Individual agents implement individually optimal (linear, nonlinear, robust, adaptive) controllers and coordinate with others to obtain global information, execute global plan for surveillance/combat, and avoid conflicts
  - Mobile communication and coordination systems
    - Time-driven for dynamic positioning and stability
    - Event-driven for maneuverability and agility

- **Research issues**
  - Intrinsic models
  - Supervisory control of discrete event systems
  - Hybrid system formalism
UAV Control Architecture

- Mission Planning
- Resource Allocation

Strategic Objective

- Generating Trajectory Constraints
- Fault Management

Trajectory Constraints

Tactical Layer

- Flight Mode Switching
- Trajectory Planning

Trajectory

Regulation Layer

- Trajectory Tracking
- Set Point Control

Actuator Commands

UAV Dynamics

- Replan

Sensor Info on Targets, UAV’s

Inter-UAV Coordination

Environmental Sensors

Tracking errors
Preliminary Control Architecture for Coordinating UAVs

- **Regulation Layer** (fully autonomous)
  - Control of UAV actuators in different modes: stabilization and tracking

- **Tactical Layer** (fully autonomous)
  - Safe and efficient trajectory generation, mode switching
  - **Strategic Layer** (semi-autonomous)
  - Generating trajectory constraints and influencing the tasks of other agents using UAV-UAV coordination for efficient
    - Navigation, surveillance, conflict avoidance
  - Fault management
  - Weapons configuration

- **Mission Control Layer** (centralized)
  - Mission planning, resource allocation, mission optimization, mission emergency response, pilot interface
The conceptual underpinning for intelligent multi-agent systems is the ability to verify sensory-motor hierarchies perform as expected

- **Difficulties with existing approaches:**
  - Model checking approaches (algorithms) grow rapidly in computational complexity
  - Deductive approaches are ad-hoc

- **We are developing hybrid control synthesis approaches that solve the problem of verification by deriving pre-verified hybrid system.**
  - These algorithms are based on game-theory, hence worst-case safety criterion
  - We are in the process of relaxing them to probabilistic specifications.
Symbolic Model Checking

Continuous Complexity

Finite Automata
- Binary Decision Diagrams
  - SMV [Clarke & McMillan]
    - 1990 -

Timed Automata
- Difference Bound Matrices
  - Kronos Uppaal [Sifakis & Larsen]
    - 1993 -

Linear Hybrid Automata
- Polyhedral Constraints
  - HyTech 1995 -

Discrete Complexity

Automata

Hybrid Systems

Dynamical Systems

Continuous Complexity

Dynamical Systems

Hybrid Systems

Discrete Complexity

Automata
HyTech [Henzinger, Ho & Wong-Toi]

Hybrid System

Approximation

Product of linear hybrid automata with parameters (e.g., cut-off values)

Requirement Specification

Formula of temporal logic

HyTech:

Disjunctive linear programming

Parameter values for system satisfies requirements
HyTech

- Applications of HyTech
  - Automative (engine control [Villa], suspension control [Muller])
  - Aero (collision avoidance [Tomlin], landing gear control [Najdm-Tehrani])
  - Robotics [Corbett], chemical plants [Preussig]
  - Academic benchmarks (audio control, steam boiler, railway control)

- Improvements necessary for next level
  - Approximate and probabilistic, instead of exact analysis
  - Compositional and hierarchical, instead of global analysis
  - Semialgorithmic and interactive, instead of automatic analysis
Hybrid Control Synthesis and Verification

• Approach
  – The heart of the approach is not to verify that every run of the hybrid system satisfies certain safety or liveness parameters, rather to ensure critical properties are satisfied with a certain safety critical probability

• Design Mode Verification (switching laws)
  – To avoid unstable or unsafe states caused by mode switching (takeoff, hover, land, etc.)

• Faulted Mode Verification (detection and handling)
  – To maintain integrity and safety, and ensure gradual degraded performance

• Probabilistic Verification (worst case vs. the mean behavior)
  – To soften the verification of hybrid systems by rapprochement between Markov decision networks
Controller Synthesis for Hybrid Systems

- The key problem in the design of multi-modal or multi-agent hybrid control systems is a synthesis procedure.

- Our approach to controller synthesis is in the spirit of controller synthesis for automata as well as continuous robust controller synthesis. It is based on the notion of a game theoretic approach to hybrid control design.

- Synthesis procedure involves solution of Hamilton Jacobi equations for computation of safe sets.

- The systems that we apply the procedure to may be proven to be at best semi-decidable, but approximation procedures apply.

