PROPOSAL
IN RESPONSE TO DARPA BAA-98-08

Part A: Research Category: Autonomy

Real-time Cooperative Behavior for Tactical Mobile Robot Teams

Submitted by
The Georgia Tech Research Corporation and
The Honeywell Technology Center

December 10, 1997

Georgia Institute of Technology

Technical Point of Contact:	Administrative Point of Contact:
Prof. Ronald C. Arkin	Mr. Christoper D'Urbano
College of Computing	Office of Contract Administration
Georgia Institute of Technology	Georgia Institute of Technology
Atlanta, Georgia 30332	Atlanta, Georgia 30332
email: arkin@cc.gatech.edu	email: Christoper.DUrbano@oca.gatech.edu
Fax: (404) 894-9846	Fax: (404) 894-6956
Phone: (404) 894-1634	Phone: (404) 894-4817

Honeywell Technology Center

Technical Point of Contact:	Administrative Point of Contact:
Steve Vestal	Bob Owen
Honeywell Technology Center	Honeywell Technology Center
3660 Technology Drive	3660 Technology Drive
Minneapolis, MN 55418	Minneapolis, MN 55418
email: vestal@htc.honeywell.com	email: Bob_Owen@htc.honeywell.com
Fax: (612) 951-7438	Fax: (612) 951-7438
Phone: (612) 951-7599	Phone: (612) 951-7474

TYPE OF BUSINESS (Prime - Georgia Tech): Other Educational
TYPE OF BUSINESS (Subcontract - HTC): Large Business

Budget Totals

FY98:$365,200	FY99:$561,496	FY00:$282,467	TOTAL:$1,209,162

Signature of Authorized Official: ——————————————

Christoper D'Urbano / Georgia Tech

1. Executive Summary

The College of Computing of the Georgia Institute of Technology, the Georgia Tech Research Institute, and Honeywell Corporation are pleased to submit this proposal entitled "Real-time Cooperative Behavior for Tactical Mobile Robot Teams" in response to DARPA BAA 98-08. We propose to develop a revolutionary set of real-time behavioral and communication strategies that will enable autonomous teams of small robots to accomplish complex military missions in dynamic, hostile environments where individual agents may perish and electronic countermeasures may be in effect. We will develop powerful platform-independent robotic control strategies that can be applied to a wide range of robot systems and future military missions, including other programmatic research efforts conducted under this BAA. Using a carefully designed and validated graphical mission specification framework, warfighters will rapidly task their supporting robot teams to perform dangerous recon/pointman duties, map/survey buildings, and conduct urban assaults.

This research directly addresses three of the key problems associated with inserting multiple robot teams in support of SUO: (1) Robust behavior in the face of highly dynamic, time-pressured, and adversarial domains; (2) Efficient and effective multi-robot coordination with low-bandwidth communication; (3) Efficient user interfaces allowing flexible specification of team missions without excessive detail or operator loading.

To address these issues and build practical, robust solutions for multi-robot control in military domains, we propose to develop: *Fault-tolerant multi-robot behaviors*; *Low-bandwidth coordination/communication tools and techniques*; *Compact, reusable mission-specification/user-interface system*; and *Real-time performance analysis and guarantees.*

Our research group at Georgia Tech has been working on multiagent robotic systems since 1990. The proposed research will leverage our extensive experience gained from fielding multiple systems, including: autonomous formation control [11] for two HMMWVs that was demonstrated live to a military audience during the UGV Demo II program; winning multi-robot teams at the AAAI-94 and AAAI-97 mobile robot competitions; and numerous laboratory demonstrations using our 3 Denning and 5 Nomad robots to display results such as team teleautonomy, multiagent mission specification, team communication minimization, formation control, etc.

The Honeywell Technology Center is the corporate R&D center for the world's largest controls company. We have extensive experience in the design, analysis, implementation and verification of distributed real-time reliable computer control systems, and vehicle planning and coordination, guidance, navigation, control. For example, the DARPA-funded Cooperative Intelligent Real-Time Control Architecture (CIRCA) and Distributed CIRCA automatically derive real-time reactive goal-directed control plans guaranteed to preserve system safety. Our DARPA-funded MetaH toolset combines modeling and analysis of performance, reliability and partition security with automatic tailoring of efficient middleware services for embedded computer systems. We are performing advanced simulation and analytic performance studies for Mode-S and STDMA, radio network protocols used by "teams" of aircraft that are cooperating to avoid collision.

As a team, Georgia Tech and HTC offer a long successful track record in both real-time and multiagent robotic systems. We will apply this expertise to develop the following innovative research results for tactical mobile robot teams:

1. A suite of *new fault-tolerant reactive multi-robot group behaviors*, incorporating behavioral characteristics such as stealth, caution, and cooperation in the context of a wide range of military tactics: e.g., bounding overwatch, traveling overwatch, sweep, formation maintenance, enemy contact, screening, ambush, and passage.

2. *Communication minimization and planning for team behaviors.* An important question for robotic teams is how to keep interrobot communications tractable. We have previously demonstrated that team cooperation is possible in the absence of any explicit communication between agents [2] and have quantified performance changes when small amounts of communication are added [10]. The need to minimize communication becomes even more significant as the size of the robotic team increases. We propose to develop new methods for maintaining coherent group activity with minimal explicit information exchange based on animal display behavior [8].

3. *Reusable mission specification system* including team communication protocols. Expanding our existing *MissionLab* multiagent mission specification system [17], developed under DARPA's Real-time and Planning and Control Program with UGV Demo II program as a customer, we propose to develop military-relevant multi-robot missions that can be easily programmed by an average end-user (and verified by rigorous usability testing) that contains a graphical user interface (GUI) and reusable software mission modules. It will also provide a faster-than-real-time simulation capability for mission testing and validation prior to downloading to the robotic team for execution.

4. Sound and predictable *real-time processing and communication* will enable users to maximize mission effectiveness and reliability subject to limited hardware resources. We will integrate real-time performance analysis with *MissionLab* and present analysis results in a way that will help the user tailor specifications to maximize important qualities-of-service (e.g., speed, stealth) subject to limited robot resources. We will provide corresponding run-time services for predictable, adaptive, efficient, dependable real-time processing and communication for cooperative multi-robot teams.

2. Technical Approach

Our technical approach to achieving intelligent cooperative multi-robot battlefield teams is described in this section. We first convey our vision for multi-robot teams, followed by our preliminary work in this area, and then the specific technical approaches for novel real-time robot team behavioral control, mission specification, communication minimization, and real-time resource management.

2.1 Vision

We envision that the nature of military operations in urban terrain (MOUT) can fundamentally change by empowering the personnel in these units with multiple mobile robot assets that extend their ability to perceive and act within the battlefield without increasing their exposure. It is insufficient merely to deploy these assets; they must be controlled and configured in a meaningful way by average soldiers. This is no mean feat, but if this vision is realized it can provide significant force multiplication capabilities and extended reach within the battlespace (force projection). This must be accompanied by feedback and control methods that do not overload the operator of the system and yet can provide uniform control of multiple advanced robotic systems while simultaneously increasing the unit's overall situational awareness. The impact of this system will be manifested in several ways:

- Reactive behavioral configurations for robot teams that support fault-tolerant operations typically found in the battlefield, to increase immunity against electronic countermeasures and individual agent failure.
- Team teleautonomy providing command and control capabilities for entire groups or subgroups of battlefield robots without producing cognitive overload on the operator.
- The ability of a military operator to expand his influence in the battlespace, dynamically controlling in real-time his deployed robotic team assets in a context-sensitive manner. This will be realized through the generation of mission-specific designs created specifically for urban operations that can be readily tailored by an easily trained operator for the situation at hand. These tools will be shown to be effective in the hands of personnel with the skills found in typical warfighting small unit leaders, through the use of visual programming, information hiding, and reusable software components.

2.2 Preliminary Work

We now review our earlier multiagent research funded by the National Science Foundation and DARPA's Real-time Planning and Control Program in support of the Unmanned Ground

Vehicle (UGV) Demo II program. The goal of the NSF project was to understand the impact of communication on the cooperative aspects of robot teams [10]. The goal of the DARPA project was to field a team of robotic scout vehicles for the U.S. Army. At present, scout platoons are composed of four to six manned vehicles equipped with an array of observation and communication equipment. The scouts typically move in advance of the main force, to report on enemy positions and capabilities. We have provided mission specification tools and multi-robot cooperative behaviors including formation control and team teleautonomy in support of these military scouting operations.

2.2.1 Mission Specification for Multi-robot Systems

A pressing problem for the Department of Defense in particular and for robotics in general is how to provide an easy-to-use mechanism for programming teams of robots, making these systems more accessible to the soldier. Toward that end, the *MissionLab* mission specification system has been developed [17]. An agent-oriented philosophy is used as the underlying methodology, permitting the recursive formulation of societies of robots.

A society is viewed as an agent consisting of a collection of either homogeneous or heterogeneous robots. Each individual robotic agent consists of assemblages of behaviors, coordinated in various ways. Temporal sequencing [9] affords transitions between various behavioral states which are naturally represented as a finite state acceptor. Coordination of parallel behaviors can be accomplished via fusion, action-selection, priority, or other means as necessary. These individual behavioral assemblages consist of groups of primitive perceptual and motor behaviors which ultimately are grounded in the physical sensors and actuators of a robot.

An important feature of *MissionLab* is the ability to delay binding to a particular behavioral architecture (e.g., schema-based, MRPL (used in Demo II)) until after the desired mission behavior has been specified. Binding to a particular physical robot also occurs after specification, permitting the design to be both architecture- and robot-independent.

MissionLab's architecture appears on the left of Figure 1. Separate software libraries exist for abstract behaviors, and the specific architectures and robots. The user interacts through a design interface tool (the configuration editor) which permits the visualization of a specification as it is created. The right side of Figure 1 illustrates an example *MissionLab* configuration that embodies the behavioral control system for one of the robots capable of conducting explosive ordnance disposal (EOD) operations that was employed for testing in usability studies. The individual icons correspond to behavior specifications which can be created as needed or preferably reused from an existing repertoire available in the behavioral library. Multiple levels of abstraction are available, which can be targeted to the abilities of the designer, ranging from whole robot teams, down to the configuration description language for a particular behavior, with the higher levels being those easiest to use by the average soldier.

