

**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**

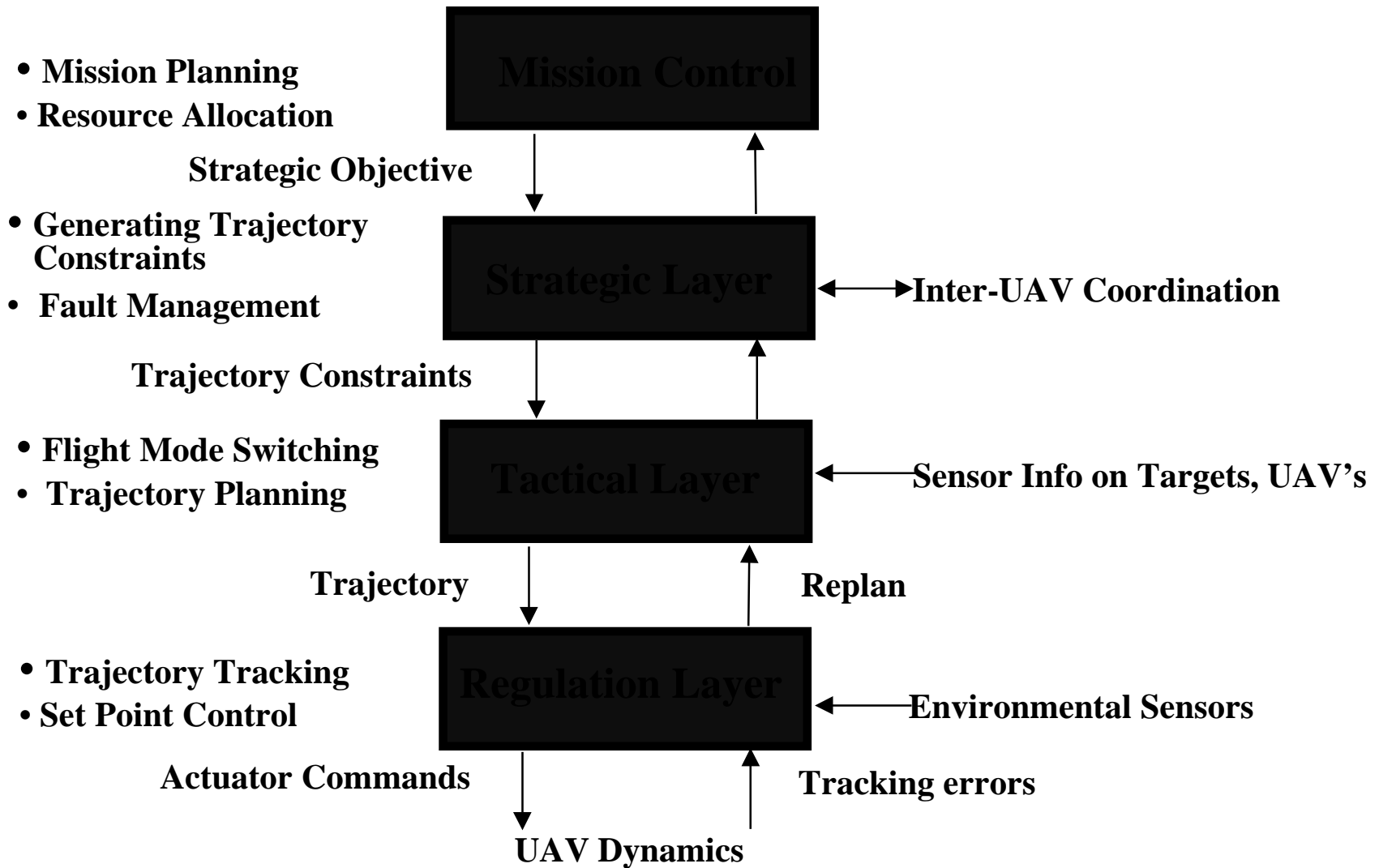
- **Semi-Formal Methods**

- **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/combata, 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

