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DARPA SEC KICKOFF
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- **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.**

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- **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)**

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- **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**

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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

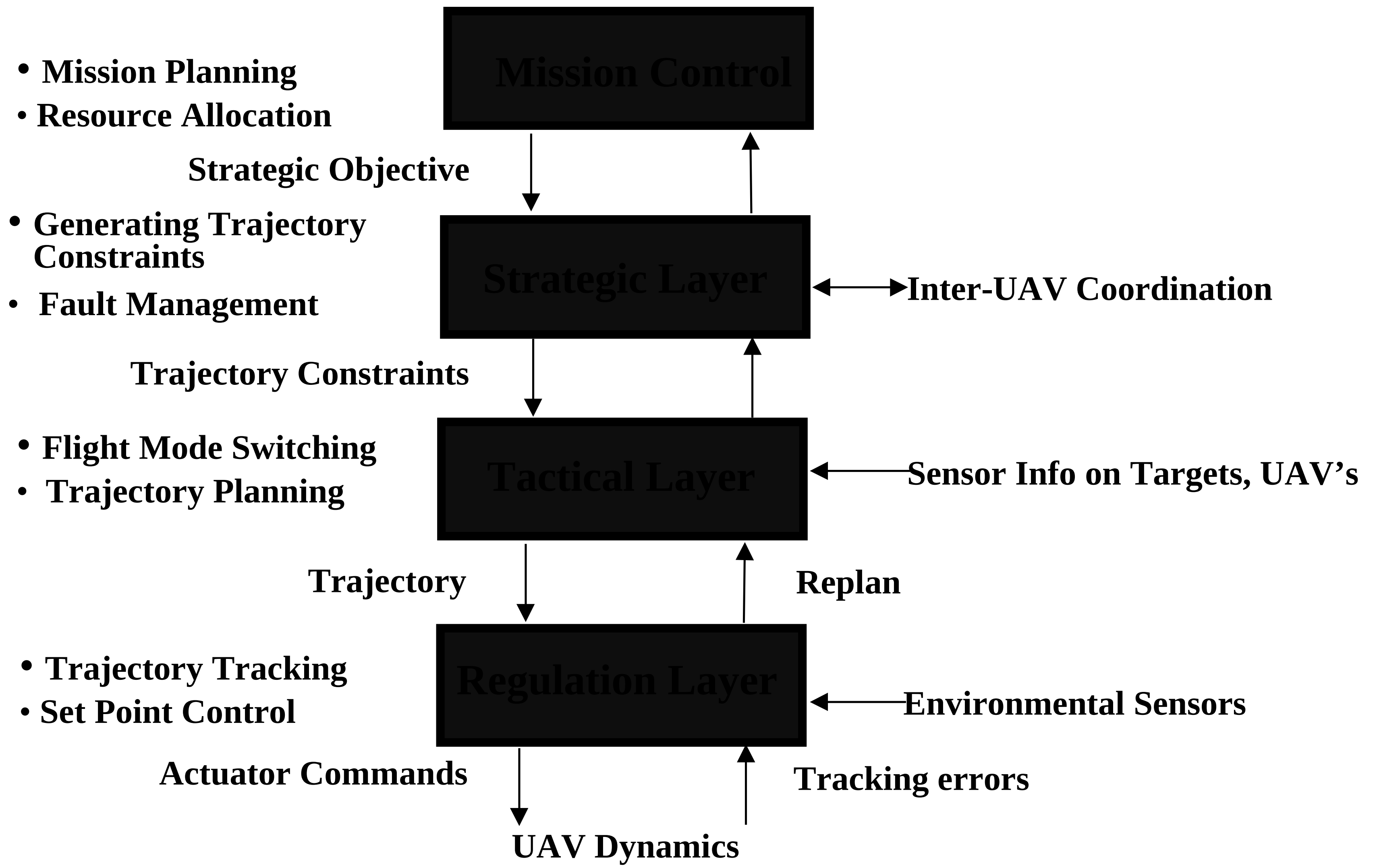
- **Formal Methods**
  - **Hybrid systems (continuous and discrete event systems)**
    - **Modeling**
    - **Verification**
    - **Synthesis**
  - **Probabilistic verification**
  - **Vision-based control**