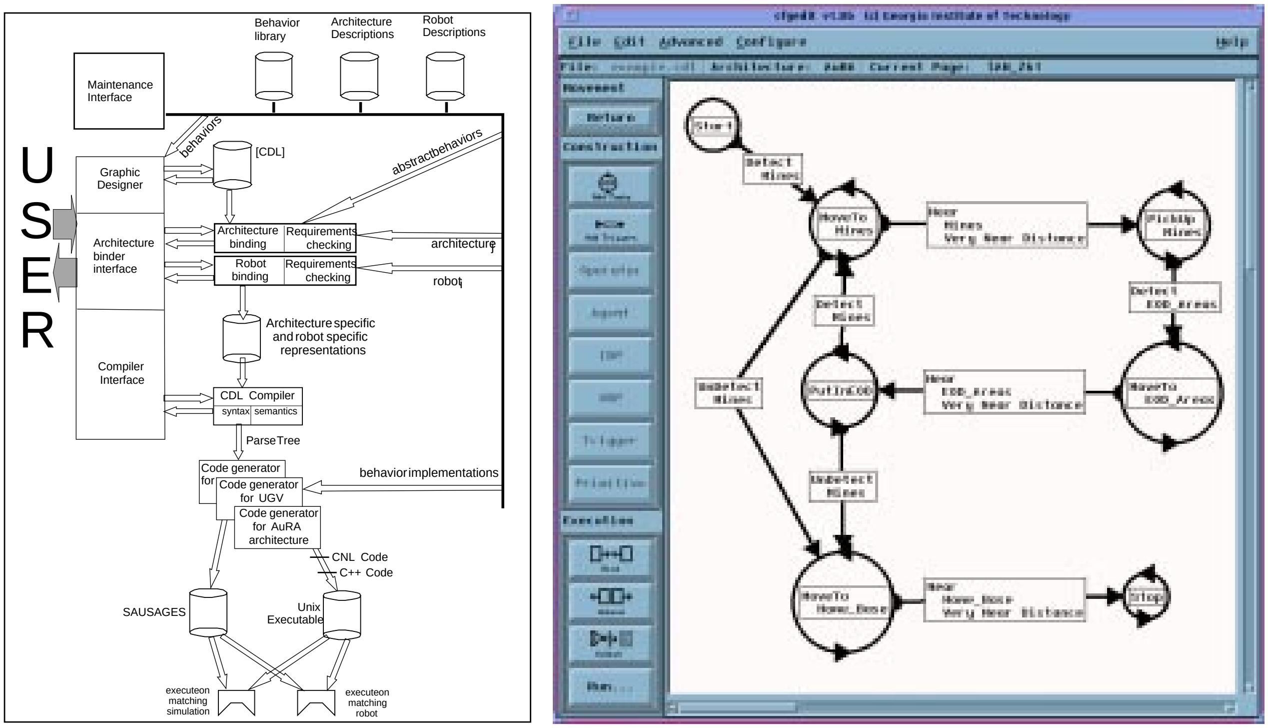


Figure 1: *MissionLab.* (See text for description).

After the behavioral configuration is specified, the architecture and robot types are selected and compilation occurs, generating the robot executables. These can be run within the simulation environment provided by *MissionLab* (Fig. 2 left) or, through a software switch, they can be downloaded to the actual robots for execution (Fig. 2 right). *MissionLab* was demonstrated at UGV Demo C in the Summer of 1995 to military personnel and again at the concluding Demo II workshop in June 1996. *MissionLab* is available via the world-wide web at: http://www.cc.gatech.edu/aimosaic/robot-lab/research/MissionLab.html.

2.2.2 Cooperative Behaviors

Applying mobile robot teams to urban military operations will require robust new cooperative behaviors. Two particularly relevant robotic team behaviors have already been developed and tested in the scouting operations context: formation control and team teleautonomy.

Formation Control: Scout teams use specific formations for a particular task. In moving quickly down roadways for instance, it is often best to follow one after the other. When

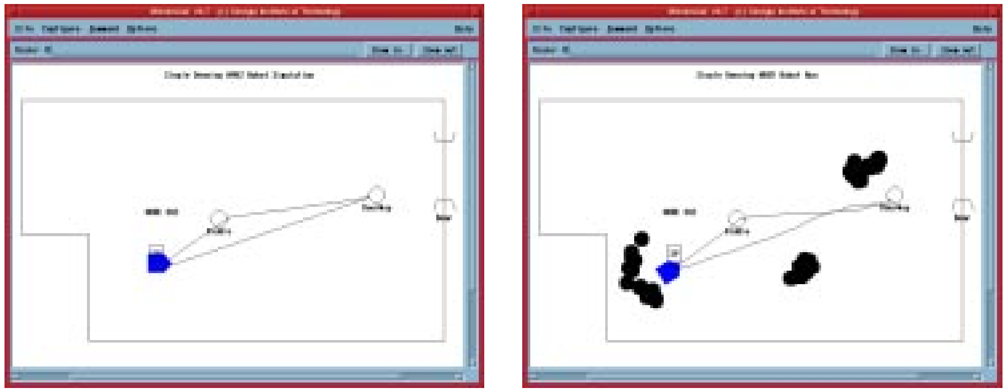


Figure 2: Left: Simulated Run on Denning Robot. Right: The same code executed on actual Denning Robot

sweeping across desert terrain, line-abreast may be better. Furthermore, when scouts maintain their positions, they are able to distribute their sensor assets to reduce overlap. Army manuals [18] list four important formations for scout vehicles: *diamond*, *wedge*, *line* and *column*. The formation behavior must work in concert with other navigational behaviors. The robots should concurrently strive to keep their relative formation positions, avoid obstacles and move to a goal location. Formation behaviors for 2, 3 and 4 robots have been developed and initially tested in simulation. They have been further tested on two-robot teams of Denning robots and Lockheed-Martin UGVs. The formation behaviors were developed using the reactive motor schema paradigm [1] within Georgia Tech's *MissionLab* environment. Each motor schema, or primitive behavior, generates a vector representing a desired direction and magnitude of travel. This approach provides an easy way to integrate behaviors. Each vector is multiplied by a gain value, then all the vectors are summed and the result is normalized. Other coordination mechanisms are also available, such as prioritized arbitration or action-selection. The gain values express the relative strength of each schema. Three different approaches for determining a robot's position in formation are described in [11]. In one approach, a unit-center is computed by averaging the positions of all the robots involved in the formation, then each robot determines its own formation position relative to that center. These behaviors were ported to Lockheed-Martin's UGVs and successfully demonstrated at Demo C on two UGVs in Denver, Colorado in the summer of 1995 (Fig. 3).

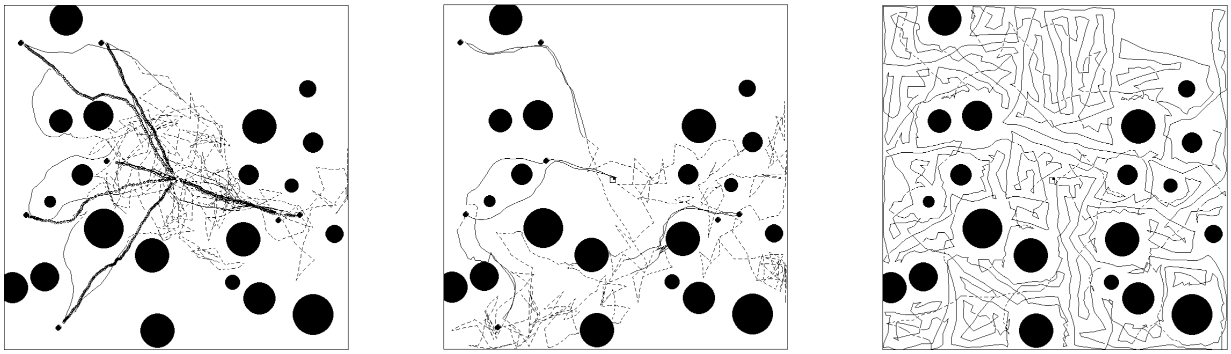
Team Teleautonomy: An important control aspect is concerned with the real-time introduction of a commander's intentions to the ongoing operation of an autonomous robotic team. We have developed and propose to extend further the software that provides this capability to the warfighter in two different ways [5]:

Figure 3: Demo C Formation Tech Demo: 2 UGVs traveling in column, wedge, then line formation.

The commander as a behavior: In this approach a separate behavior is created that permits the commander to introduce a heading for the robot team using an on-screen joystick (this can be easily replaced by a voice command system or other no-hands control method). This biases the ongoing autonomous control for all of the robots in a particular direction. All other behaviors remain active, including, for example, obstacle avoidance and formation maintenance. The output of this behavior is a vector which represents the commander's directional intentions and strength of command. All of the robotic team members have the same behavioral response to the operator's goals and the team acts in concert without any knowledge of each other's behavioral state.

