Model-based Design and Qualification of Complex Systems

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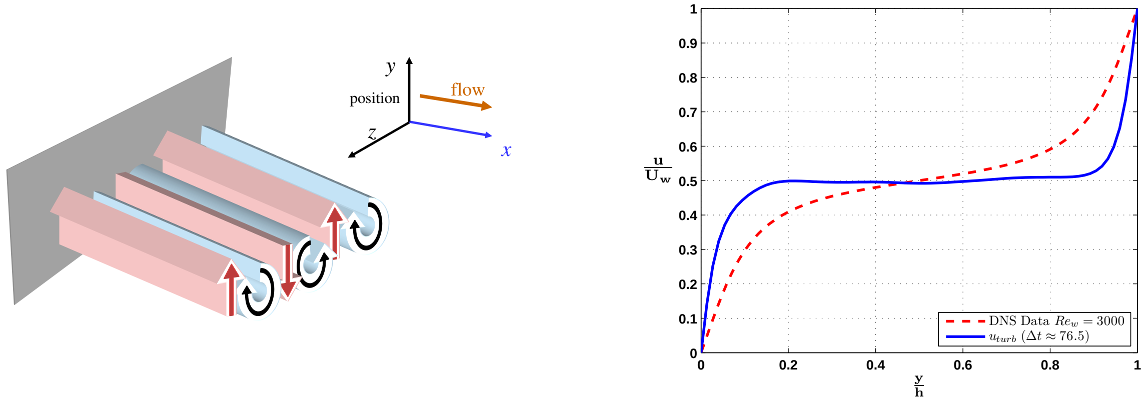
This report summarizes the work supported by Boeing over the period of May 2007 through April 2008.

1 Project Overview

The broad goal of this project is to develop new theory, algorithms and demonstrations of model-based design strategies for complex systems. This activity is broken up into three broad themes:

1. *Systems Modeling Theory and Practice:* Development of modeling and analysis tools, with emphasis on hierarchies of simulations that can be used for verification and testing at different levels of fidelity. A key issue is the development of multiple simulations that can be combined to form high fidelity models while at the same time being used in simpler combinations for rapid testing of higher level functions (where highly detailed models are too large or too slow to allow exploration of the relevant design space).
2. *Multiscale Analysis of Complex Systems:* Novel approaches to multiscale analysis based on methodologies and techniques developed for physical dynamical systems. To develop the required methodologies and techniques we are focusing on an archetype complex system which may contain a multitude of scales, namely collections of disparate coupled nonlinear oscillators where each oscillator may have its own natural frequency.
3. *Engineering Implementation:* Application of new tools in modeling, design and qualification of complex systems to specific engineering systems of systems that will provide an evaluation of the efficacy of both the framework and the tools toward applications. Two specific testbeds are being used for this purpose: the Caltech multi-vehicle wireless testbed (MVWT) and the Caltech autonomous vehicle testbed ("Alice").

In the first year of the project, the focus was primarily on the theory of robust yet fragile behavior in complex systems and multi-resolution modeling. Beginning in year two, a new activity in engineering implementation was added, to explore the use of theoretical tools on more practical applications, under the direction of Richard Murray. Last year, a new activity in multiscale modeling, focusing on physical and networked systems, was added, with Michael Cross and Gil Refael becoming part of the project. In the coming year, the project is being refocused to reflect



(a) (b)

Figure 1: Modeling of complex fluids. (a) The stream-wise constant rolls believed to be present in turbulent wall bounded shear flows. Turbulent velocity profile obtained by simulation (at $Re_w = 6000$) vs. profile obtained from DNS. (at $Re_w = 3000$). Increased blunting of the velocity profile with increased Reynolds number is observed as expected. (U_w is velocity of moving plate and h is channel height).

the themes listed above, with the modeling tasks more focused on design-oriented tools. This refocusing is only partially reflected in the current report, since it is being phased in over the current year.

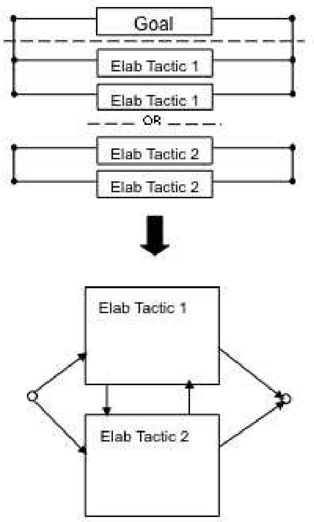
2 Core Theory

Our approach to the development of core theory has been to focus on case studies that allow us to build appropriate conceptual frameworks, methods, and mathematical tools. This section describes some the key results of the project over the last year in areas related to robust yet fragile behavior as well as analysis and design of complex, networked systems.

