A Multi-Vehicle, Wireless Testbed for Networked Control, Communications, and Computing

Richard M. Murray (PI)
John Doyle Michelle Effros Jason Hickey Steven Low
Division of Engineering and Applied Science
California Institute of Technology

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Summary

We plan to build a testbed consisting of 8-10 mobile vehicles with embedded computing and communications capability for use in testing new approaches for command and control across dynamic networks. The proposed system will allow testing of a variety of communications-related technologies that are relevant to future DoD systems, including distributed command and control algorithms, dynamically reconfigurable network topologies, source coding for real-time transmission of data in lossy environments, and multi-network communications. A unique feature of the testbed is the use of vehicles that have second order dynamics, requiring real-time feedback algorithms to stabilize the system while performing cooperative tasks. This testbed will be used for ongoing and proposed programs in control of multiple vehicles systems, networked control systems, control of communications networks for real-time systems, network channel and source coding, and high confidence software for distributed computation.

The testbed will be constructed in the Caltech Vehicles Laboratory and will consist of individual vehicles with PC-based computation and controls, and multiple communications devices (802.11 wireless ethernet, Bluetooth, and infrared). The vehicles will be freely moving, wheeled platforms propelled by high performance ducted fans. The room will contain access points for the 802.11 and Bluetooth networks, overhead visual sensing (to allow emulation of GPS signal processing), a centralized computer for emulating certain distributed computations, and network gateways to control and manipulate communications traffic.

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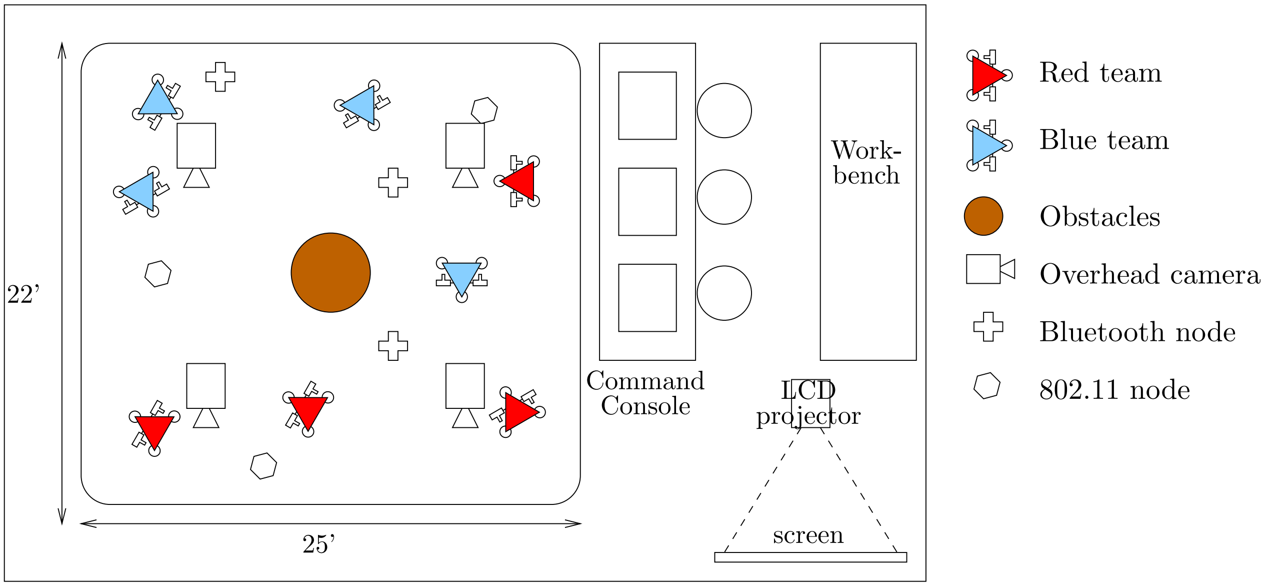

Figure 1: Multi-vehicle testbed layout.