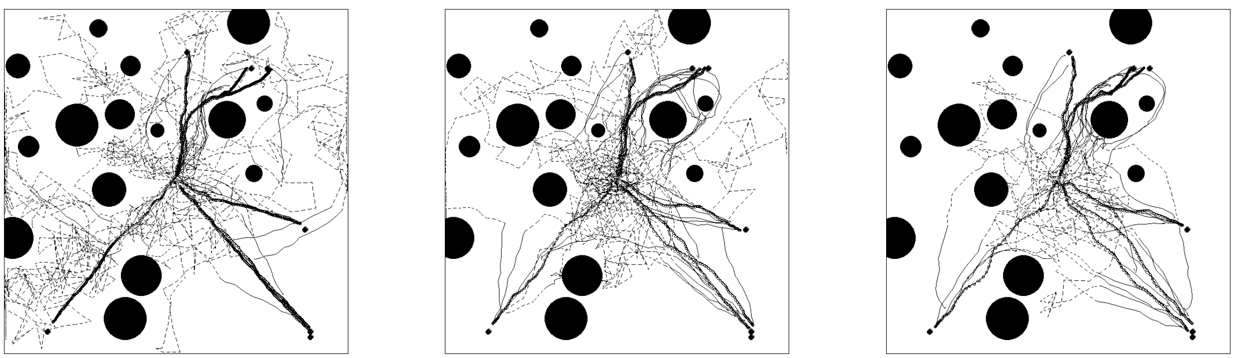
The commander as a supervisor: With this method, the operator is permitted to conduct behavioral modifications on-the-fly. This can occur at two levels. For the knowledgeable operator, the low-level gains and parameters of the active behavioral set can be adjusted directly if desired, varying the relative strengths and behavioral composition as the mission progresses. For the normal operator, behavioral traits ("personality characteristics") are abstracted and presented to the operator for adjustment. These include such things as aggressiveness (inversely adjusting the relative strength of goal attraction and obstacle avoidance) and wanderlust (inversely varying the strength of noise relative to goal attraction and/or formation maintenance). These abstract qualities are more natural for the operator unskilled in behavioral programming and permit the concurrent behavioral modification of all of the robots in a team according to the commander's wishes in light of incoming intelligence reports.

The directional control team teleautonomy software has been successfully integrated by Lockheed-Martin into the UGV Demo II software architecture and was demonstrated in simulation to military observers during UGV Demo C. Both directional and personality control have been integrated into the *MissionLab* system. Additional information on team teleautonomy can be found in [5].



(a) Forage (b) Consume (c) Graze

Figure 4: Simulation of three generic tasks with two robots and seven attractors.



(a) No Communication (b) State Communication (c) Goal Communication

Figure 5: Typical run for Forage task with varying levels of communication.

2.2.3 Communication Minimization and Planning

The impact of communication on performance in reactive multiagent robotic systems [10] has been investigated through extensive simulation studies under funding from NSF. Initial results from testing on mobile robots are shown to support the simulation studies. Performance results for three generic tasks (forage, consume, graze) illustrate how task and environment can affect communication payoffs (Fig. 4). Three different types of communication levels were studied (Fig. 5): (1) *none*, where cooperation can still be elicited even in the absence of explicit inter-agent communication; (2) *state*, which is analogous to display behavior in animals and requires, in our studies, only one bit; and (3) *goal* communication.

The principal results for these tasks are:

- Communication improves performance significantly in tasks with little environmental communication.
- Communication is not essential in tasks which include implicit communication.

- More complex communication strategies offer little or no benefit over low-level communication for many multi-robot tasks.

More detailed conclusions from this study appear in [10].

2.2.4 Real-Time Resource Management

The main idea behind the real-time component of our work is the integration of computer systems performance analysis into a high-level user specification system. We have demonstrated this basic idea on the DARPA ITO Domain-Specific Software Architectures and Evolutionary Design of Complex Software programs. In this earlier work, the end-users were engineers developing guidance, navigation and control (GN&C) behaviors using the ControlH toolset (for this proposed activity we will be concerned with *MissionLab* and specifications of robot team mission behaviors). We developed a back-end language and toolset called MetaH to specify details of various target architectures, to do various computer systems analyses including performance/schedulability analysis, and to optimize "middleware" scheduling and communication services and build executable images from the various functional components. These tools have been used in a variety of demonstrations based on real-world requirements, such as by Army AMCOM for the Army TACMS missile, the Lockheed-Martin Joint Strike Fighter, and International Space Station attitude control and ground simulation.

2.3 Approach

2.3.1 Reactive Multiagent Schema-based Behavioral Control

In our coordinative multiagent approach, reactive primitive behaviors are specified for each of the individual battlefield robots which yield global societal task-achieving action in an unstructured environment. When implemented over multiple robots, collective goal achievement is facilitated. Reactive behavioral control [4] is now a well established technique for providing rapid real-time response for a robot by closely tying perception to action. Behaviors, in various forms, are the primary building blocks for these systems, which typically operate without conventional planning or the use of global world models. Schema-based systems [1] are a form of reactive behavioral control that are further characterized by their neuroscientific and psychological plausibility, the absence of arbitration between behaviors (schemas), the fusion of behavioral outputs through the use of vector summation in a manner analogous to the potential fields method, inherent flexibility due to the dynamic instantiation and deinstantiation of behaviors on an as-needed basis, and easy reconfigurability through the use of high-level planners or adaptive learning systems [6].

Motor schemas are the basic building blocks of a schema-based system. These motor behaviors have an associated perceptual schema which provides only the necessary sensory information for that behavior to react to its environment, and ideally nothing more. Perceptual schemas are an embodiment of action-oriented perception, where perception is tailored to the needs of the agent and its surrounding environment. As stated earlier, each motor schema produces a single vector that provides the direction and strength of the motor response for a given stimuli. All of the active behaviors' vectors are summed together, normalized, and sent to the actuators for execution. Other coordination mechanisms can also be employed, such as arbitration, should it be deemed appropriate for the mission.

Another coordination operator, temporal sequencing, ties together separate collections of behaviors (assemblages) and provides a means for transitioning between them. Typically, perceptual triggers are defined which monitor for specific events within the environment. If a relevant event is detected, a state transition occurs resulting in the instantiation of a new behavioral assemblage. Finite state acceptor (FSA) diagrams are typically used to represent these relationships.

Over the past seven years, we have employed these methods for the control of multiagent robotic teams [2,5,10,11,12,17]. Our research covers a wide range of tasks, including foraging, consuming, grazing, and group movement behaviors that serve as archetypes for many robotic military missions.

2.3.2 Real-Time Resource Analysis and Management

Our approach is to integrate preemptive real-time schedulability analysis (timing analysis) and real-time "middleware" generation with the *MissionLab* specification front-end. Key requirements are to provide efficient run-time services necessary for robot control behaviors, to accurately and reliably analyze in advance what the performance characteristics of a specified system will be, and to present timing analysis and specification alternatives to the end-user in a manner that helps the end-user tailor a specification to maximize mission effectiveness.

Schedulability (timing) analysis can determine if a specification can be executed in a timely manner on a designated target system. The analysis can also identify bottlenecks and provide parametric data to show how sensitive various performance metrics are to the various timing requirements in a specification. Reasonable analysis can be done for a fairly complex set of run-time services, such as event-driven tasks, ranking of tasks by importance in case there is a transient overload, dynamic reconfigurations that change the task set, and distributed execution on multiple processors. We have already demonstrated that both analysis and implementation can be automatically performed from user specifications. The use of an analytically sound real-time scheduling approach also avoids timing and sequencing anomalies that are common in event-driven distributed systems that make a lot of data-dependent decisions designed using more informal techniques.

2.4 Specific Tasks

The four specific tasks this proposal addresses are: fault-tolerant reactive group behaviors, communication minimization and planning, integrative mission specification and usability testing, and real-time multiagent robotic control.

2.4.1 Task 1: Fault-tolerant Reactive Group Behaviors

Teams of mobile robots operating in hazardous environments will require new reactive behaviors to help them overcome newfound difficulties due to the dynamic and unpredictable environment in which they reside. How can a robot team efficiently move through the world? How can they subdivide and coordinate the needs of a high-level task among themselves under circumstances where there is likely to be loss of constituent members? How can the global team behavior be sufficiently robust to cope with unexpected occurrences?

Our experience has shown that schema-based reactive navigation provides an excellent vehicle for this form of cooperative behavior in multi-robot societies [5,8,11,12]. We will expand these tested methods to new team tasks that exploit the physical scale, numbers, and environments that confront military multiagent robotic teams. Ethological studies of group behavior will provide a basis for developing curiosity, aggressive, defensive, and other strategies for these forces [8].

The very nature of this hostile environment requires these agents to act in special ways. A wide range of behavioral characteristics are needed, including:

- Stealth: The ability to avoid detection by opposing forces.
- Caution: Self-preservation in highly hazardous environments.
- Cooperation: Coordination with multiple agents in a diverse force.

These and other behavioral characteristics are essential for successful mission completion in hazardous environments, i.e., the battlefield conditions these system will typically encounter. The creation and incorporation of a set of new robot team tactical behaviors is envisioned, including actions such as:

- Bounding overwatch: Provide protection while another advances.
- Traveling overwatch: Provide protection while both agents advance.

- Sweep: Move somewhat uniformly through an area (e.g,. along the axis of advance).
- Formation maintenance: Provide the best utilization of sensor assets or provide protection during station-keeping operations.
- Maximize or preserve communications: Moves in a concerted manner to ensure that line-of-sight communications links are preserved.
- Enemy contact behaviors: Bypass, support hasty attack, undertake hasty retreat, establish hasty defense.
- Screening behaviors (moving or stationary).
- Ambush: Initiate a surprise attack.
- Passage of line: Coordinate motion across a phase line.
- Reconnaissance techniques: Visual, auditory, or seismic.
  - Proof a route: Verify route is safe for passage.
  - Reconnaissance by fire: Observe when indirect fire is targeted at a suspect area.
  - Obstacle reconnaissance: Detect and report barriers to movement.
  - NBC (nuclear, biological, chemical) detection: Search for threats.
- Stealth behaviors
  - Avoid skylining: Prevent silhouettes of the vehicles against the horizon.
  - Avoid open areas: Prevent detection by opposing force.
  - Use all available cover and concealment: Exploit vegetation or other natural features.
  - Avoid forward motion from a defilade position: Prevent enemy detection.
  - Avoid possible kill zones: Stay away from areas of known threat.

In addition, more generic group movement behavioral classes will be useful, such as:

- Aggregation where the robots rally to a particular location. (e.g., in task-specific formations involving multiple specialized subunits).
- Dispersion where the robots spread out for surveillance operations (according to operator-specified task and environmental characteristics).
- Formation behaviors where teams of robots move in specialized task-specific patterns.
- Team teleautonomy where the entire team is controlled by a single operator as a group by either altering the behavioral composition of the team or by considering the operator as another behavior [5] in concert with higher level mission goals.