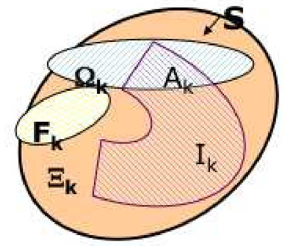
2.1 2D/3C Modeling of Turbulence in Fluids (Dennice Gayme)

Given the consensus that turbulent flow is characterized by coherent structures and observations of streamwise constant structures (as depicted in Figure 1a) in numerical simulations and experiments, (in the near wall region), we model the mean behavior of fully turbulent plane Couette flow using a streamwise constant projection of the Navier Stokes (NS) equations. This so called $2D/3C$ model uses all three velocity components so that the true $3D$ nature of turbulent flow is not lost. It comprised of two equations; one in terms of the spanwise/wall normal stream function $\psi(y, z, t)$ with noise forcing, and the other in terms of the stream-wise velocity, $u(y, z, t)$, and $\psi(y, z, t)$. This model is nonlinear but analytically more tractable than the full NS equations. It was previously shown to have a single globally stable solution [1] and can be used to explore the full space of the equations with appropriate forcing.

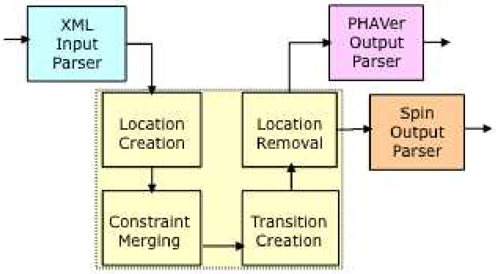
In our work we use DNS data from [20] with $Re_w = 3000$, ($Re_\tau = 52$) to validate the model in the full turbulent velocity field. The data is also used with the steady state $2D/3C$ model to show



Goal network to hybrid automata conversion



Sets of elements for failure probability calculation



Automatic conversion software schematic

Figure 2: Verification using goal networks.

that it explains large scale behaviors of the turbulent flow, such as blunting of the velocity profile. A full time varying simulation also predicts this important flow feature (as shown in Figure 1b) and shows promise in identifying other known flow characteristics.

2.2 Safety Verification of Fault Tolerant Goal-based Control Programs (Julia Braman)

Fault tolerance and safety verification of control systems, including those that have state estimation uncertainty, are essential for the success of autonomous robotic systems. A control architecture called Mission Data System (MDS), developed at the Jet Propulsion Laboratory, takes a goal-based control approach. An automatic software algorithm for converting goal network control programs into linear hybrid systems has been developed, as shown in Figure 2. The resulting linear hybrid system can then be verified for safety in the presence of failures using existing symbolic model checkers.

Many autonomous robotic systems must have control programs that are robust to errors in state estimation; therefore a process for calculating the probability of failure of some verifiable goal networks due to state estimation uncertainty has been developed. This process allows uncertainty in sensor health, and determines the probability that such uncertainty could lead to mission failures. As with the deterministic verification results, the approach has been implemented as an automated procedure to facility usage in engineering applications.

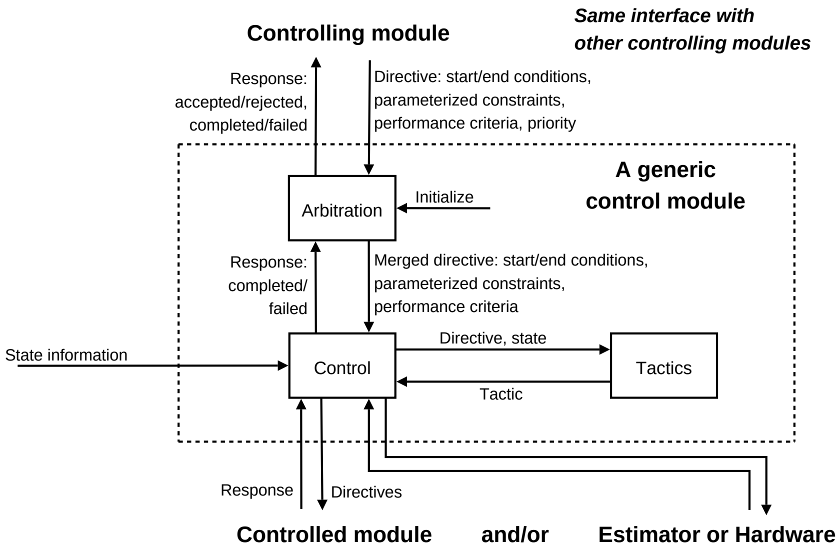


Figure 3: A generic control module in the Canonical Software Architecture.