1 Project Description

We propose to build a multi-vehicle, wireless testbed that contains the key features of mobile command, control, and communications networks for military and commercial applications. This testbed will be used for a variety of ongoing and proposed projects at Caltech and we intend that it serve as a valuable resource for future research in the area of networked control, communications and computing systems. In this section we give a detailed description of the main features of the testbed and provide some preliminary design criteria.

1.1 Testbed overview

Figure 1 shows the layout of the multi-vehicle testbed that we propose to construct. The testbed consists of

- 8–10 mobile vehicles with integrated computing and communications, including wireless ethernet (802.11), Bluetooth, and infrared communications capability
- 2-4 fixed communications nodes, capable of broadcasting on multiple channels, connected to fixed computing platforms
- A set of overhead cameras that can be used to provide position information to the vehicles (perhaps by simulating GPS information across the wireless ethernet network)
- A command console consisting of computing and communications nodes

Each of these items is described in more detail in the subsequent sections.

An important element of the testbed is that the individual vehicles will consist of freely rolling platforms, driven by thrust vectored fans. This will make the dynamics of the system be second order, requiring more advanced control techniques. In particular, momentum effects must be taken into account by the control system and hence real-time sensing and actuation will be important.

Flight area

Command area

Figure 2: Caltech Vehicles Laboratory.

This is in contrast to many other multi-vehicle testbeds that consist of mobile robots and other "kinematic" systems, where the motion of the system can be stopped and the dynamics of the system are a secondary consideration.

The testbed will be constructed in the Caltech Vehicles Laboratory, shown in Figure 2. This laboratory is currently being used for research in flight control using the Caltech ducted fan [8] and was constructed with a multi-vehicle testbed in mind. In addition to the "flight area" (left picture) and "command area" (right picture), the lab has a specially design ceiling which can accommodate cameras and fixed communications nodes. The multi-vehicle testbed will use the floor space and will not require that the current flight control experiment be dismantled.

The testbed will be capable of serving as an experimental platform for a variety of problems. From the controls perspective, the use of networked control systems can be studied, including the role of different communications protocols and topologies on overall system performance. From a communications perspective, the testbed allows the study of source coding algorithms for lossy communications across networked systems, routing protocols for *ad hoc* networks with real-time information constraints, and communications with redundant channels. Finally, the testbed can also be used for work in high-confidence, distributed computing in a dynamic environment.

1.2 Vehicle control system

The individual vehicles will consist of power, propulsion, computing and communications. A conceptual design is shown in Figure 3. To minimize cost and complexity, we intend to use commercial parts as much as possible. The overall platform will be 25–30 cm square and weigh approximately 5–6 kg. Ball casters will be used to allow free motion of the system across the floor (with some damping due to rolling friction).

The propulsion system will consist of two electrically driven, ducted fans, which are readily available through hobby dealers. These fans are capable of producing approximately 7N of force each and are similar to those that are employed on the Caltech ducted fan [8]. The fans will be used in a differential mode to vector the thrust on the vehicle, allowing rotation. The motors will be powered by batteries and we expect to be able to run the system for 30–60 min between charges.

The location of the vehicles will be provided by overhead cameras, augmented by local sensors,