Our research group has extensive experience in designing reactive behaviors for robotic systems [1,3,7,11] and will use the existing methods we have developed for the creation of a new suite of control strategies that are suitable for military multi-robot tactical operations. Using design techniques such as temporal sequencing [9], we are able to construct arbitrarily complex behaviors from assemblages of lower-level primitives that are coordinated over a wide range of operations. (See [17] for an example construction of a military relevant mission). The *MissionLab* mission specification software that serves as the vehicle for this research provides easy creation and integration of new behaviors using the configuration description (CDL) and configuration network (CNL) languages. CDL in particular supports the recursive composition of operators and partitions coordination mechanisms from the motor behaviors themselves. CDL [15] is an agent-based functional programming language used to specify the collection of agents used in a configuration, how they are parameterized, the coordination mechanisms used to group them together, and the hardware bindings required to deploy the mission configuration.

2.4.2 Task 2: Communication Minimization and Planning

Our previous research in this area provided fruitful results that have been widely disseminated [2,10]. These earlier results have been restricted to relatively small teams of robots undertaking generic tasks. It is our intention to develop new protocols and communication strategies for larger teams of robots involved in tactical military operations and incorporate these results into a planning system which provides specific design recommendations to an operator when confronted with a particular mission and environment.

An analysis will be conducted for a broad range of military relevant tasks along several dimensions including:

- **Role of Communication**: It is perhaps most important to understand the impact of communication in multiagent units for tactical operations. It is crucial to determine the effects of the nature of information flow on task accomplishment. The analysis will be performed along the dimensions of direction of communication, quantity and content of the information transmitted, broadcast or direct inter-agent communication, and specific inter-agent communication protocols that are similar to what are used in polling multi-processor systems. The overall goal of this analysis will be to minimize or eliminate any superfluous communication to reduce both battlefield bandwidth and maximize reliability in the presence of enemy countermeasures. Our previous research in multiagent communication serves as the basis for this study [10].
- **Effects of Organization**: Multiagent robot societal configurations will be analyzed in light of communication requirements for both teams of identical physical robots

(homogeneous) and teams possessing units with different functional attributes (heterogeneous - as is the case with drones, workers, etc.). How they can cooperate and allocate difficult tasks effectively will be studied.

- **Effects of Task Type and Complexity**: The results of this analysis will be design guidelines for the construction and tasking of multiagent robot teams. Given a particular task, criteria for an appropriate number of robots, an effective organization, and a reliable communication protocol will be prescribed.

These guidelines will be integrated into the mission specification described below.

2.4.3 Task 3: Integrative Mission Specification and Usability Testing

The mission specification system serves as the integrative framework for the behaviors and communication strategies developed in Tasks 1 and 2. Drawing upon our experience in the design of the *MissionLab* multiagent mission specification system [17], we propose incorporating these newly developed techniques into a system in a manner which is demonstrably easy to use for a typical warfighter. Employing reusable mission components and a graphical user interface, the end-user will be able to design multiagent robotic missions with minimal training. The results will be refined and validated through the use of formal usability testing methods that we have developed and piloted within our laboratory [16]. Our previous experience in developing multiagent coordination strategies for autonomous multi-robot scout operations in the UGV Demo II program positions us well to move to these new military scenarios. We anticipate that straightforward extensions of some aspects of this earlier work (i.e., coordinative formation control for RSTA operations) will enable us to progress rapidly into the tactical robotics arena. *MissionLab*, our mission specification software system developed at Georgia Tech, is poised to enter into this new domain. Novel extensions to this system are required to support the necessary diversity of tactical operations. This will include a tighter integration of the military operator with the system than even before (through team teleautonomy and other means of interaction), better means for controlling larger numbers and heterogeneous teams of robots, and new methods to convey situational awareness. Novel behaviors will also be constructed to cope with the unique aspects of urban warfare.

Mission specification by an average user is facilitated through the use of abstraction. The role of abstraction in military organizations is easy to see. Commanders refer to units as the basis of their command (e.g., squads, platoons, companies, battalions) each of which is built up of individual agents organized in various ways. This notion of interchangeable units makes it easy to plan without having to worry about the performance of each constituent soldier. The commander knows a company or platoon's capabilities and, due to the uniformity of training and doctrine, can rely on their acting in a prescribed manner. It is this notion of abstraction that our mission specification strategies are most capable of taking advantage of. Recursively expressing robotic teams as an assemblage of robots, each comprising a set of stimulus-response behaviors, and recognizing that an assemblage of machine agents can also be viewed as another larger abstract agent, provides multiple levels of accessibility for operators with various operational skills.

Using the graphical programming interface, it is anticipated that tactical missions ultimately will be easy to deploy by the average operator. Whole teams of robots can be treated as reusable icons on the display, in a form that is already natural for many military personnel. Detected objects (e.g., troops, snipers, explosives, etc.) will appear on the operator's console as they are reported back by the executing agents. *MissionLab* currently provides a faster than real-time simulation environment that runs the identical control code as do the robots themselves. This can provide a high degree of confidence that actual mission execution will occur as expected. The delayed architectural and target hardware binding that this system affords also presents the ability to design highly abstract missions, and then when in the field, the operator binds the assets that are available to the particular situation for the mission at hand.

2.4.4 Task 4: Real-Time Resource Analysis and Management

We will first identify how the results of schedulability (timing) analysis can be translated into feedback that is meaningful to the end-user. For example, if analysis shows an overload on an interrobot communication channel, the user display might show that a particular set of communication-intensive behaviors cannot all be supported at the same time. Such information would be presented to users in a way that helps them identify specification alternatives to work around the resource limitation, such as creating two less-demanding behaviors and specifying the conditions under which each is to be active. We will identify qualities-of-service that are meaningful to the end-user for sets of behaviors (e.g. speed, positional accuracy, metrics affecting probability of detection); identify how real-time performance attributes (e.g. dispatch rates, CPU demand) impact these qualities-of-service; and develop ways of displaying this information in a manner that assists the user in tailoring the behavioral specification to maximize mission effectiveness.

We will also identify and demonstrate appropriate run-time services for robot control behaviors, including services that allow behaviors to dynamically adapt (e.g. incremental processing, multi-criticality scheduling, dynamic reconfiguration) in mobile distributed computer systems. This ultimately translates into development guidelines that can be used by robotics experts to develop individual behaviors that can dynamically adapt their execution

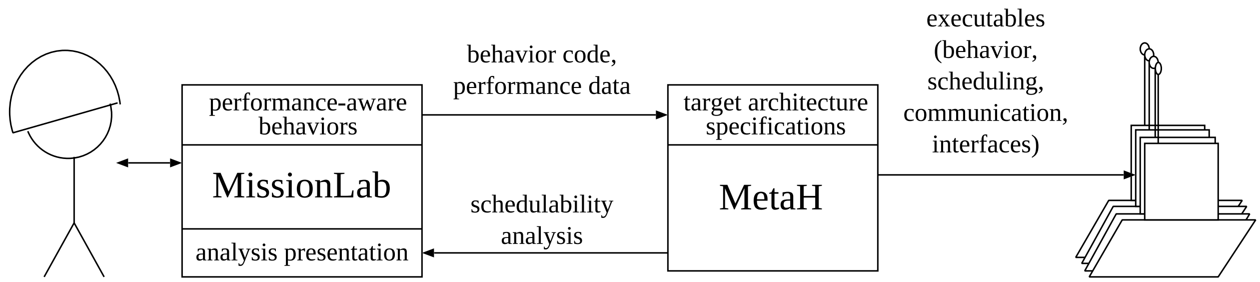


Figure 6: *MissionLab* Extended with MetaH Real-Time Analysis and Implementation

to take best advantage of available resources, e.g. through the use of anytime algorithms, by structuring a behavior as a set of tasks of varying importance or dispatch rates.

Figure 6 illustrates our approach to providing timing analysis and a real-time implementation, using the *MissionLab* and MetaH toolsets as specific examples. The warfighter uses *MissionLab* to specify a mission behavior for a team of robots, where *MissionLab* supports concepts and an interface that are meaningful to, and powerful for, this user for this purpose. *MissionLab* translates these specifications into lower-level behavioral code, which would be passed to the MetaH toolset along with performance data. The MetaH toolset uses such information for two purposes. It performs a real-time schedulability analysis to determine schedule feasibility and resource utilizations and parameter sensitivities, and it tailors "middleware" or "glue code" to handle task scheduling, synchronization, communication, and reconfiguration across a multi-processor system. In order to provide such a solution, we need to extend *MissionLab* and its behavior libraries to provide the information needed by MetaH, we need to develop specifications of target architectures for MetaH, and we need to extend *MissionLab* to present the results of schedulability analysis in terms that are meaningful and helpful to the end-user. MetaH in particular, and any analysis toolset and run-time system in general, only provides a particular set of schedulability analyses and run-time scheduling services. We must determine the set of analyses and run-time services that are appropriate for this application, and we must select a specific set of tools and run-time systems, and extensions to them, to accomplish our objectives.

An important characteristics of this approach is that by using analytically sound scheduling, we avoid timing "glitches" that are common in event-driven distributed decision-making systems that were developed using more informal methods.

We will demonstrate this new technology, and the benefits that can be obtained, by adapting and integrating existing tools (e.g. *MissionLab*, MetaH). We will show how timing analysis can be presented to the user in a way that facilitates the development of better specifications, and hence increase the mission effectiveness for a given set of robot resources.

2.5 Proposed Experimental Testbed

Although the Georgia Tech Mobile Robot Laboratory already has in excess of 10 mobile robots, in order for us to work on a size scale comparable with the spirit of this BAA, we propose acquiring a new testbed of minirobots. It is tentatively proposed that this experimental team be composed of up to 10 DARPA-provided robots.