- **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



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**

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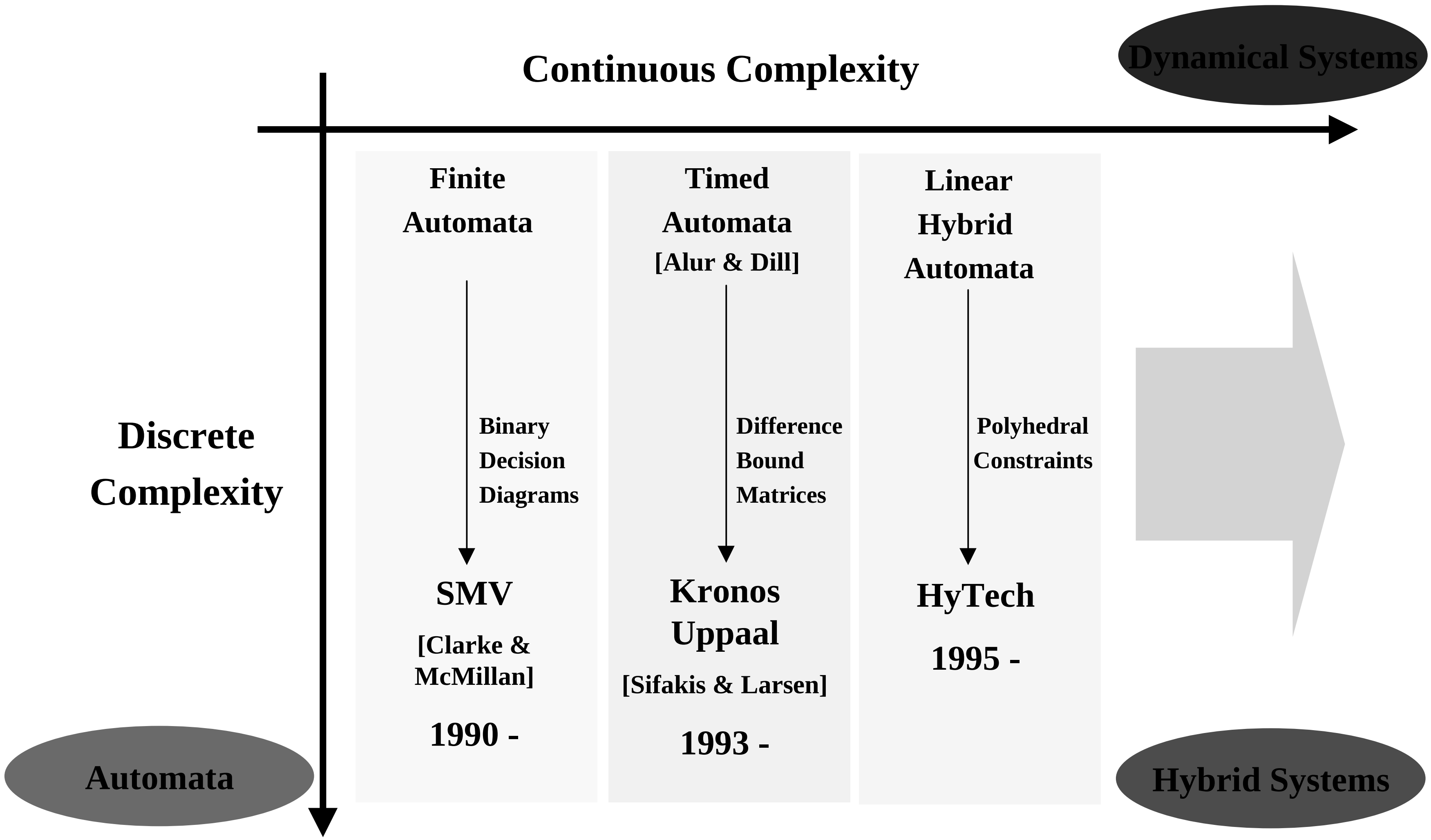
The conceptual underpinning for intelligent multi-agent systems is the ability to verify sensory-motor hierarchies perform as expected

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

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

Symbolic Model Checking



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Hybrid System

Approximation

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

Requirement Specification

Formula of temporal logic

HyTech:

Disjunctive linear programming

Parameter values for system satisfies requirements

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- **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**

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- **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.**

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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**