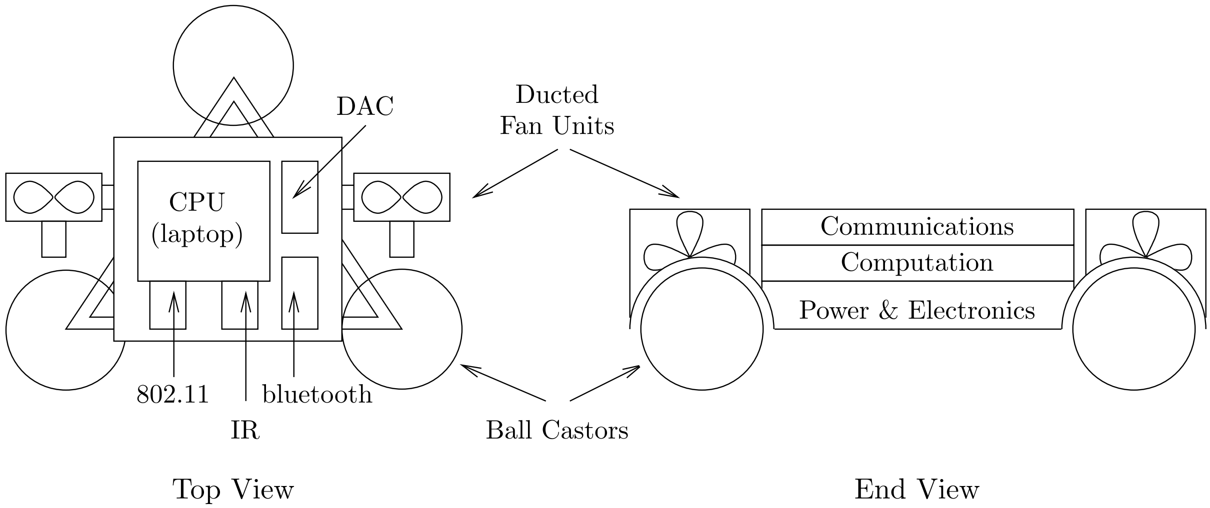

Figure 3: Proposed vehicle configuration.

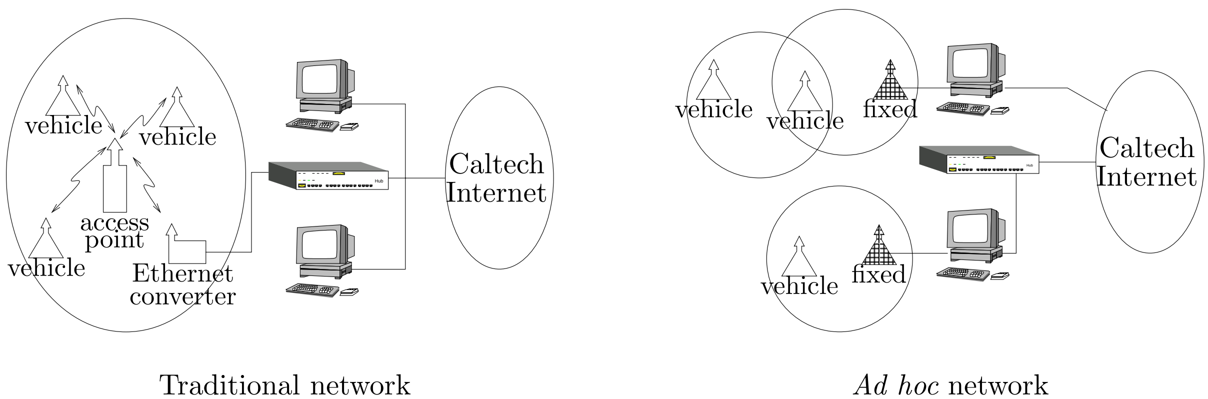

Figure 4: Possible communications topologies.

if needed. We intend to use a system similar to that used in the RoboCup competition,[1] where markers are placed on each vehicle to simplify the localization problem. The vision system is described in more detail in Section 1.4.

Computation on the vehicle will use ruggedized, laptop computers. The computers will be responsible for running the vehicle real-time control systems, performance guidance and navigation tasks, and managing the communications system. The real-time control system will use commercial data acquisition and control hardware to interface with the propulsion system.

1.3 Vehicle communications

A key element of the overall testbed is the use of multiple communications devices in a mobile environment. The system will be designed to operate using a variety of different communications topologies. Two such topologies are shown in Figure 4. In the traditional network topology, all vehicles are in a single communications domain and communications are via wireless ethernet.

[1]See `http://www.robocup.org` for more information.

In the *ad hoc* network topology, vehicles communicate with each other through a network whose interconnections are local (nearest neighbors) and dynamic. In this mode, latency due to network routing and congestion plays an important role in the overall performance of the system and hence routing and coding protocols will be critical for achieving high performance.