Our existing *MissionLab* system will be expanded to include whatever particular class of robots DARPA chooses as a target platform. *MissionLab* already supports multiple target robots, including two different Denning robot architectures (DRV-1 and MRV-2), the Nomad 150, and our locally constructed Hummer robotic platform. This vehicle-independent nature of mission specification was a completed design goal of the *MissionLab* system. Schema-based controllers have also been developed for an RWI B21 running Beesoft/Linux. Thus it will be straightforward to retarget the software developed on DARPA-specified robot hardware.

Equipment funds are requested for dedicated laptops, vision systems, and communication links for a subset of the DARPA-provided robot team (existing equipment in the Georgia Tech Mobile Robot Laboratory can provide for the balance).

2.6 Evaluation Process and Metrics

It is crucial that metrics be generated early in the life of a development effort in order to ensure the utility of the final product and acceptance by the intended end-user community. An evaluation process must also be constructed that is capable of measuring the performance of the product relative to those metrics, in order to guide its ongoing development and to ensure end-user acceptance. Usability studies will provide one of the vehicles for testing many of our research products, based upon our earlier experiences in this area [16].

Our evaluation methods will include:

1. Extensive simulation studies demonstrating the effectiveness of both the novel military behaviors and the communication planning methods in DARPA-specified scenarios (e.g., urban assault, recon, and building clearing). Analysis of the performance of a mission and its resistance to faults will be obtained through these studies within our laboratory's *MissionLab* software framework. This will allow us to compare between various mission configuration design alternatives for various robot team taskings using metrics such as the speed of mission completion, the likelihood of success in the presence of risk, how sensitive the designed system is regarding interagent communication failure, and other related factors.

2. A sequence of challenging demonstrations on the actual robotic testbed and, where appropriate, utilizing our existing Hummer ground station [13] (Fig. 8 left). A target

demonstration capability is designated for each year of the effort. This will culminate in a complex military scenario that will likely involve realistic aspects of MOUT operations. At all times an effort will be made to ensure relevancy to DARPA's military goals.

3. Demonstrations that show how timing analysis can be used to tailor more effective specifications for a given set of robot resources. We will provide examples of ways to adapt specifications to achieve higher qualities-of-service (e.g. time to perform, reliability, survivability) given limitations on the available processing and communications resources. We will assess the degree to which overall mission effectiveness can be enhanced by making these analysis and tailoring capabilities available to the end-user.

4. Usability studies to determine the effectiveness of integrating multi-robot teams into tactical forces. Using methods that have been developed within our laboratory [16] that are consistent with usability testing in general, we will evaluate the ease of use of the design of relevant military missions by various personnel, including those with skills comparable to actual warfighter end-users. Whenever possible, actual military personnel will be used for subjects (e.g., Army ROTC students or in collaboration with military bases within Georgia) to provide feedback for the iterative design necessary in perfecting a system that will ultimately be satisfactory to customer requirements. Metrics we have used for evaluating such systems include:

   - Time to create a mission configuration.
   - Enabling the creation of a mission configuration.
   - Time to modify a mission by specializing a step, adding a step, specializing a transition, or adding a transition.
   - Time compared to design with the system as opposed to programming directly.
   - Subjective evaluation of the general feeling after use.
   - Quality of configuration.

   Mission configuration performance must also be measured, i.e., how well a particular design satisfies the requirements of the task. Selection of a performance metric is important because these metrics are often in competition - e.g., cost versus reliability. Some potential metrics for multiagent missions are:

   - **Cost** - Accomplish the task for the minimum cost. Use of this metric will tend to reduce the cost of the system and minimize the number of robots used.
   - **Time** - Accomplish the task in minimum time. This metric will likely lead to a solution calling for the maximum number of robots that can operate without interference.

- **Energy** - Complete the task using the smallest amount of energy. This is appropriate in situations where fuel reserves are limited.
- **Reliability** - Accomplish the task in a manner that will have the greatest probability of completion even at the expense of time or cost.
- **Survivability** - Accomplish the task in a manner that is most likely to preserve individual assets.

The task metric can also be a numeric combination of several measurements. Whatever the metric is, it must be measurable, especially in simulation. In our previous research [10], time to complete the task was chosen as the primary performance metric. It is easily and accurately measurable and conforms to what is frequently thought of as performance. No claim is made however that this is the "best" metric; distance, reliability, survivability, energy consumption or some context-dependent combination may be more useful. Analysis of which metrics are best suited for tactical robot teams will be an important aspect of the research.

A set of usability attributes will be defined that is captured in a usability criteria specification table [14]. This will include data on the attribute in question, what values reflect that attribute, the current level of user performance, and worst-acceptable, target, and best-possible levels. Based on these data, a series of usability experiments will be constructed, each of which contains specific objectives regarding the evaluation of the attributes in the specification table.

Standard operating procedures for the administration of our usability studies include:

- Administration of the experiments by a third party to eliminate bias.
- A uniform introduction to the toolset to all subjects.
- Participants are sequenced through a series of tasks over several days as necessary to prevent tiredness from affecting performance.
- The subjects are isolated in a usability lab and are observed via one-way glass and video cameras.
- Computer logs are recorded for the entire session.

Statistical analysis of the resulting data can provide confirmation of the achievement of target level performance or provide feedback for the modification of the underlying software product.

A fundamental contribution that transcends our own laboratory's particular approach to mission specification is the development of metrics and methodologies to evaluate tactical mission configurations in general. Consequently, it is expected that these usability methods and metrics could be applied to other DARPA programmatic efforts funded under this BAA as well.

3. Program Plan

The planned organization of the project is shown in Figure 7. The researchers are affiliated with two units of the Georgia Institute of Technology: the Georgia Tech Research Institute and the College of Computing, as well as the Honeywell Technology Center. The diverse resources of these organizations will be supplemented by access to other multidisciplinary facilities of the Georgia Institute of Technology, including the Graphics, Visualization, and Usability Laboratory. For contractual purposes, the coordinating agency is the Georgia Tech Research Corporation.

Since 1946, the Georgia Tech Research Corporation (GTRC) has served as a "university-connected research foundation," one of approximately one hundred located at state universities throughout the country. These foundations are organized primarily to permit their host universities to operate research programs by minimizing the impact of restrictive state contracting and financial procedures. The natures of these foundations vary as the state environments to which their host universities are subject vary. Some are "full service" foundations performing contracting, financial, personnel, purchasing, accounting, and other functions. Others have a narrow range of functions including only those which are difficult or impossible for the university itself to handle. GTRC falls into the latter category, and its functions are almost all financial. GTRC contracts and is paid for the research done at Georgia Tech, paying Georgia Tech for all direct costs and 78.3% of the overhead. The 21.7% of the overhead retained by GTRC is used to establish reserves for the research program, and to pay certain expenses which Georgia Tech cannot pay. Administrative expenses of GTRC are included in the approved overhead, so a portion of the 21.7% is reimbursement for those expenses. Appropriations are made to Georgia Tech from reserves, as requested by the Georgia Tech Administration and approved by the Board of Trustees of the Corporation. Other GTRC functions include:

- Providing a short reaction time in contract matters with sponsors, on some occasions handling them informally, if desirable.
- Assisting Georgia Tech in attracting research dollars by appropriating funds for facilities and equipment - particularly when a research award may be contingent upon Tech having the facilities or equipment.
- Serving as a fiscal buffer between external agencies and Georgia Tech through such

activities as: carrying accounts receivable, assuming responsibility for retroactive provisional overhead adjustments, and by absorbing bad debts.

- Assisting Georgia Tech in recruiting research faculty by appropriating funds for initial program costs for new senior research faculty, extraordinary costs of relocation, doctoral fellowships for research faculty, and subsidies for the purchase of personal computers.
- Assisting Georgia Tech in attracting high quality graduate students by providing direct financial support.
- Carrying comprehensive liability insurance on research operations.
- Leasing research equipment and facilities for use by Georgia Tech.
- Advancing funds to Georgia Tech on a no-interest and loan basis when availability of state funds is delayed.
- Serving as patent agency for obtaining patents on Georgia Tech inventions and for licensing, development and commercialization by industry.

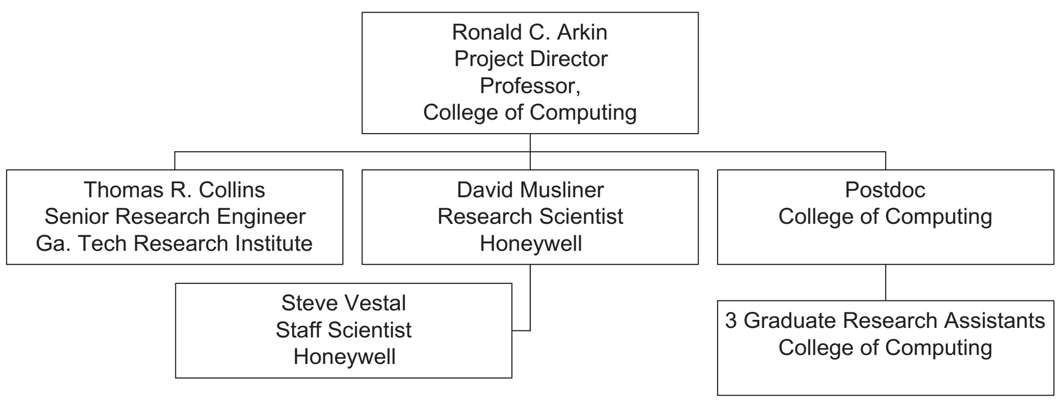


Figure 7: Organizational Chart

4. Statement of Work

1. The design, development, simulation, and testing on multiagent robotic hardware of a broad range of real-time fault-tolerant reactive group behaviors.

2. The development of communication minimization and planning methods and tools for multiagent robotic teams operating in hazardous environments. The test domains will be assumed to be hostile, where individual agents may perish and electronic countermeasures may be in effect, potentially disrupting communications between the robots.

3. The development of multiagent mission specification software that incorporates the results of Tasks 1 and 2 above. This work extends our previous DARPA research on multiagent robotic teams that resulted in the *MissionLab* mission specification system [17]. The system incorporates a faster than real-time simulator and the ability to test mission scenarios prior to their deployment when the same control code that runs in simulation is downloaded onto the actual physical robot team. We have also conducted usability studies using this system in the context of scouting missions [16]. We intend to deploy similar methods for testing the validity of the software developed herein.