2.3 A Canonical Software Architecture for Distributed Mission and Contingency Management (Nok Wongpiromsarn)

Unexpected adverse situations such as hardware and software failures and unexpected changes in the environment are inevitable in any complex system. Due to an absence of human intervention, an autonomous system needs to be able to "properly" detect and respond to these situations in order to ensure safety and mission success. This is often achieved using a centralized approach where a central module communicates with nearly every software module in the system and directs each module sequentially through its various modes in order to recover from failures. A drawback of this approach is that the central module usually has so much functionality and responsibility that it easily becomes unmanageable and error prone as the system gets more complicated.

The complexity and dynamic nature of the urban driving problem make centralized mission and contingency management impractical. We have therefore developed a Canonical Software Architecture (CSA) for a hierarchical planning subsystem that allows mission and contingency management to be achieved in a distributed and dynamic manner. This architecture builds on the state analysis framework developed at JPL. To separate communication from the core functionality of the module, a CSA module is divided into three components: Arbitration, Control and Tactics, as shown in Figure 3. The inputs and outputs are also limited to the following: state information, directives/instructions and responses/status reports.

In the CSA framework, fault handling is embedded into all the modules and their communication interfaces in the planning subsystem hierarchy. Each module has a set of different control strategies which allow it to identify and resolve faults in its domain and certain types of failures propagated from below. If all the possible strategies fail, the failure will be propagated up the hierarchy along with the associated reason. The next module in the hierarchy will then attempt to resolve the failure. These mechanisms make the system capable of exhibiting a fail-operational/fail-safe and intelligent responses to a number different types of failures in the system. This approach has been implemented on Alice, an autonomous vehicle developed by Caltech for the 2007 DARPA Urban

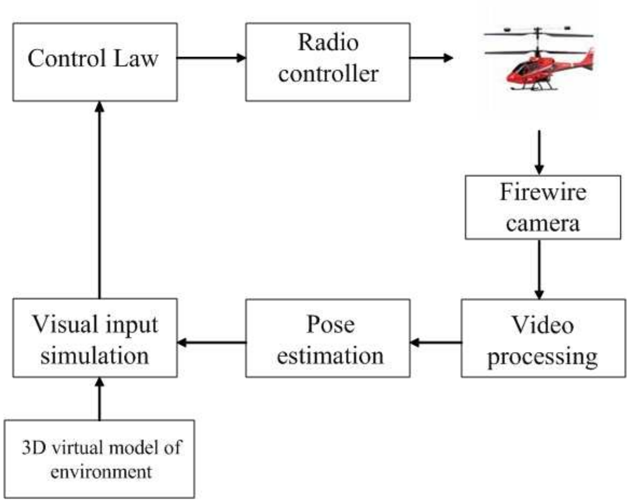


Figure 4: Block diagram for helicopter testbed with simulated visual input.

Challenge. Extensive testing has demonstrated the desired behavior of the system which is that it will keep trying different strategies in order to get closer to completing the mission and never stop as long as it is capable of operating safely.

The structure of a module and its communication interfaces imposed by the CSA can also be exploited in formal verification to address the state explosion problem in automatic verification based on model checking. Our approach is to decompose the overall system-level requirements into a set of component-level requirements. Each of the components can then be model checked separately. Certain properties of Alice such as state consistency of certain software modules have been formally verified using this approach.

2.4 An indoor helicopter testbed for simulation-based, bio-inspired controller design (Shuo Han)

It is generally accepted by the biology community that vision plays an important role in insect flight control. From an engineering perspective, it is interesting to study how the way that insects utilize their visual stimuli can be implemented in controller designs, which have potential applications in micro aerial vehicles (MAV). Motivated by this, we have been building an indoor testbed that aims to maneuver a mini radio-controlled model helicopter from visual inputs. Due to the fact that indoor model helicopters are usually lightweight and thus do not offer a large carrying capacity, simulated visual inputs rather than video stream from onboard image sensors are used. Generating simulated visual input requires knowledge of the current pose (position and orientation) of the helicopter. This is estimated by tracking the 5 LEDs equipped on the helicopter from a ground firewire camera operated at 60 frames/s. The pose estimation algorithm is implemented from existing methods called POSIT and SoftPOSIT in FORTRAN/C to ensure speed. The post information, combined with a 3D model that describes the virtual surrounding environment, is fed into a program called fsee, developed by Andrew Straw in Michael Dickinson's lab at Caltech, to generate the equivalent visual inputs as if one were looking from the helicopter. A suitable control law (currently under development) will then command the helicopter through its radio controller, which is modified to