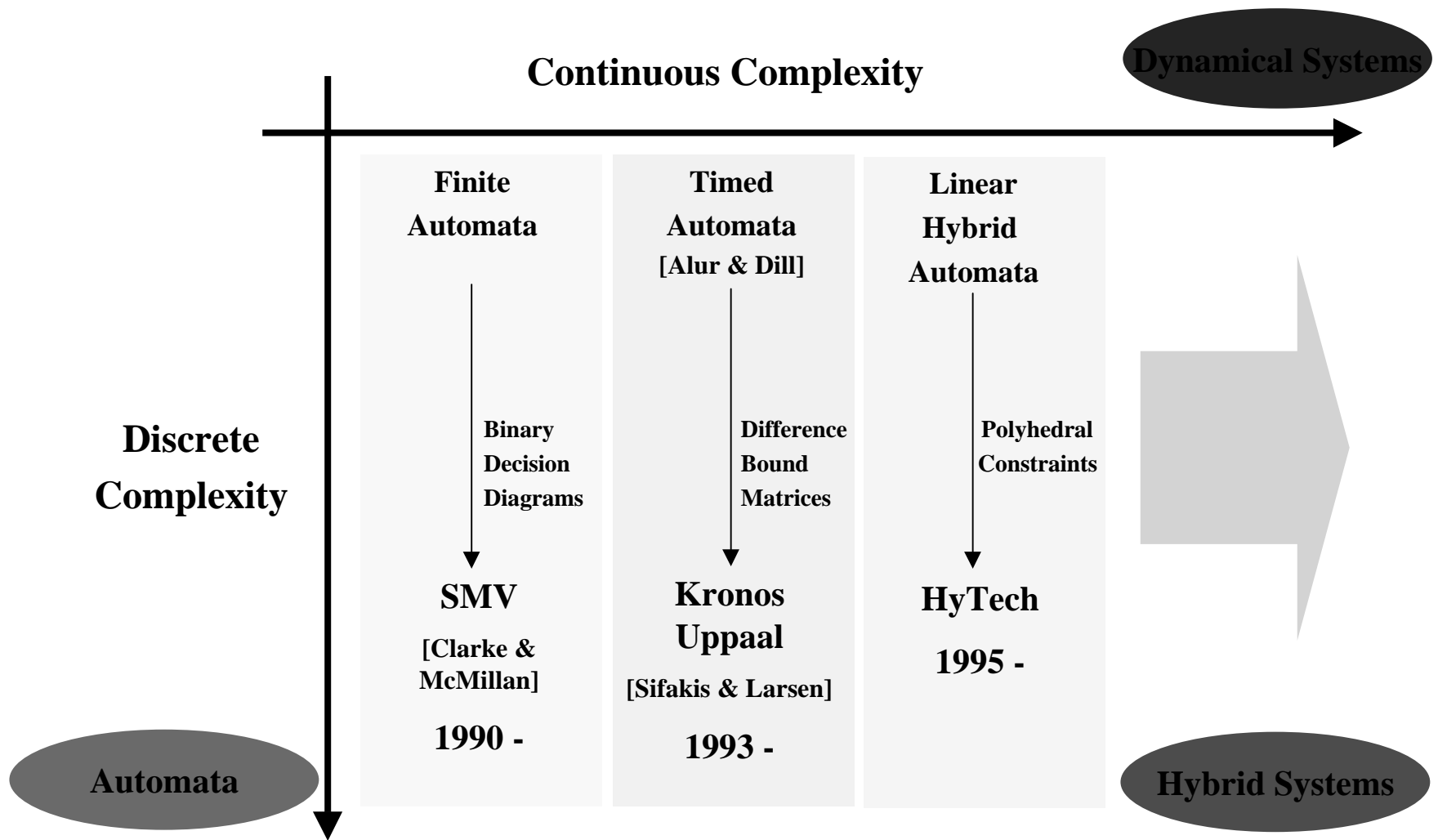
- **Regulation Layer (fully autonomous)**
 - **Control of UAV actuators in different modes: stabilization and tracking**
- **Tactical Layer (fully autonomous)**
 - **Safe and efficient trajectory generation, mode switching**
 - **Strategic Layer (semi-autonomous)**
 - **Generating trajectory constraints 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**