We plan to explore the use of multiple communications technologies within the testbed. Wireless ethernet (802.11) will be used to communicate with all vehicles in the flight area. We will have the capability of multiple channels, allowing multiple teams to communicate independently. We anticipate that interference will be present and the system will have to tolerate such system degradation. Communications rates across current 802.11 networks is up to 11 Mbps, allowing almost real-time communication between nodes.

We will also make use of the the emerging Bluetooth protocol for more localized communications topologies.[2] Bluetooth nodes can be programmed to have a range of 10 cm to 10 m, depending on power usage. For data rates, Bluetooth specifies two types of channels. *Synchronous channels* are meant for telephony and are symmetric with 64 Kbps in each direction. *Asynchronous channels* can have either symmetric rate or asymmetric rates. For symmetric channels, the rate can be from 108.8 Kbps up to 433.9 Kbps in each direction (whatever the rate chosen, it is the same for both directions). For asymmetric channels, it can be from 108.8 Kbps up to 723.2 Kbps in either direction, while supporting a matching rate of 108.8 Kbps down to 57.6 Kbps in the return direction.

We will also explore the use of other communications technologies, such as infrared, point-to-point communications. This is standard equipment on modern laptop computers and hence will be automatically included on the platform. Infrared communications allows individual vehicles to communications at up to 4 Mbps over a range of 1–2 meters. Some alignment of the sensors is required, complicating the use of this system in a dynamic environment. We anticipate some future work using multi-antenna arrays as part of the system, in conjunction with ongoing work by Professors Rutledge, Hajimiri, and Hassibi in the Electrical Engineering Department at Caltech.

1.4 Command and control system

The command and control system will consist of two desktop computers that are responsible for managing the communications in the workspace and performing system level command functions. Since one of the functions of the testbed will be to test new network routing protocols, we will make use of one of the computers as a communications gateway (multiple ethernet cards).

The position of the cards within the room will be determined using a set of four overhead cameras, connected to a quad video multiplexer (to produce a single image). Special markings on the vehicles will be used to simplify the problem of determining each vehicles location in the image (this is similar to the approach used in the RoboCup competition). The command computer will process these images and send out position information to the vehicles across the wireless ethernet channel, roughly simulating the type of data that would be available with a GPS system.

Local measurement of the vehicle position and orientation may be required to achieve stability in the presence of large network latency. If needed, we will augment the vehicle with a simple dead reckoning system consisting of a rotating wheel with encoders to measure the wheel angle and velocity.

[2] See `http://www.bluetooth.com` for more information on this emerging standard.

1.5 Integration with existing facilities

As described briefly above, the system will be placed in the existing Caltech Vehicles Lab. This laboratory has a 25'x22' flight area that can be separated from the rest of the room by blackout curtains and/or a safety net. The flight area has a raised wooden floor that can be used to run cables to the workspace without impeding vehicle motion.

In addition to the local networking on the vehicles and in the flight area, the system will be integrated with the Caltech intranet, allowing use of additional network resources. This includes integration with several existing real-time control systems capable of real-time trajectory generation for the ducted fan flight control experiment.

The programming environment for the system will make use of existing hardware and software at Caltech, including software development tools for real-time programming and programming languages for distributed computing.

2 Budget

A summary of the proposed budget for the project is show in Table 1. Since this is a specialized facility, the testbed will be built from individual components. With the exception of machining time for the vehicles, labor associated with assembling the testbed will be done as part of work on the individual projects that will make use of this facility and hence will not be charged to the project.

Table 1: Budget summary.

Item	Cost	Qty	Total
Vehicle frame and propulsion	2,314	10	$23,140
Vehicle computing and communications	6,386	10	63,860
Room instrumentation	20,505	1	20,505
Command center	14,561	1	14,561
Tax and shipping (estimated)			18,310
Total			**$140,376**

A detailed listing of the parts required to build the system is shown in Table 2. A short description of each major component is given below.