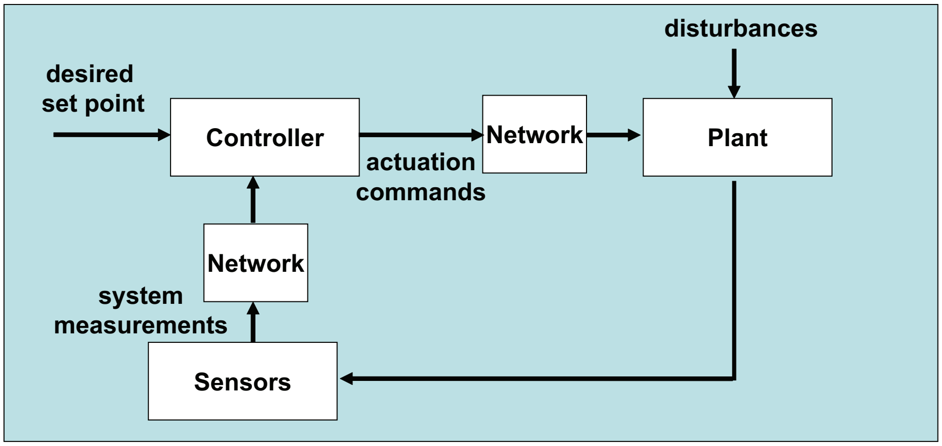


Figure 5: Block diagram for a networked control system.

communicate with PC through a parallel or USB port. The testbed also has abilities to incorporate other factors such as gust generation for studying different controllers performance on disturbance rejection.

2.5 Managing Information in Networked and Multi-Agent Control Systems (Michael Epstein)

In recent years the field of Networked Control Systems (NCS) has emerged to describe situations where information in feedback control loops is passed through imperfect communication channels that can result in quantized, delayed and even lost information. The research in this field focuses on quantifying performance degradations in the presence of network effects and proposing algorithms for managing the information flow to counter those negative effects. The focus of this work it to propose and analyze algorithms for managing information flow for several NCS scenarios; state estimation with lossy measurement signals, using input buffers to reduce the frequency of communication with a remote plant, and performing state estimation when control signals are transmitted to a remote plant via a lossy communication link with no acknowledgment signal at the estimator (see Figure 5). Multi-agent coordinated control systems serve as a prime example of an emerging area of feedback control systems that utilize feedback loops with information passed through possibly imperfect communication networks. In these systems, agents use a communication network to exchange information in order to achieve a desired global objective. Hence managing the information flow has a direct impact on the performance of the system. We also explore this area by focusing on the problem of multi-agent average consensus. We propose an algorithm based on a hierarchical decomposition of the communication topology to speed up the time to convergence. For all these topics we focus on designing intuitive algorithms that intelligently manage the information flow and provide analysis and simulations to illustrate their effectiveness.

2.6 Delay Sensitivity in Networked Stochastic Systems (Johan Ugander)

The dynamics of genetic regulatory networks contain many complex facets that require careful consideration during the modeling process. The basic modeling approach for genetic regulatory networks involves studying systems of ordinary differential equations (ODEs) that model biochemical reactions in a deterministic, continuous, and instantaneous fashion. In truth, the dynamics of these systems are stochastic, discrete, and widely delayed. The first two complications are often successfully addressed by modeling regulatory networks using the Gillespie stochastic simulation algorithm (SSA), while the delayed behavior of biochemical events such as transcription and translation are often ignored due to their mathematically difficult nature. We are developing techniques based on delay-differential equations (DDEs) and the delayed Gillespie SSA (DSSA) to study the effects of delays, across both continuous deterministic and discrete stochastic settings.

Our preliminary findings show that applying techniques from Floquet theory and advanced numerical analysis within the context of delay-differential equations, we are able to derive stability sensitivities for biochemical switches and oscillators across the constituent pathways, showing which pathways in the regulatory networks improve or worsen the stability of the attractor. These delay sensitivities can be far from trivial, and we aim to develop a computational framework validated across multiple levels of modeling fidelity. We are currently studying this behavior within a discrete stochastic framework.