4. Real-time performance of tactical robot teams

   (a) Real-time requirements: We will identify tactical mobile robot team mission scenarios, end-user performance and quality-of-service metrics, behaviors used in such scenarios, behavioral tasking models, and methods and technologies to support specification refinement by the end-user.

   (b) Real-time implementation: We will identify distributed real-time scheduling, synchronization and communication technologies, tools and methods that will allow us to reliably support robotics behaviors, and will allow us to rapidly and automatically produce implementations from data obtained from high-level end-user specifications.

   (c) Real-time analysis: We will identify modeling and analysis technologies, tools and methods that will allow us to determine schedule feasibility, identify bottlenecks, provide parametric analysis, and verify timing and sequencing correctness.

   (d) Real-time demonstration: We will perform integrated demonstrations that show how real-time distributed resource management technologies can enhance the mission effectiveness of teams of tactical mobile robots.

   (e) Real-time coordination: We will attend meetings, provide technical presentations and reports, provide financial reports, and perform other coordination and management tasks as required for this effort.

4.1 Deliverables

4.1.1 Military-relevant scenarios

We intend to develop behavioral, communication, and mission specification strategies in a manner that is consistent with ongoing and future military protocol and missions. We will consult with, as we have in the past, appropriate military personnel and doctrinal literature to ensure that the multi-robot tasks and missions are relevant to the Department of Defense. At this early stage, we envision several potential missions such as those described in the BAA. These include those mentioned in the PIP and perhaps others, for example: building clearing by dismounted infantry; urban reconnaissance; and countersniper.

4.1.2 Specific Deliverables

The following deliverables will be available at the end of the two year project:

- Laboratory grade behavioral software suitable for technology transfer and running on DARPA-provided robots.
- A sequence of relevant multi-robot demonstrations performed each year on DARPA-provided robotic hardware.
- Design guidelines and protocols for communication minimization in multi-robot teams operating in hazardous environments where communication is generally unreliable and possibly subject to electronic countermeasures.
- Mission specification software for multiagent robotic systems suitable for use throughout the DARPA Tactical Robotics program that provides the following capabilities to the warfighter:
  - Reusable mission specifications.
  - Visual programming environment.
  - A suite of demonstrable tactical scenarios embodying existing military protocol.
  - Minimal training and ease of use.
  - Compilation and downloading of multiagent mission plans into multi-robot hardware configurations.
- Usability studies analyzing which aspects of mission specification tools in general are and are not suitable for multi-robot end-users.
- Timing analysis technology, real-time run-time infrastructure, and specification guidelines and protocols for maximizing assurance of timing correctness and mission effectiveness subject to robot resource constraints.
- Annual and final project reports.
- Numerous publications in relevant journals and conference proceedings.

4.2 Technology Transition Plan

The Georgia Tech Mobile Robot Laboratory has had considerable success within the context of DARPA's UGV Demo II program in the transfer of our software to Lockheed-Martin for inclusion in the Demo II vehicles. We anticipate that we will be able to cooperate closely with any co-contractors of this program in integrating our software into their multi-robot system should it be deemed appropriate by our sponsor. Additionally, *MissionLab* is now in its third release and is available over the world-wide web at http://www.cc.gatech.edu/ai/robot-lab/research/MissionLab/index.html. For example, it was adopted for use by the University of Texas at Arlington as the basis for their multi-robot sensor pointing strategies for their use in reconnaissance, surveillance and target acquisition in the UGV Demo II program.

The Honeywell Technology Center (HTC) has the experience and knowledge to successfully transfer advanced DARPA-funded technologies into military and industrial applications. HTC's corporate charter is to transfer leading-edge technology to Honeywell customers including Honeywell product divisions, related industrial partners, and military prime contractors. HTC's technology transfer success stories include the highly-successful Boeing 777 integrated avionics, dual-use ring-laser-gyro product family, and Very High Speed Integrated Circuits (VHSICs). Because HTC supports both military and commercial product divisions, we have demonstrated dual-use technology transfer for more than ten years. In addition, HTC has a proven record of technology transfer to both industrial and academic communities. We continue this tradition of open community technology transfer in the NIST-sponsored Abnormal Situation Management program and in current DARPA-sponsored programs including SARA, DSSA, RASSP, and Prototech. Other examples of HTC technology transfer include model-based tool development methods and constraint-based scheduling.

5. Timetable

The research will unfold over a two year period:

- **Year One:**

  1. Development of multiagent behaviors including team teleautonomy for two specific military scenarios.
  2. Acquisition and integration of DARPA-provided robot testbed.
  3. Begin *MissionLab* mission specification system extensions for these robots.
  4. Extensive simulation testing of new classes of behaviors.
  5. Specification of interagent communication requirements and protocols.

6. Demo A: Demonstration on robot testbed of one military scenario within laboratory confines (e.g., building clearing, decoy, or urban reconnaissance operations).
7. Demonstration of schedulability (timing) analysis of behavioral specifications, with execution of selected behaviors using the associated real-time services on a laboratory testbed.

- **Year Two:**

1. Ongoing refinement of year one results, including completion of the tactical behavior repertoire.
2. Full implementation and analysis of minimal communication protocols and methods and integration with *MissionLab*.
3. Demonstration of end-user benefits of schedulability (timing) analysis, using timing analysis feed-back to tune a behavior specification to improve qualities-of-service and mission effectiveness.
4. Demo B: Demonstration on full multi-robot testbed as part of a multistep mission specified through the newly developed mission specification software, in a more realistic outdoor setting, utilizing our existing HUMMER vehicle as the operator base (Fig. 8 left).
5. Adaptation of software to DARPA Tactical Robotics community's needs to facilitate technology transfer.

Annual reports will be provided for each of the funded years.

6. Facilities and Equipment Description

6.1 Facilities of the Georgia Tech Mobile Robot Laboratory

In addition to the extensive equipment base, networking capabilities, and support provided within the College of Computing, the Mobile Robot Laboratory has specific resources dedicated to this and other related projects. Its facilities include:

- **Robots:** 2 Denning MRV-II Mobile Robots; 1 Denning DRV-I Mobile Robot; 5 Nomad 150 Mobile Robots; 1 Robotic actuated AM General Hummer with DGPS; 1 Hermes II robot hexapod; 1 CRS+ A251 5DOF robot arm; 3 Blizzard Mobile Robots.
- **Computer Workstations:** 6 Sun Sparcstations; 2 SGI Indys; 1 SparcBook 3 Laptop; 1 Macintosh 6100; 5 Toshiba PC laptops running Linux; 3 RDI Sun Laptops with vision boards; 1 Zenith 486 PC Clone running Linux; 1 Decstation 5000/120.

Figure 8: Left: GT Hummer. Right: Robots of the GT Mobile Robot Lab.

- **Vision Hardware:** 1 Sensar PV-1 Pyramid Image Processor; 1 Teleos AV100 Image Motion Processor; 6 Newtonlabs Cognachrome Vision Systems; 9 CCD Pulnix/Cohu cameras; 1 Pulnix low lux image-intensified video camera; 3 Directed perception pan/tilt platforms; 1 Zebrakinesis pan/tilt platform.
- **Other Sensors:** 1 Denning laser scanner (bar code reader); 1 RWI laser range scanner; 1 Sensus sonar ring; 3 Electronic compasses; 1 Lasiris laser striping system with Watec video camera.
- **Communications:** Radio links (10 freewaves, 2 proxims, 6 lawns)

6.2 GTRI

The Georgia Tech Research Institute (GTRI) is a nonprofit applied research organization that is an integral part of Georgia Tech. GTRI facilities include laboratories in electronics, computer science and technology, the physical sciences, and most branches of engineering. A 52-acre field test site for research in electromagnetics, radio-direction finding, and propagation studies is located at GTRI's Cobb County facilities, along with a 1,300-foot far field antenna range and radar cross-section ranges, GTRI researchers can also use a 14-acre satellite communications station south of Atlanta that includes two 105-foot diameter dish antennas and a 14,000 square foot building.

This project utilizes the resources of the Electronic Systems Laboratory, which works in broad areas of modeling, simulation, and analysis; human factors; technology insertion; systems integration; and test and evaluation. It has broad Department of Defense experience with integrating modeling, simulation, test, and evaluation to improve the acquisition and life-cycle operation of electronic warfare systems. For the U.S. Air Force, lab researchers also transfer useful technology into fielded electronic warfare and radar systems to improve both system reliability and performance. To optimize aircraft self protection assets, the laboratory serves as an integrator of multiple and multi-spectral electronic defense systems. Finally, laboratory researchers are studying the human-centered design of advanced traffic management centers, facilities that will be used in large metropolitan areas to better manage traffic flow.

6.3 Honeywell Technology Center

HTC has an extensive internal network of hundreds of workstations, PCs, file servers, graphics processors, etc., with full Honeywell intranet and world internet services available (e.g., telnet, ftp, public web pages). Of more direct relevance to this effort are several real-time testbeds using various commercial (e.g., VxWorks, LynxOS) and research real-time operating systems, and numerous commercial and research cross-development toolsets for producing embedded control software. HTC is a central R&D facility, which means we also have access to extensive research library capabilities, and to in-house experts in a large number of related fields (e.g., navigation, vehicle guidance and control, motion control, signal and image processing, sensor and radio technologies) in addition to planning and real-time technologies. Use of HTC facilities is not charged directly to contracts, these costs are recovered in our normal overhead.

7. Relevant Prior Work

7.1 Georgia Tech

Our research team has extensive experience in the area of multiagent robotic systems and has numerous publications in this area. A more complete description of our work on our multiagent robotics projects is available at:

http://www.cc.gatech/edu/aimosaic/robot-lab/research/multi-agent.html.

This site summarizes our research on communication in robot teams, team teleautonomy, multiagent mission specification and control, formation control, our multi-robot competition winners, and learning teams of robots.