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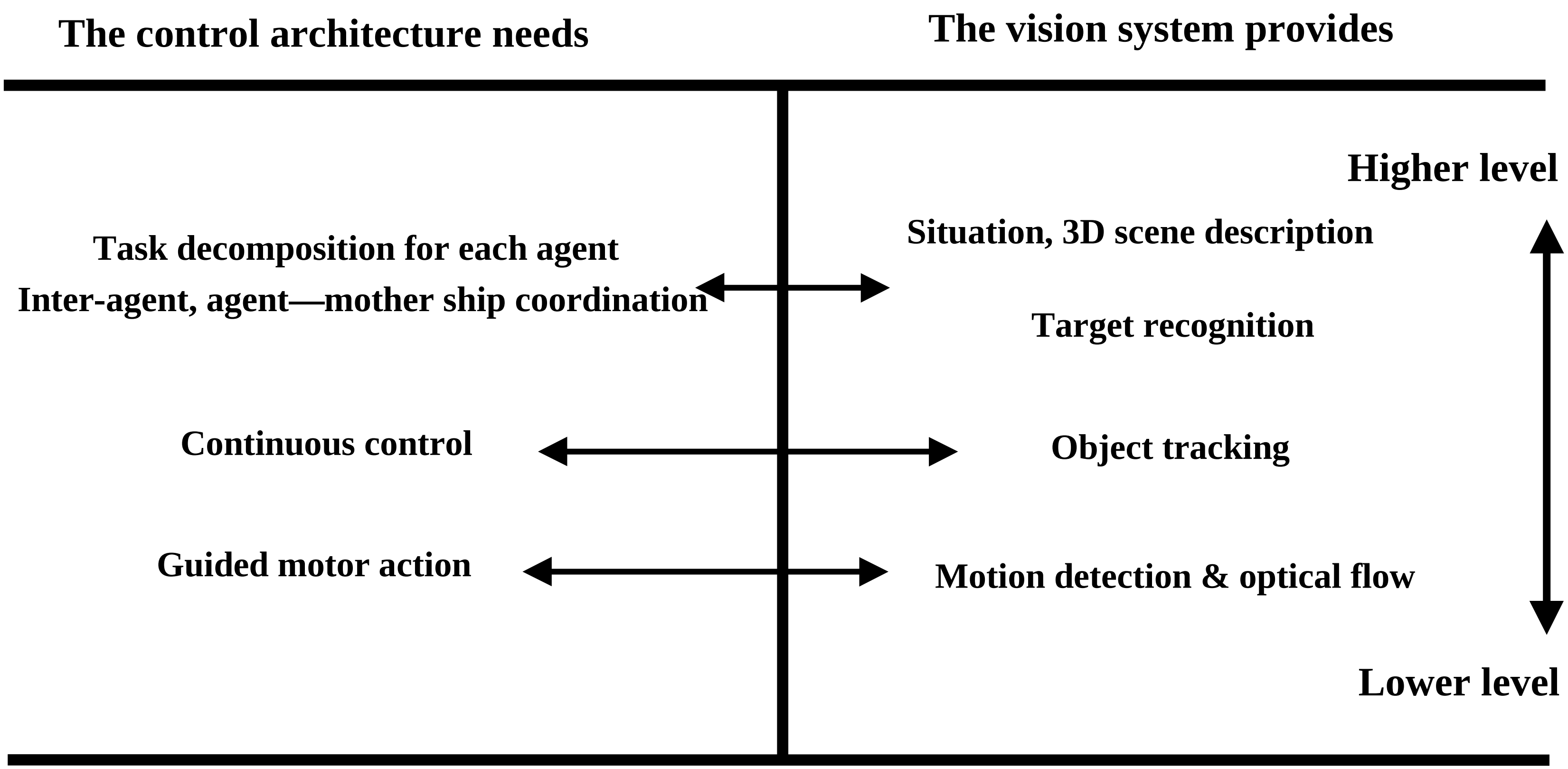
- **Global situation scene description and assessment**
  - **Estimating the 3D geometry of the scene, object and target locations, behavior of the objects**
    - **Allows looking ahead in planning, anticipation of future events**
    - **Provides additional information for multi-agent interaction**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