This work suggests that delays may play an important and previously overlooked role in providing robust dynamical behavior for certain genetic regulatory networks, and perhaps more importantly, may offer an accessible tuning parameter for robust bioengineering.

2.7 Opportunistic source coding for data gathering in wireless sensor networks (Lijun Chen)

Data gathering is the base for most functionalities and applications of mobile ad hoc sensor networks. When sensor nodes are concentrated geographically, data sampled at distributed nodes are highly correlated. In this situation, one can carry out in-network data compression, so as to reduce expensive data transmission. Such compression and its interaction with routing has been the subject of several previous studies, e.g., distributed source coding (DSC) and routing driven compression (RDC). However, DSC requires the sources to have perfect knowledge about their correlation, which is impractical in a network environment, and both DSC and RDC assumes routing techniques similar to those in wireline networks, neglecting the characteristics of wireless transmission. On the one hand, wireless transmission is error-prone. Sequential forwarding of packets along a fixed path may incur many retransmissions, and thus exhaust scarce network resources such as energy and capacity. On the other hand, wireless transmission is broadcast in nature. The chance that all the neighboring nodes fail to receive the packet is small (multiuser diversity in packet reception). Moreover, multiple receptions of a packet by different nodes can also be exploited for opportunistic data compression. By leveraging the wireless broadcast advantage and multiuser diversity, we can reduce the number of wireless transmissions needed for data gathering.

In [14], we proposed a jointly opportunistic source coding and opportunistic routing (OSCOR) protocol for correlated data gathering in wireless sensor networks. OSCOR broadcasts each packet, which is received by possibly multiple sensor nodes, and opportunistically chooses a receiving neighbor to forward the packet, with the goal of obtaining a path online with highest possible compression and best possible link quality. Opportunistic forwarding with opportunistic compression allows OSCOR to exploit multiuser diversity in packet reception, data compression and path selection, resulting in high expected progress per transmission. OSCOR consists of three modules. The first module is a low overhead consensus protocol to coordinate wireless transmission and packet forwarding so as to exploit multiuser diversity in packet reception. The second module is a practical

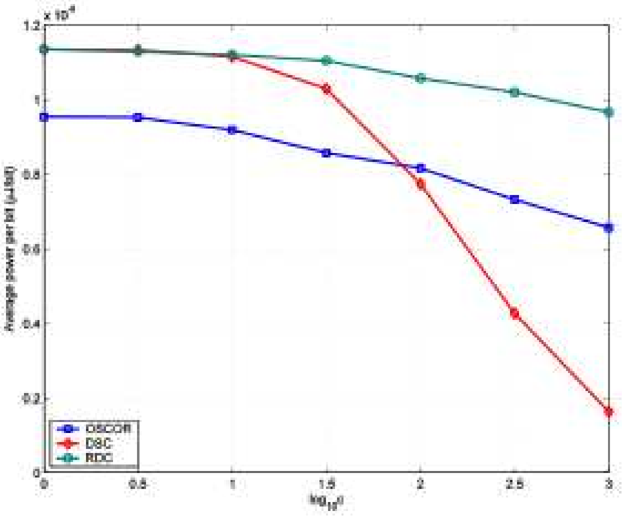


Figure 6: Average power consumption versus correlation parameter c with OSCOR, RDC and DSC.

distributed source coding scheme that combines and takes advantage of both Lempel-Ziv code and network coding. Lempel-Ziv code does not require the knowledge of the statistics of the data and is used to obtain an estimate of the number of coded bits needed, and random network coding is applied to do distributed compression of information in networks. The third module is a routing algorithm that updates a path metric that is the expected transmission count discounted by node compression ratio (cETX) along the path from a node to the sink or the central command. The consensus protocol will use this path metric to prioritize neighboring nodes, and choose the receiving neighbor with highest priority to forward the coded data towards the central command. The use of such a path metric makes opportunistic source coding interact beneficially with opportunistic routing so as to route packets over paths with high compression and good link quality.

Figure 6 shows the average power consumption per bit versus the correlation parameter c with different schemes in a 4-by-4 grid network. We see that OSCOR always outperforms RDC, and outperforms DSC for moderate correlation. Note that the performance gain of OSCOR comes from the compression opportunities and the multiuser diversity. We expect OSCOR outperforms DSC in a densely-packed network, due to more diversity in packet reception and more chances in data compression in such a network. So, OSCOR is well suited to exploit the heavy-tailed spatial distribution to achieve efficient and effective data gathering in wireless ad hoc sensor networks. It performs better in a denser network that experiences higher contention.