Research Thrust : Verification and Design Tools

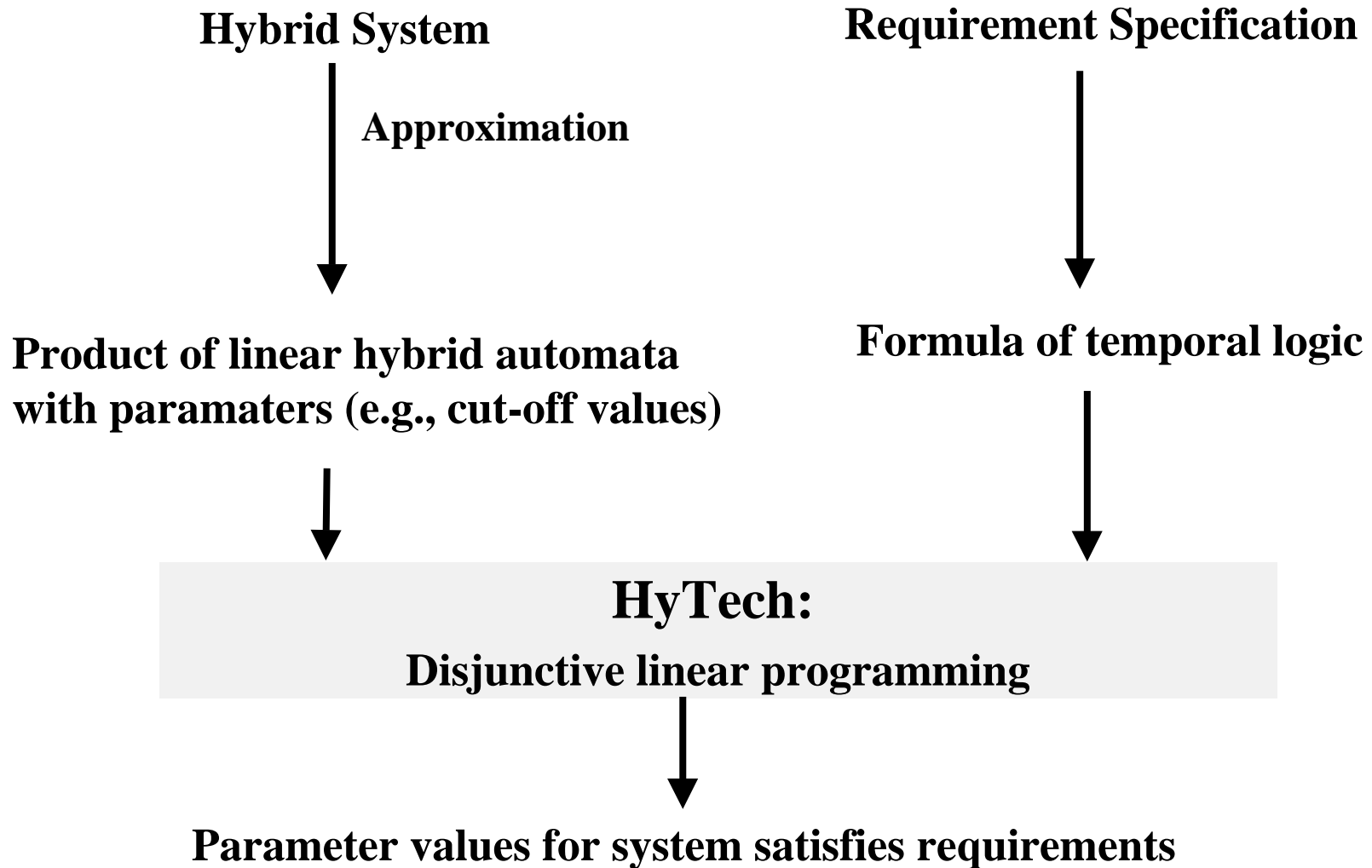
The conceptual underpinning for intelligent multi-agent systems is the ability to verify sensory-motor hierarchies perform as expected