- Latex presentation of synthesis technique goes here.
Research Thrust: Perception and Action Hierarchies

Design a perception and action hierarchy centered around the vision sensor to support surveillance, observation, and control functions

• Hierarchical vision for planning at different levels of control hierarchy
  – Strategic or situational 3D scene description, tactical target recognition, tracking, and assessment, and guiding motor actions

• Control around the vision sensor
  – Visual servoing and tracking, landing on moving platforms
What Vision Can Do for Control

• Global situation scene description and assessment
  – Estimating the 3D geometry of the scene, object and target locations, behavior of the objects
    • Allows looking ahead in planning, anticipation of future events
    • Provides additional information for multi-agent interaction

• Tactical target recognition and tracking
  – Using model-based recognition to identify targets and objects, estimating the motion of these objects
    • Allows greater flexibility and accuracy in tactical missions
    • Provides the focus of attention in situation planning
The control architecture needs

- Task decomposition for each agent
- Inter-agent, agent—mother ship coordination
- Continuous control
- Guided motor action

The vision system provides

- Situation, 3D scene description
- Target recognition
- Object tracking
- Motion detection & optical flow

- Higher-level visual processing: precise, global information, computational intensive
- Lower-level visual processing: local information, fast, higher ambiguity
Research Contributions

• Fundamental Research Contributions
  – Design of hybrid control synthesis and verification tools that can be used for a wide range of real-time embedded systems
  – Design of simulation and verification environments for rapid prototyping of new controller designs
  – Hierarchical vision for planning at different levels of control hierarchy
    • Control around the vision sensor

• Our multi-agent control architecture can be used for many applications
  – Military applications
    • UAVs, simulated battlefield environment, distributed command and control, automatic target recognition, decision support aids for human-centered systems, intelligent telemedical system
  – General engineering applications
    • Distributed communication systems, distributed power systems, air traffic management systems, intelligent vehicle highway systems, automotive control
Research Schedule

FY 99

Intelligent Control Architectures
- Preliminary UAV Architecture
- Generalized Hybrid Systems
- Deterministic Hybrid Probabilistic Verification Control Synthesis Methods

Synthesis Tools
- Ptolemy-based Hybrid Systems
- Probabilistic Verification Theory
- Matlab+SHIFT Simulation Comparison

Simulation Tools
- Performance Evaluation of UAV Architecture
- Probabilistic Synthesis Tools
- Synthesis+Verification Environment

Public Tests
- Robotic Helicopter Competition
- Cal Day Demo

FY 00

Final UAV Architecture
- Cal Day Demo
- Robotic Helicopter Competition

- MatLab + SHIFT Simulation Comparison

- Probabilistic Verification Theory
- Probabilistic Synthesis Tools
- Synthesis + Verification Environment
## Deliverables

<table>
<thead>
<tr>
<th>Task</th>
<th>Duration</th>
<th>Deliverables</th>
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<tr>
<td><strong>Intelligent Control Architectures (SSS)</strong></td>
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<tr>
<td>Specification Tools</td>
<td>8/98 - 11/98</td>
<td>software, technical reports</td>
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<tr>
<td>Design Tools</td>
<td>8/98 - 9/99</td>
<td>software, technical reports</td>
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<tr>
<td>Architecture Evaluation Environment</td>
<td>8/98 - 12/00</td>
<td>software, technical reports</td>
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<tr>
<td>UAV Application</td>
<td>8/98 - 8/00</td>
<td>experiments, technical reports</td>
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<td><strong>Synthesis Toolkit (SSS, TAH)</strong></td>
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<td>Design Mode Verification</td>
<td>8/98 - 7/99</td>
<td>software, technical reports</td>
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<tr>
<td>Faulted Mode Verification</td>
<td>1/99 - 12/99</td>
<td>software, technical reports</td>
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<tr>
<td>Probabilistic Verification</td>
<td>9/98 - 9/99</td>
<td>software, technical reports</td>
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<td><strong>Simulation Toolkit (EAL)</strong></td>
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<td>Generalized Hybrid systems</td>
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<td>Matlab + SHIFT comparison</td>
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<td>Synthesis + Verification environment</td>
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Expected Accomplishments

• **Controller synthesis for hybrid systems.**
  Developed algorithms and computational procedures for designing verified hybrid controllers optimizing multiple objectives

• **Multi-agent decentralized observation problem.**
  Designed inter-agent communication scheme to detect and isolate distinguished events in system dynamics

• **SmartAerobots. 3D virtual environment simulation.**
  Visualization tool for control schemes and vision algorithms—built on top of a simulation based on mathematical models of helicopter dynamics
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