3 Multiscale Analysis

Many engineering and physics problems require an understanding of how a large number of unit-modules interact with each other to produce the desired or observed large scale global behavior. The goal of the nonlinear-oscillator project is to develop a general framework that will optimize calculations in such systems, and will be able to extract the complicated global behavior of an inter-dependent system from a series of solutions of simple local problems. Our attempt to construct such a general framework relies on what physicists refer to as scaling, coarse graining, and the

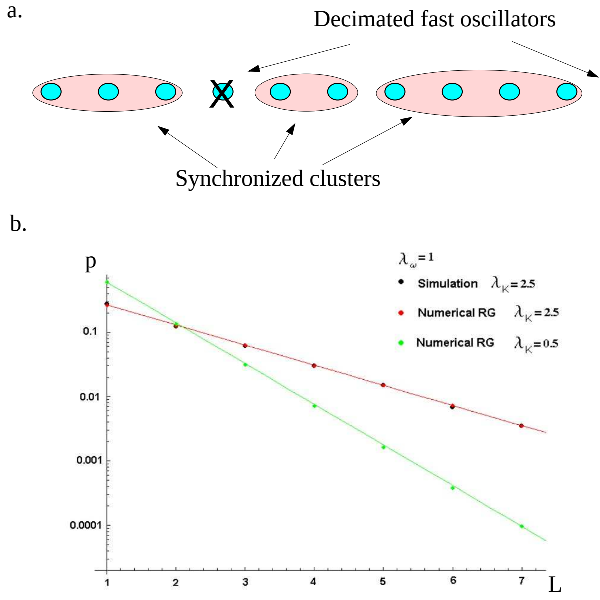


Figure 7: Synchronization of oscillator chains. (a) A chain of oscillators with random frequency breaks down to an array of synchronized clusters. The Renormalization Group allows us to identify the clusters, marked with ellipses, through a process of decimating very fast oscillators, marked with X. (b) Semi-log plot of the density of clusters vs. cluster size. This plot compares the results of exact numerics, with the results of the much simpler RG calculation, for a chain with a Lorentzian distribution of oscillator frequencies (omega) and couplings (K). For the case in which RG and numerics are compared, the agreement is clear. In addition, this calculation reveals a global principle in these systems: cluster-density decays exponentially with its size, with a characteristic length which depends on the width of the coupling distribution.

renormalization group (RG).

The first stage of the project has been to develop a reliable RG framework for a chain of oscillators interacting with their neighbors through a synchronizing interaction, but with each oscillator having an independent (randomly distributed) bare oscillation frequency, as illustrated in Figure 7. It has been proven rigorously in the literature that the oscillators do not form a global synchronized cluster in this system, no matter how strong the interaction. Instead, the competition between the synchronizing interaction and the width of the bare frequency distribution gives rise to complicated behavior: many oscillators join into synchronized clusters which move together, but these clusters have widely varying sizes. Our RG framework allows the extraction of large scale properties of the solution of the complicated dynamical equations of motion from simple local constructions, such as the formation of synchronized clusters, and of decoupled fast-moving oscillators. Oleg Kogan, a student in our group, applied these rules to many oscillator chains with a Lorentzian distribution of frequencies. He carried out a direct comparison of both global properties, such as cluster-size distribution, and of the actual oscillating frequencies of single oscillators, to resource-heavy exact numerical solutions of the system done by Jeff Rogers. The major results are:

1. The two-step renormalization approach gives excellent agreement with exact numerical solution for statistical properties such as the cluster size distribution and the distribution of

frequencies for each cluster size, and also for the actual clusters and their frequencies for individual realizations of the random frequencies and couplings.

2. The distribution of cluster length sizes n is *exponential*

   $$P(n) \propto e^{-n/\xi},$$

   with ξ a characteristic length scale that depends on the widths of the distributions. The exponential behavior is valid over all of the wide range of distribution widths investigated.

3. The dependence of the length ξ on the ratio κ of the width of the coupling distribution to the width of the frequency distribution is close to a *square root*

   $$\xi \propto \kappa^{0.47}.$$

Having demonstrated the efficacy of our RG approach for the special case of a Lorentzian distribution for oscillator frequencies in one dimension, a major longer term goal is to apply the RG principle to systems with higher connectivities that will feature more of the difficult issues that need addressing. Therefore we have also investigated two-dimensional systems of non-linear oscillators. Very little is known about two dimensional oscillator arrays, since the increased connectivity between the units of the system significantly complicates the problem. We have characterized the global behavior of two-dimensional oscillator arrays by conducting numerical studies of synchronization patterns (mainly the work of student Heywood Tam in our group working closely with Jeff Rogers), again for Lorentzian distributions for the frequencies and nearest neighbor coupling strengths. The major results are:

1. The distribution of cluster sizes r (given by the square root of the number of oscillators in a locked cluster) follows an interesting scaling form

   $$P(r) \propto \frac{1}{r^p} e^{-r/\xi(\kappa)} \tag{1}$$

   where $p \simeq 2$.