- **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



HyTech [Henzinger, Ho & Wong-Toi]



HyTech

- **Applications of HyTech**
 - **Automotive (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**

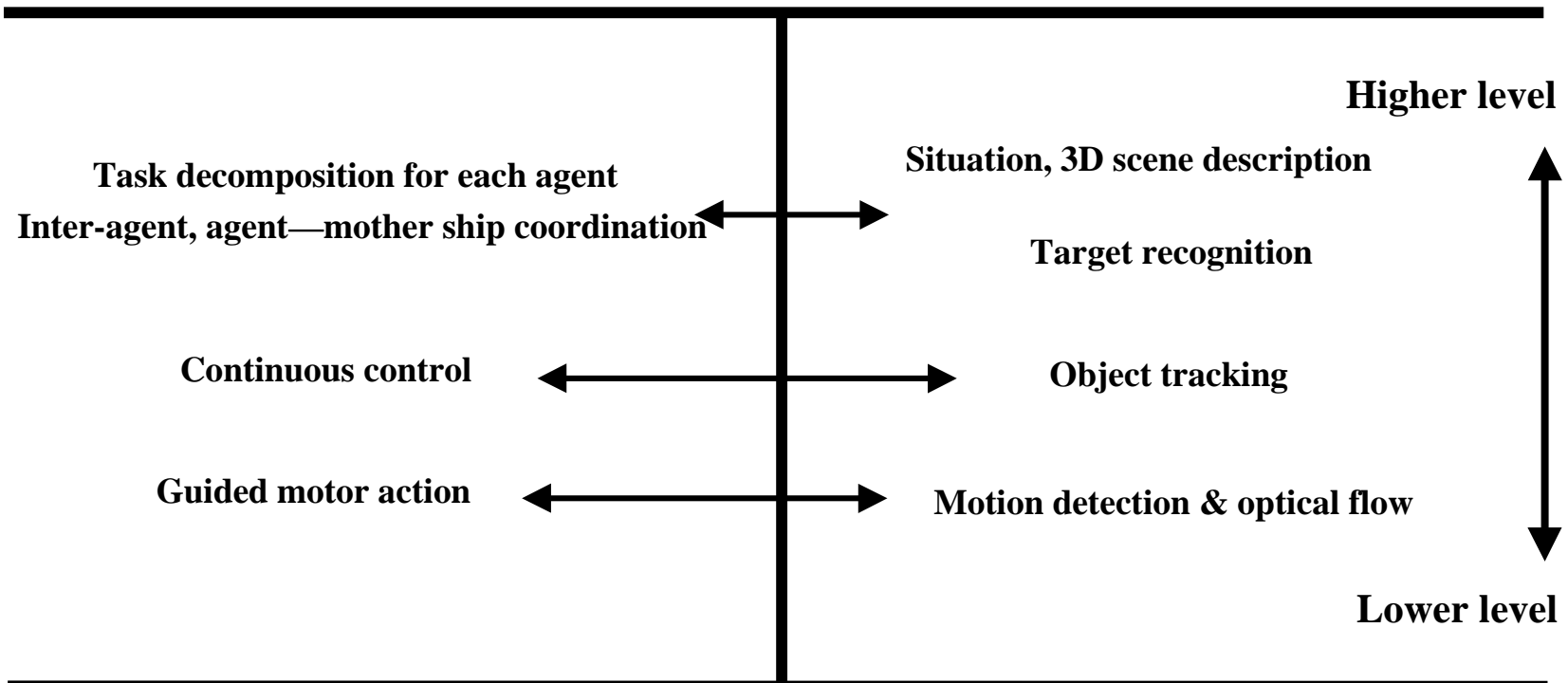
What Vision Can Do for Control

- **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**

Relation between Control and Vision

The control architecture needs

The vision system provides



- **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

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

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

Berkeley Team

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