Relation between Control and Vision



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

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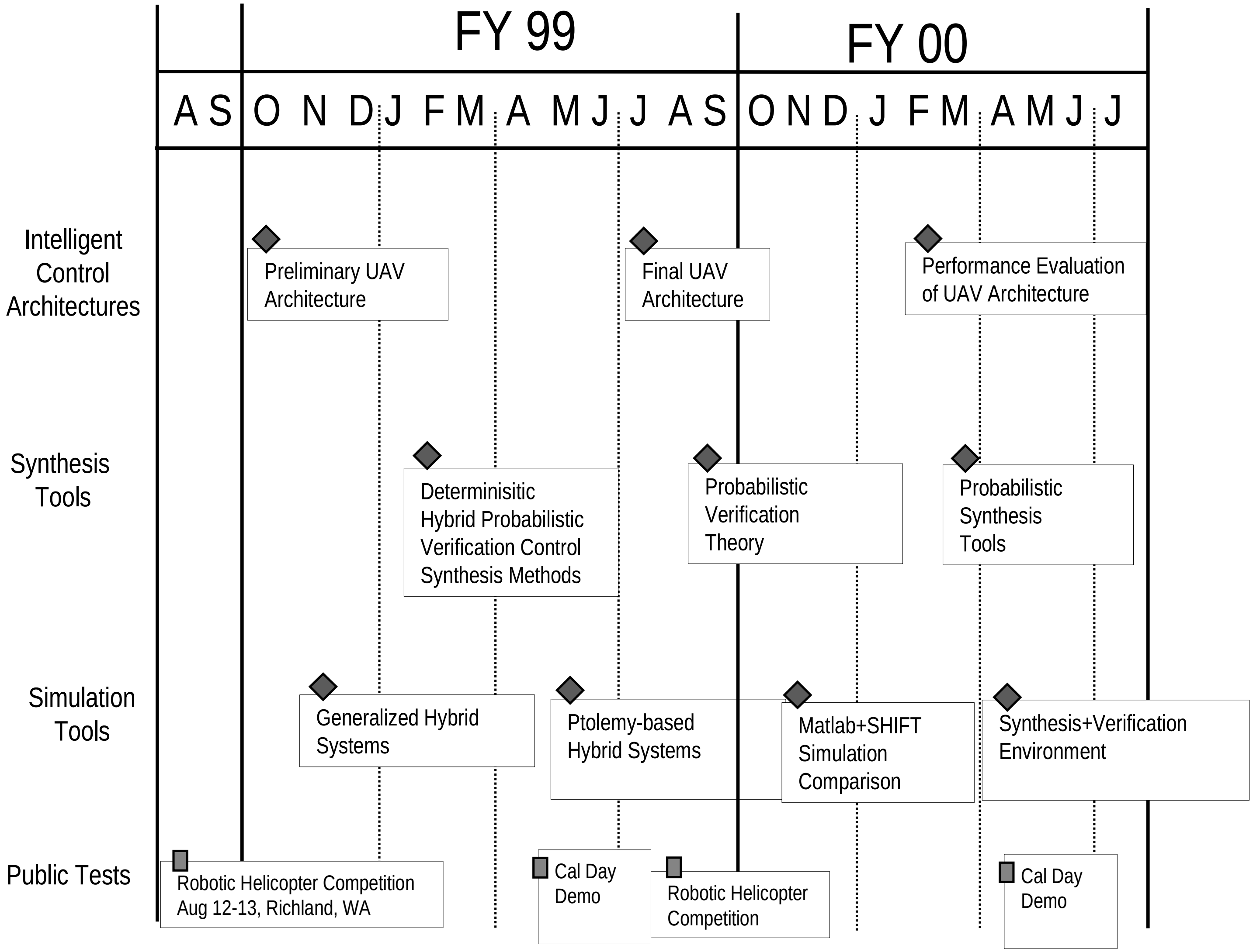
- **Fundamental Research Contributions**
  - **Design of hybrid control synthesis and verification tools that can be used for a wide range of real-time embedded systems**
  - **Design of simulation and verification environments for rapid prototyping of new controller designs**
  - **Hierarchical vision 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



Deliverables

Task	Duration	Deliverables
Intelligent Control Architectures (SSS)		
Specification Tools	8/98 - 11/98	software, technical reports
Design Tools	8/98 - 9/99	software, technical reports
Architecture Evaluation Environment	8/98- 12/00	software, technical reports
UAV Application	8/98 - 8/00	experiments, technical reports
Synthesis Toolkit (SSS, TAH)		
Design Mode Verification	8/98 - 7/99	software, technical reports
Faulted Mode Verification	1/99- 12/99	software, technical reports
Probabilistic Verification	9/98 - 9/99	software, technical reports
Simulation Toolkit (EAL)		
Generalized Hybrid systems	8/98 - 12/98	technical reports, software
Ptolemy based hybrid systems	8/98- 8/99	software
Matlab + SHIFT comparison	8/98-8/00	technical reports, software
Synthesis + Verification environment	8/99 -8/00	software

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- **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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