2.1 Vehicle frame and propulsion

The vehicle will be constructed using an aluminum frame and will be supported on a set of three ball casters. These casters have good friction properties and allow unimpeded motion in any direction.

The propulsion system will consist of two electrically-driven, ducted fans, mounted to the sides of the vehicle. Each motor requires approximately 100W (peak power) and will be driven by a 3000 mAh battery. The ducted fan units are high performance units designed for thrust-vectored, radio-controlled (R/C) aircraft and will be driven through a commercially available, R/C amplifier unit.

The control system for the vehicle will consist of a Matlab-based, real-time control system (Real-Time Windows Target) connected to a PCMCIA data-acquisition system. In addition to receiving position information through the network interface, a simple pivoting, rolling wheel with optical encoders will be used to measure local position changes.

2.2 Vehicle computing and communications

Each vehicle will have a laptop as its primary control computer. PCMCIA (PC Card) ports will be used to host the data acquisition and control (DAC), 802.11 (wireless ethernet) and Bluetooth hardware. Bluetooth hardware is not yet commercially available and hence all prices for Bluetooth related hardware are estimates. These are roughly based on initial prices of wireless ethernet hardware upon introduction to the market (approximately $1500/node). Current Bluetooth development systems are available for $4000/node in quantities of 5 or more.[3]

2.3 Room instrumentation

Overhead cameras will be used to measure the location of the vehicles and provide a visual description of the state of the system. Four cameras are required due to the layout of the room (the support post for the ducted fan is in the center of the flight area). The cameras will be integrated using a "quad multiplexor", which takes four video signals and produces a single image (used for security systems).

There will also be several fixed communications nodes in the workspace, to allow exploration with mobile and fixed communications nodes. For the 802.11 nodes, we will use ethernet converters to allow individual PC's in the command center to have a physical presence in the flight area.

2.4 Command center

The command center will consist of two computers (one for command and control, one for communications), as well as some simple networking hardware. An LCD projector will be used to display the combined images from the overhead camera onto a screen for real-time visualization.

[3] Digianswer Bluetooth demo card; see `http://www.digianswer.com/prod_view.asp?P_ProdID=14`.

3 Supporting Information

In this section we describe how the proposal will enhance the quality of ongoing projects at Caltech, contribute to projects currently being proposed to DoD, and add new capabilities that will enable research in areas of interest to DoD.

3.1 Ongoing projects

The following ongoing projects would make use of the proposed testbed.

High Confidence, Reconfigurable, Distributed Control (Murray, Doyle; DARPA) The theme of our research is the development of distributed control systems that can be dynamically reconfigured and in which DoD can have high confidence. In this project we are developing the underlying theory, building software tools, and experimentally implementing our results. This project is part of the Online Control Customization (OCC) task for the Software Enabled Control program (Helen Gill, program manager). The objectives for this program are:

- Optimization-based, hierarchical control architectures for motion control systems
- Theoretical framework for multi-vehicle coordination and distributed control
- Exploration of trajectory spaces for aggressive flight vehicles
- Experimental implementation using the Caltech Ducted Fan

Initial progress is reported in [4, 8, 9]. The proposed testbed would allow experimental implementation and testing of the multi-vehicle framework that will be developed under this project.

Formation Flight of Micro-Satellite Clusters (Murray; AFOSR) One of the significant challenges to successful formation flight of spacecraft is maintenance of the formation, i.e., control of the motion of the individual spacecraft to maintain an overall formation. This includes both stabilization of a given formation and reconfiguring of the formation. While the dynamics and control a single spacecraft is well understood, a formation of spacecraft effectively acts a deformable body due to control forces which restore it to its desired formation. As a deformable body, the formation is capable of exhibiting complex dynamic behavior. Effective control strategies must exploit this behavior and the natural dynamics of the system to achieve goals such as formation error minimization and minimal fuel consumption during formation reconfiguration. An additional concern is the impact a decentralized control structure would have control algorithm design and formation controllability. This project is studying theoretical approaches to such problems and the testbed would provide an experimental platform to test some of these approaches.