2. The characteristic size ξ *diverges* as the width of the distribution of the coupling strengths increases at a *finite, critical* value κ_c of κ.

3. For $\kappa > \kappa_c$ the system remains dominated by *large* but *finite clusters* with distribution $P(r) \propto r^{-p}$ with again $p \simeq 2$.

A paper reporting these results is being prepared.

The scaling results suggest for the first time that a synchronization related phase transition occurs in the two-dimensional oscillator array. Therefore the lower critical dimension of this system must be below two. Furthermore, our scaling results indicate that an RG approach may be useful. We tried to apply the simplest version of the renormalization group technique used for the oscillator chains to this system, but the results showed that this RG is insufficient. The two-dimensional system is therefore an example of one that will allow us to understand and tackle the challenges in generalizing the RG framework beyond the simplest case of a one dimensional chain. A new student, Tony Lee, has very recently joined the project, and will work to extend the RG approach.

Figure 8: Alice, Team Caltech's entry in the 2007 Urban Challenge.

4 Applications: Alice

The theory and algorithms being developed under this contract are being applied to two experimental systems at Caltech: the Caltech multi-vehicle wireless testbed (MVWT) and the Caltech autonomous vehicle testbed ("Alice"). Over the past year, the majority of the work has been focused on Alice, which competed in the 2007 DARPA Urban Challenge in November 2007, and is shown in Figure 8.

As part of the 2007 Urban Challenge, a number of significant technical accomplishments were achieved under the support the support of DARPA:

1. A highly distributed, information-rich sensory system was developed that allowed real-time processing of large amounts of raw data to obtain information required for driving in urban environments. The distributed nature of our system allowed easy integration of new sensors, but required sensor fusion in both time and space across a distributed set of processes.
2. A hierarchical planner was developed for driving in urban environments that allowed complex interactions with other vehicles, including following, passing and queuing operations. A rail-based planner was used to allow rapid evaluation of maneuvers and choice of paths that optimized competing objectives while insuring safe operation in the presence of other vehicles and static obstacles.
3. A canonical software structure was developed for use in the planning stack to insure that contingencies could be handled and that the vehicle would continue to make forward progress towards its goals for as long as possible. The combination of a directive/response mechanism for intermodule communication and fault-handling algorithms provide a rich set of behaviors in complex driving situations.

The features of our system were demonstrated in approximately 300 miles of testing performed in the months before the race, including the first known interaction between two autonomous vehicles (with MIT, in joint testing at the El Toro Marine Corps Air Station).

In addition, under partial support from Boeing, we developed a substantial simulation infrastructure that was used to try to test and validate the algorithms used to implement our system.

This simulation capability consisted of a hierarchy of simulators that could be used at different levels of resolution:

- Vehicle simulation - at the simplest level, a dynamic simulation of the vehicle (including actuation models and tire slippage) was used to test the basic driving and control software. This simulator allowed rapid testing of basic functions that did not require sensory input.
- Traffic simulation - to allow planning in the presence of other vehicles, a simple traffic simulator was built that generated motion for a set of simulated vehicles. These vehicles were "inserted" into the sensing subsystem as data objects, allowing testing of the algorithms without changing the data interfaces.
- Sensor simulation - if desired, a sensing simulation module could be inserted in the simulation stack to generate noisy features. The statistics of these features were carefully matched to the statistics obtained from field data, to try to capture the behavior of the running systems.
- Logged data - to test the sensing subsystem, raw data logged from the sensors (cameras, LADAR units, etc) could be fed into the sensing and perception algorithms in place of talking the hardware. This output of these algorithms could then be compared to manual interpretations of the data.

This simulation infrastructure provides a baseline capability that can be used for planned work in 2008-09 on system modeling theory and practice.

5 Synergistic Activities

In addition to the activities fully and partially sponsored under this contract, a number of other activities funded by the federal government are synergistic with the main themes of this work.