Of particular note are three recent grants that provided the basis for this research:

- **Flexible Reactive Control for Multi-Agent Robotic Systems in Hostile Environments**. Advanced Research Projects Agency. ONR/ARPA Grant #N00014-94-1-0215, 11/93-3/97, $659,567.
- **Ecological Robotics: A Schema-Theoretic Approach.** NSF Grant #IRI-9505864. 8/95-7/98. $96,107.

- **Cooperation and Communication in Multi-Agent Reactive Robotic Systems.** National Science Foundation Grant #IRI-9100149, 3/92-8/94, $119,901.

The laboratory has produced extensive publications on multiagent systems, some of which appear in the references: [2,5,8,10,11,12,16,17].

7.2 Honeywell

For the DARPA ITO Domain-Specific Software Architectures (DSSA) program, we developed the initial ControlH and MetaH languages and tools. ControlH is a front-end toolset that guidance, navigation, and control engineers use to specify functionality (somewhat analogous to the way the *MissionLab* front-end toolset will be used by warfighters to specify robot mission behaviors). MetaH is a back-end designed to be integrated with multiple such "domain-specific" front-ends. MetaH is used to specify target architectures and interfaces between major subsystems, to perform schedulability analysis (and reliability and partition impact analysis), and to tailor real-time distributed fault-tolerant "middleware" for execution of whatever code the front-end tools produce. Among other things, MetaH is being extended with adaptive resource management technologies on the current DARPA ITO Evolutionary Design of Complex Software (EDCS) program, results that may be of benefit to this proposed program. More information is available at *http://www.htc.honeywell.com/projects/dssa.*

On our Real-Time Adaptive Resource Management and Adaptation with Predictable Real-Time Performance projects (funded under the DARPA Quorum program), Honeywell, Georgia Tech, and University of Texas A&M are developing adaptive scheduling methods for dynamic widely-distributed systems, such as command and control systems. Our approach will allow applications to request and negotiate desired qualities-of-service (e.g. reliability, bandwidth, delay), where the system may dynamically reallocate resources to provide the negotiated quality of service even as the resource demands and availability change. The architecture includes quality-of-service models, real-time self-monitoring of performance, decision and resource allocation models, and methods to negotiate and effect changes to resource allocations. More information is available at *http://www.htc.honeywell.com/projects/arm.*

The Cooperative Intelligent Real-Time Control Architecture (CIRCA) combines novel planning, scheduling, and plan execution techniques to automatically derive and execute real-time reactive control plans that are guaranteed to preserve system safety while pursuing goals. CIRCA has been used to control several simulated and real-world robotic systems performing a variety of tasks requiring both real-time reactive behaviors and longer-term, goal-directed planning. The recently-completed DARPA-funded Distributed CIRCA project began investigating the issues associated with extending the single-agent CIRCA architecture to multi-robot systems, focusing on real-time control of multiple Uninhabited Aerial Vehicles (UAVs) under the high-level supervisory control of a human user.

One focus of the Mobile Communications (MobCom) program at HTC last year was a comparative performance analysis of the Mode-S and STDMA real-time radio network data protocols. These protocols are used or proposed for communicating information between commercial aircraft. For example, the current Traffic Alert and Collision Avoidance System (TCAS) uses the Mode-S protocol to communicate between a "team" of aircraft that are coordinating to avoid collision. Enhanced performance and reliability of such real-time mobile communications protocols are necessary for the up-coming transition to "free-flight," increased use of automated operations and flight management, and increasing airspace and radio spectrum densities.

8. Management Plan

The robotic testbed will reside at Georgia Tech. One postdoctoral associate will be hired and dedicated with the day-to-day operations of this project. Prof. Arkin will devote one-third of his time for coordination, control, and direction of the program and will be responsible for the overall management and representation of this effort with DARPA and its co-contractors. Dr. Thomas Collins will dedicate one-third of his time for this research effort with equal involvement in all four statement of work tasks and will serve as the primary Georgia Tech coordinator with HTC. Three half-time Ph.D. Graduate Research Assistants will assist in conjunction with the other team members for the implementation of the ideas contained within this proposal.

The Honeywell subteam will include both an expert in robot planning, scheduling and agent coordination; and an expert in modeling, analysis and implementation of real-time systems. Honeywell will focus on real-time resource management issues. Georgia Tech will provide Honeywell with baseline robotic behavioral specification technologies (e.g. *MissionLab* and example specifications), which Honeywell will use as a basis for developing and demonstrating real-time robot team resource management capabilities.

Project team members will attend the quarterly DARPA meetings for exchange of information with other members of the Tactical Robotics community.

9. Brief Resumes

9.1 Principal Investigator: Ronald C. Arkin

Ronald C. Arkin received the B.S. Degree from the University of Michigan, the M.S. Degree from Stevens Institute of Technology, and a Ph.D. in Computer Science from the University of Massachusetts, Amherst in 1987. He then assumed the position of Assistant Professor in the College of Computing at the Georgia Institute of Technology where he now holds the rank of Professor and is the Director of the Mobile Robot Laboratory.

Dr. Arkin's research interests include reactive control and action-oriented perception for the navigation of mobile robots and unmanned aerial vehicles, robot survivability, multiagent robotic systems, and learning in autonomous systems. He has over 80 technical publications in these areas. Prof. Arkin has recently completed a new textbook entitled *Behavior-Based Robotics* to be published by MIT Press in the Spring of 1998 and has co-edited (with G. Bekey) a book entitled *Robot Colonies* published by Kluwer in the Spring of 1997. Funding sources have included the National Science Foundation, DARPA, U.S. Army, Savannah River Technology Center, and the Office of Naval Research. Dr. Arkin serves/served as an Associate Editor for IEEE Expert and the Journal of Environmentally Conscious Manufacturing, as a member of the Editorial Boards of Autonomous Robots and the Journal of Applied Intelligence and is the Series Editor for the new MIT Press book series entitled *Intelligent Robotics and Autonomous Agents*. He is a Senior Member of the IEEE, and a member of AAAI and ACM. A vita for Prof. Arkin is available at http://www.cc.gatech.edu/aimosaic/faculty/arkin/vita.html. Relevant publications include:

Arkin, R.C.. *Behavior-based Robotics*, MIT Press, to appear Spring 1998.

MacKenzie, D., Arkin, R.C., and Cameron, R., 1997. "Multiagent Mission Specification and Execution", *Autonomous Robots*, Vol. 4, No. 1, Jan. 1997, pp. 29-52.

Arkin, R.C. and Bekey, G. (editors), 1997. *Robot Colonies*, Kluwer Academic Publishers.

Arkin, R.C. and Balch, T., 1997, "Cooperative Multiagent Robotic Systems" to appear in *Artificial Intelligence and Mobile Robots*, ed., D. Kortenkamp, et al., AAAI Press.

Arkin, R.C. and Balch, T., 1995. "Communication and Coordination in Reactive Robotic Teams", to appear in *Coordination Theory and Collaboration Technology*, ed. G. Olson et al.

MacKenzie, D., Cameron, J., Arkin, R., 1995. "Specification and Execution of Multiagent Missions", *Proc. 1995 Int. Conf. on Intelligent Robotics and Systems (IROS '95)*, Pittsburgh, PA, Vol. 3, pp. 51-58.

Balch, T. and Arkin, R.C., 1995. "Motor Schema-based Formation Control for Multiagent Robot Teams", *Proc. 1995 International Conference on Multiagent Systems*, pp. 10-16.

Balch, T. and Arkin, R.C., 1994. "Communication in Reactive Multiagent Robotic Systems", *Autonomous Robots*, Vol. 1, No. 1, pp. 27-52, 1994.

Arkin, R.C. and Ali, K., 1994. "Integration of Reactive and Telerobotic Control in Multiagent Robotic Systems", *Proc. Third International Conference on Simulation of Adaptive Behavior, (SAB94) [From Animals to Animats]*, Brighton, England, Aug. 1994, pp. 473-478.

Arkin, R.C. and MacKenzie, D., 1994. "Temporal Coordination of Perceptual Algorithms for Mobile Robot Navigation", *IEEE Transactions on Robotics and Automation*, Vol. 10, No. 3, June 1994, pp. 276-286.

Arkin, R.C., Balch, T., and Nitz, E., 1993. "Communication of Behavioral State in Multi-agent Retrieval Tasks", *Proc. 1993 IEEE International Conference on Robotics and Automation*, Atlanta, GA, May 1993, Vol. 3, pp. 588-594.

Arkin, R.C. and Hobbs, J.D., 1992, "Dimensions of Communication and Social Organization in Multi-Agent Robotic Systems", *Proc. 2nd Inter. Conf. on Simulation of Adaptive Behavior*, Dec. 1992, MIT Press, pp. 486-493.

Arkin, R.C., 1992. "Behavior-based Robot Navigation in Extended Domains", *Journal of Adaptive Behavior*, Vol. 1, No. 2, pp. 201-225.

Arkin, R.C., 1992. "Cooperation without Communication: Multi-agent Schema Based Robot Navigation", *Journal of Robotic Systems*, Vol. 9(3), April 1992, pp. 351-364.

9.2 Senior Research Engineer: Thomas Collins

Thomas R. Collins is a Senior Research Engineer in the Electronic Systems Laboratory at the Georgia Tech Research Institute, with recent shared appointments in the School of Electrical Engineering and the Office of Interdisciplinary Programs. He received a Bachelor's degree in Mechanical Engineering in 1980, a Master of Science in Electrical Engineering in 1982, and a Ph.D. in Electrical Engineering in 1994, all from the Georgia Institute of Technology. His research interests include robotic manipulators, unmanned systems, hardware/software architecture for parallel computation in intelligent machine applications, modeling and simulation, and high-performance computer architectures. Funding sources have included the U.S. Air Force, the Ballistic Missile Defense Organization, the U. S. Army Aviation Technology Directorate, and the Department of Energy. He has authored or co-authored over two dozen publications and technical reports and is a member of IEEE. Relevant publications include:

T.R. Collins and T.R. Balch, "Teaming Up: Georgia Tech's Multi-robot Competition Teams," Proceedings of Fourteenth National Conference on Artificial Intelligence, July 1997.