Network Source Coding (Effros; NSF) This project aims to prove that existing approaches to source coding for network systems are fundamentally flawed and to demonstrate that far superior performance is attainable through a radical shift in the source coding paradigm. The project involves proving this concept in theory, demonstrating that the gains promised by the theory are enormous for real data sets, and developing practical codes to achieve those gains. The proposed proof of concept is being carried out on both broadcast systems and multiple access systems, and includes work in

- Rate-distortion theory for broadcast and multiple access system source codes

- Practical broadcast and multiple access system source code design
- Generalized source coding algorithms

Initial results have been reported in [1, 7, 2, 3, 10, 11].

3.2 Pending proposals

Theoretical Foundations for Networked Control, Communication, and Computing (Doyle, Effros, Low, Hickey, plus UCLA; MURI/ARO) The objectives of this proposed effort are to develop new concepts for radically embedded networks and a more integrated theory of control, communications, and computing relevant to the design of embedded, complex, uncertain, distributed and dynamic networked systems. The approach is to combine the "pull" of advanced network designs and application scenarios with the "push" of new theory development to create a spectrum of synergistic research. Concepts for advanced network design will be explored using simulation and experiment, typically beyond what can be systematically treated theoretically. This will motivate fundamental research in the development of more integrated theory.

This testbed would enhance the research under this MURI proposal by allowing different communications technologies (eg, wireless versus Bluetooth), as well as mobile networks, to be explored.

Cooperative Control of Distributed Autonomous Vehicles in Adversarial Environments (Murray, Hickey, with Cornell (lead), UCLA, and MIT; MURI/AFOSR) In this project, our goal is to develop the tools required for the systematic design of cooperative control systems for distributed vehicles in adversarial environments. Our approach will bring together as a foundation methods from the disciplines of control theory, computer science, and biological systems. We will use case studies of DoD interest to motivate and demonstrate our results. Two case studies of specific interest are coordinated multi-vehicle control with obstacle and mutual avoidance and autonomous unmanned aerial vehicle (UAV) suppression of enemy defenses.

Expected outcomes and deliverables of this research include:

- Theory: An analytical understanding of achievable performance of cooperative, distributed systems as a function of decision architectures, communication topologies and constraints, computational complexity, physical constraints and adversarial conditions.
- Computation: Algorithms and software tools for control design, test, evaluation, and rapid prototyping.
- Experimentation: Virtual application to specific case studies. Hardware testbeds for internal demonstration as well as open national team-on-team investigations.

The testbed described in this proposal would augment the testbeds proposed in this MURI (which would be located at UCLA and Cornell). In addition, it would allow increased exploration of communications protocols and their impact on coordinated control algorithms.

3.3 New research capabilities

In addition to the ongoing and proposed activities described above, this testbed will enable progress and build capability in additional research areas.

Network flow control For network flow control research, the testbed will be useful in understanding, designing, and evaluating proposed and new TCP flow control schemes in wireless environments. The current TCP schemes are designed for wireline networks and use packet loss as an indication of congestion (i.e., buffer overflow) and/or assume that the path from a source to its destination does not change. Both assumptions are violated in wireless *ad hoc* network, where TCP is widely known to perform badly. There have been a few proposals to patch up the current schemes, but they are either ineffective or incur excessive processing at the base station because of their desire to continue to use loss to signal congestion. Professor Low and his coworkers are developing a simple solution, based on REM [6], by abandoning this restriction. The testbed will provide an opportunity to evaluate its performance in a realistic setting.

Distributed software systems Caltech's research in distributed software systems focuses on three key areas: 1) how to develop reliable and robust communication protocols and distributed applications, 2) high-level programming environments that assist in the development of distributed applications, and 3) theoretical models for which we can prove performance and reliability guarantees. For example, our recent work has focused on the development of reliable *group communication protocols* [5] where there are guarantees about consistency between the different processes that make up a distributed application. The *theoretical* model provides both a specification that all processes handle events in an order consistent with failures and changes in network connectivity, and development techniques for building protocols by composition of micro-protocols with specific features. High level programming environments provide a method for building communication protocols by selecting their desired features, and also provide an automated mechanism that optimizes the protocol to its environment.