MURI on V&V for Distributed Embedded Systems In 2006 we were awarded a Multidisciplinary University Research Initiative (MURI) award to investigate the specification, design and verification of distributed systems that combine communications, computation and control in dynamic, uncertain and adversarial environments. These systems consist of autonomous components (vehicles, sensors, communications nodes and command and control elements) that cooperate with each other and operate in environments with adversarial and random elements.

Our goal is to develop methods and tools for designing control policies, specifying the properties of the resulting distributed embedded system and the physical environment, and proving that the specifications are met. We partition the problem into three parts:

- Specification: How does the user specify—in a single formalism—continuous and discrete control policies, communications protocols and environment models (including faults)?
- Design and reasoning: How can engineers reason that their designs satisfy the specifications? In particular, can engineers reason about the performance of computations and communication, and incorporate real-time constraints, dynamics, and uncertainty into that reasoning?
- Implementation: What are the best ways of mapping detailed designs to hardware artifacts, running on specific operating systems? What languages are suitable for specifying systems so that the specifications can be verified more easily?

Our project focuses on the first two parts of the overall problem, with linkage to industry (Boeing) and national laboratories (JPL, AFRL) as a mechanism for transitioning the research results to implementation.

2007 DARPA Urban Challenge Caltech participated in the 2007 Urban Challenge and advanced to the semi-finals. Our primary technical thrusts were in three areas: (1) mission and contingency management for autonomous systems; (2) distributed sensor fusion, mapping and situational awareness; and (3) optimization-based guidance, navigation and control. Our autonomous vehicle, Alice, demonstrated new capabilities in each of these areas and drove approximate 300 autonomous miles in preparation for the race. The vehicle completed 2 of the 3 qualification tests, but did not ultimately qualify for the race due to poor performance in the merging tests at the National Qualifying Event.

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- Michael Epstein, ME graduate student (partial support)
- Melvin Flores, CDS graduate student (partial support)
- Dennice Gayme, CDS graduate student
- Shuo Han, EE graduate student
- Oleg Kogan, Physics graduate student
- Tony Lee, Physics graduate student
- Dominic Rizzo, CS gradaute student
- Haywood Tam, Physics graduate student
- Peter Trautman, CDS graduate student (partial support)
- Johan Ugander, CDS visiting student (partial support)
- Tichakorn (Nok) Wongpiromsarn, ME graduate student (partial support)

Papers

See references.

Conference presentations

- Julia Braman, "Verification Procedure for Generalized Goal-based Control Programs", AIAA Infotech@Aerospace Conference and Exhibit, May 2007.
- Lijun Chen, "A Game-Theoretic Model for Medium Access Control", International Wireless Internet Conference, October 2007.
- Julia Braman, "Safety Verification of a Fault Tolerant Reconfigurable Autonomous Goal-Based Robotic Control System", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), November 2007.
- Lijun Chen, "Contention Control: A Game-theoretic Approach", IEEE Conference on Decision and Control, December 2007.
- Michael Epstein, "Estimation schemes for networked control systems using UDP-like communication", Conference on Decision and Control (CDC), December 2007.
- Oleg Kogan, "Renormalization group method for predicting frequency clusters in a chain of nearest-neighbor Kuramoto oscillators", Dynamic Days, January 2008.
- Oleg Kogan, "Renormalization group method for predicting frequency clusters in a chain of nearest-neighbor Kuramoto oscillators", APS March Meeting, March 2008.
- Richard Murray, "Safety Verification of Fault Tolerant Goal-based Control Programs with Estimation Uncertainty", American Control Conference, June 2008.

- Michael Epstein, “Using Hierarchical Decomposition to Speed Up Average Consensus”, International Federation of Automatic Control (IFAC) World Congress, July 2008.

Invention disclosures

None.

Major results

- Validation of 2D/3C models for turbulent fluids again full DNS solutions, demonstrating the efficacy of models that capture the sensitivity of the flow to perturbations as a mechanism for describing the onset of turbulence (Section 2.1).
- New techniques, architectures and automated tools for verifying the behavior of complex (autonomous) systems that combine continuous and discrete dynamics in hierarchically organized planning algorithms [3, 4, 5, 6, 7, 15, 21, 22].
- Exploration of dynamics in multi-scale, networked systems, including stochastic properties of coupled oscillators using renormalization group theory (Section 3), as well as the effects of packet-loss in networked information systems [18, 19].
- Preliminary development of networked simulation technologies for sensor-drive, autonomous navigation in land and air vehicles (Section 2.4 and [8]), and implementation and verification of planning algorithms for autonomous driving [21, 22]. These technologies will serve as a baseline for new work in system modeling theory and practice.