D.P. Schrage, et al., "The Autonomous Scout Rotorcraft Testbed (ASRT) as an Integrated System," American Helicopter Society 53rd Annual Forum, April 1997.

T. Balch, G. Boone, T. Collins, H. Forbes, D. MacKenzie, and J. Santamara, "Io, Ganymede and Callisto - a Multiagent Robot Trash-collecting Team," AI Magazine, 1995.

T.R. Collins, D. Cardoze, and D. Gerber, "Object-Oriented Development of an Integrated Processor System for an Unmanned Aerial Vehicle," in Proceedings of AUVS '95 (Washington, DC), July 1995.

T. Balch, J. Santamara, G. Boone, T. Collins, H. Forbes, and D. MacKenzie, "Lessons Learned in the Implementation of a Multi-robot Trash-collecting Team," in Working Notes of 1995 AAAI Spring Symposium: Lessons Learned from Implemented Software Architectures for Physical Agents, March 1995.

T.R. Collins, A. Henshaw, R.C. Arkin, and W. Wester, "Narrow Aisle Mobot Robot Navigation in Hazardous Environments," in Proc. 1994 American Nuclear Society Annual Meeting (New Orleans), June 1994.

T. Collins, R. Arkin, and A. Henshaw, "Integration of Reactive Navigation with a Flexible Parallel Hardware Architecture," in Proc. IEEE Robotics and Automation Conference (Atlanta, GA), May 1993.

R.C. Arkin, T. Balch, T.R. Collins, A. Henshaw, D. McKenzie, E. Nitz, and K. Ward, "Buzz: An Instantiation of a Schema-Based Reactive Robotic System," in Proc. International Conference on Intelligent Autonomous Systems: IAS-3, Feb. 1993.

9.3 Principal Research Scientist: David Musliner

David Musliner, a principal research scientist at the Honeywell Technology Center, received a B.S.E. degree in Electrical Engineering and Computer Science from Princeton University and a Ph.D. in computer science from the University of Michigan. He designed and implemented the Cooperative Intelligent Real-Time Control Architecture (CIRCA), one of the first AI control architectures capable of reasoning about and interacting with dynamic, hard real-time domains. He was principal investigator on the DARPA D-CIRCA project, investigating extensions to the CIRCA architecture for multiagent planning and control in real-time domains, with target applications including teams of UAVs and mobile robots. Dr. Musliner has extensive experience in robotic control system design and mobile robot programming, real-time systems, scheduling, and AI planning techniques. Relevant publications include:

D. J. Musliner, E. H. Durfee, and K. G. Shin, "CIRCA: A Cooperative Intelligent Real-Time Control Architecture," *IEEE Trans. Systems, Man, and Cybernetics*, vol. 23, no. 6, pp. 1561–1574, 1993.

D. J. Musliner, E. H. Durfee, and K. G. Shin, "World Modeling for the Dynamic Construction of Real-Time Control Plans," *Artificial Intelligence*, vol. 74, no. 1, pp. 83–127, March 1995.

D. J. Musliner, J. A. Hendler, A. K. Agrawala, E. H. Durfee, J. K. Strosnider, and C. J. Paul, "The Challenges of Real-Time AI," *IEEE Computer*, vol. 28, no. 1, pp. 58–66, January 1995.

9.4 Staff Scientist: Steve Vestal

Steve Vestal, a staff scientist at Honeywell Technology Center, received bachelor's degrees in computer science and mathematics from Vanderbilt University and a Ph.D. in computer science from the University of Washington. He was principal investigator on our DARPA DSSA program, managing development of ControlH (a GN&C development toolset) and serving as principal designer and chief programmer for MetaH (a real-time fault-tolerant systems analysis and integration toolset). He currently serves as PI on the DARPA EDCS program, which is integrating design constraint management, adaptive scheduling, hardware modeling and portability, and verification technologies with MetaH. He is also PI on an AFOSR contract whose goal is to develop an integrated model for real-time scheduling and analysis of concurrent processes (real-time reactive systems). Relevant publications include:

Steve Vestal, "An Architectural Approach for Integrating Real-Time Systems," *Workshop on Languages, Compilers and Tools for Real-Time Systems*, June 1997.

Pam Binns, Matt Englehart, Mike Jackson and Steve Vestal, "Domain-Specific Software Architectures for Guidance, Navigation and Control," *International Journal of Software Engineering and Knowledge Engineering*, v. 6, n. 2, 1996.

Steve Vestal, "Fixed Priority Sensitivity Analysis for Linear Compute Time Models," *IEEE Transactions on Software Engineering*, April 1994.

Steve Vestal, "On the Accuracy of Predicting Rate Monotonic Scheduling Performance," *Tri-Ada '90*, December 1990.

REFERENCES

[1] Arkin, R.C., 1989. "Motor Schema Based Mobile Robot Navigation", *International Journal of Robotics Research*, vol. 8(4), pp. 92-112.

[2] Arkin, R.C., "Cooperation without Communication: Multi-agent Schema Based Robot Navigation", *Journal of Robotic Systems*, Vol. 9(3), April 1992, pp. 351-364.

[3] Arkin, R.C., "Behavior-based Robot Navigation in Extended Domains", *Journal of Adaptive Behavior*, Vol. 1, No. 2, pp. 201-225, 1992.

[4] Arkin, R.C., *Behavior-based Robotics*, MIT Press, to appear April, 1998.

[5] Arkin, R.C. and Ali, K., "Integration of Reactive and Telerobotic Control in Multi-agent Robotic Systems", *Proc. Int. Conf. on Simulation of Adaptive Behavior*, 1994, pp. 473-478.

[6] Arkin, R.C. and Balch, T., "AuRA: Principles and Practice in Review", *Journal of Experimental and Theoretical Artificial Intelligence*, Vol. 9, No. 2-3, April-Sept. 1997, pp. 175-189.

[7] Arkin, R.C., Carter, W., and MacKenzie, D., "Active Avoidance: Escape and Dodging Behaviors for Reactive Control", *International Journal of Pattern Recognition and Artificial Intelligence*, Feb. 1993, Vol. 7, No. 1, pp. 175-192.

[8] Arkin, R.C. and Hobbs, J.D., "Dimensions of Communication and Social Organization in Multi-Agent Robotic Systems", *Proc. SAB92*, 1992, pp. 486-493.

[9] Arkin, R. and MacKenzie, D., "Temporal Coordination of Perceptual Algorithms for Mobile Robot Navigation", *IEEE Transactions on Robotics and Automation*, Vol. 10, No. 3, June 1994, pp. 276-286.

[10] Balch, T. and Arkin, R.C., "Communication in Reactive Multiagent Robotic Systems", *Autonomous Robots*, Vol. 1, No. 1, pp. 27-52, 1994.

[11] Balch, T. and Arkin, R.C., "Motor Schema-based Formation Control for Multiagent Robot Teams", *Proc. 1995 Intern. Conf. on Multiagent Systems*, San Francisco, CA, pp. 10-16.

[12] Balch, T., Boone, G., Collins, T., Forbes, H., MacKenzie, D., and Santamaría, J., "Io, Ganymede, and Callisto - A Multiagent Robot Trash-collecting Team", *AI Magazine*, Vol. 16, No. 2, Summer 1995, pp. 39-51.

[13] Bentivegna, D., Ali, K., Arkin, R.C., and Balch, T., "Design and Implementation of a Teleautonomous Hummer", *Mobile Robots XII*, Pittsburg, PA, Oct. 1997.

[14] Hix, D. and Hartson, H., *Developing User Interfaces*, John Wiley and Sons, N.Y., 1993.

[15] MacKenzie, D., "A Design Methodology for the Specification of Behavior-based Robotic Systems", *Ph.D. Dissertation*, College of Computing, Georgia Tech, Draft, 1996.

[16] MacKenzie, D. and Arkin, R., "Evaluating the Usability of Robot Programming Toolsets", accepted to appear in *International Journal of Robotics Research*, 1998.

[17] MacKenzie, D., Arkin, R.C., and Cameron, R., "Multiagent Mission Specification and Execution", *Autonomous Robots*, Vol. 4, No. 1, Jan. 1997, pp. 29-52.

[18] U.S. Army, *Field Manual No 7-7J*. Department of the Army, Washington, D.C., 1986.

10. Description of Proprietary Data Rights

10.1 Restrictions

Software and technical data developed under this program at Georgia Tech will be deliverable to the government with non-exclusive license, with no restrictions on Government use, release, or disclosure. This includes the *MissionLab* system. None of the software to be delivered has been, or will be, developed at private expense.

Honeywell retains all rights to its pre-existing DoME commercial software that will be licensed to the government under our standard license agreement, and any enhancements, improvements or modifications developed under this effort will be made available commercially. Any software (MetaH, DCIRCA, ARM and RT-ARM) used in the proposed effort that Honeywell has previously received government purpose rights, we request these same rights. In recognition of Honeywell's interest in this technology and our continued investment and technology transfer to our commercial products, we request Government Purpose Rights to any extensions or enhancements to our pre-existing MetaH, DCIRCA, ARM and RT-ARM software to be developed under the proposed effort. The rights to any third party commercial software to be use in performance of this proposed effort will be governed by the terms set forth by the third-party license agreement.

10.2 Duplication

The technical data and software developed by Georgia Tech represents a new major release of *MissionLab*, new cooperative behaviors, and results from experiments conducted entirely under this program. None of these items have been delivered to the Government previously, nor will they be developed under other Government funding. Previous versions of *MissionLab*, however, have been developed under ONR/ARPA Grant #N00014-94-1-0215.

Contractor-owned equipment will be used in the development of the deliverables. This equipment will primarily consist of Sun workstations and laptop computers. The Government will not be furnished with this equipment. Vendor-supplied software libraries and other development tools are not deliverable, but will be purchasable from third-party sources. This vendor-supplied software includes the operating system (Linux or Sun Solaris), standard O/S utilities, and compilers.