So far, our work has been concerned with *safety*: can we guarantee that a distributed application will work correctly in the presence of failures? Performance has not been addressed except at the theoretical level.

Our proposed testbed takes the next step. The testbed presents a highly dynamic distributed environment with requirements on robustness and real-time performance. It presents an ideal platform for validating our theoretical models and extending the scope of our work to include hard real-time requirements for distributed applications. We expect that the testbed will provide key insights that we can use to enhance our theoretical models, and and allow us to develop practical programming languages and environments that can be used to address general problems in high-performance real-time distributed systems.

Research on these topics is very relevant to future DoD missions. Specific applications include robust distributed applications in adversarial environments, formal methods to construct secure distributed software, programming environments that facilitate rapid development and deployment of safety-critical software, and open environments for collaborative development of safe and secure systems.

4 References

[1] D. Dugatkin and M. Effros. Setting priorities: a new SPIHT-compatible algorithm for image compression. In *Proceedings of SPIE International Symposium on Optical Science and Technology*. SPIE, 2000.

[2] M. Fleming and M. Effros. Generalized multiple description vector quantization. In *Proceedings of the Data Compression Conference*, pages 3–12. IEEE, 1999.

[3] M. Fleming and M. Effros. The rate-distortion region for the multiple description problem. In *Proc. Interntional Symposium on Information Theory*. IEEE, 2000.

[4] J. E. Hauser and A. Jadbabaie. Aggressive maneuvering of a thrust vectored flying wing: A receding horizon approach. In *Proc. IEEE Control and Decision Conference*, 2000. Submitted.

[5] X. Liu, C. Kreitz, R. van Renesse, J. Hickey, M. Hayden, K. Birman, and R. Constable. Building reliable, high-performance communication systems from components. In *17^{th} ACM Symposium on Operating Systems Principles (SOSP'99)*, volume 34 of *Operating Systems Review*, pages 80–92, 1999.

[6] S. H. Low and D. E. Lapsley. Optimization flow control, I: Basic algorithm and convergence. *IEEE/ACM T. Networking*, 7(6):861–874, 1999.

[7] M.Effros. Network souce coding. In *Proceedings of the 34th Annual Conference on Information Sciences and Systems*, 2000.

[8] M. B. Milam and R. M. Murray. A testbed for nonlinear flight control techniques: The Caltech ducted fan. In *Proc. IEEE International Conference on Control and Applications*, 1999.

[9] M. B. Milam, K. Mushambi, and R. M. Murray. A computational approach to real-time trajectory generation for constrained mechanical systems. In *Proc. IEEE Control and Decision Conference*, 2000. Submitted.

[10] Q. Zhao and M. Effros. Broadcast system source codes: a new paradigm for data compression. In *Conference Record, Thirty-Third Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, October 1999. IEEE. Invited paper.

[11] Q. Zhao and M. Effros. Lossless and lossy broadcast system source codes: theoretical limits, optimal design, and empirical performance. In *Proceedings of the Data Compression Conference*. IEEE, 2000.

5 Personnel

Five faculty at Caltech have teamed together to work on this proposal, representing the areas of control (Murray and Doyle), communications (Effros and Low) and computation (Hickey). Resumes for these individuals are attached.

In addition, the testbed will be made available to faculty at other institutions who have research interactions with Caltech. This includes members of the DARPA Software Enabled Control (SEC) program as well as an AFOSR sponsored project on coordinated control for micro-satellite cluster.

We have already had discussions with several additional faculty at Caltech who are interested in communications technology and we anticipate future use of this testbed by those faculty. These include Professors Rutledge and Hajimiri, who have an ongoing project to develop a 24 GHz silicon antenna array, and Professor Hassibi, who is interested in multi-antenna communications protocols.