Year 1 Report:
Science of Integration for Cyber Physical Systems

Our objective in this NSF project is to develop a science of integration for *cyber physical systems (CPS)*. The proposed research program has three focus areas:

(1) *theory of compositionality*,
(2) *tools and tool architectures*,
(3) *systems/experimental research.*

This report discusses our progress during the third year of the award. Section 1 discusses the progress on the theory compositionality organized in two parts: passivity based approaches and component based network synthesis. Section 2 presents the tools and tool architectures that include a compositional framework for tool integration and a multi-model simulation environment. Finally, Section 3 describes the experimental research that includes the development of an open automotive experimental platform (currently in progress), a group of quadrotor UAVs, and a networked multi-robot system.

1. Theory of Compositionality

1.1 Theory of Compositionality based on Passivity

During its first year, the project has focused on passivity for cyber-physical systems and networked systems including switched systems, symmetric systems, event-based systems, and feedback systems in a game-theoretic framework. This report covers background material on passive systems and passive switched systems. It then covers the application of passivity to networked Euler-Lagrange systems, the concept of passivity indices used to extend results on the stability of interconnections to systems that are not necessarily passive, results on passivity for networked switched systems, output synchronization of event-triggered networked systems using passivity, control of large-scale distributed systems using dissipativity and symmetry, and the use of dissipativity-based certificates for state-feedback in a game-theoretic framework. Finally, this report ends with a discussion of using passivity based methods for design and integration of CPS including quadrotor UAVs and wireless control networks.

Control of Networked Passive Systems

Passivity is an appealing concept. It is a dynamic system characterization based on energy dissipation. A passive system is one that stores and dissipates energy without generating its own. This approach is very intuitive for physical systems [14]. The concept of passivity is quite general, as it has been applied to switched systems with arbitrary nonlinear dynamics, as covered in the following section. Passive systems theory is mathematically similar to the Lyapunov stability theory, but it is applicable to a smaller class of systems, that is, it is more restrictive. These added restrictions make Lyapunov theory less conservative and more relevant for stability analysis of a single system, than passivity theory. However, there are benefits to the passive approach. The most useful benefit from a controls perspective is that passivity is a property that is preserved when systems are interconnected in parallel or in feedback configurations. This means that many practical interconnections of passive systems that include feedback and parallel interconnections are stable. On the large scale, passivity allows for simple design of stable systems. This assumes that each system component is passive or can be made passive with a local controller. If these components are sequentially connected in parallel or in feedback the entire interconnection is passive and stable. Current research by our group is also addressing the issue of preserving passivity when passive systems are connected in series [20].

Passivity has been applied to many systems using a traditional notion of energy. Examples include simple systems such as electrical circuits and mass-spring-dampers. More complex applications include robotics, distributed systems, and chemical processes. It has also been applied to networked control systems with time-varying delays. In this case, the feedback interconnection with delays is made passive using the wave variable transformation (see for example [9]. In these more general cases, passivity can be applied even when there isn't a traditional notion of energy, but rather a generalized energy. This generalized energy can be defined for each specific system using an energy storage function. When a storage function exists and the energy stored in a system can be bounded above by the energy supplied to the system, the system is passive.

Recent work for this project includes connecting classic results on conic systems (G Zames - On the Input-Output Stability of Time-Varying Nonlinear Feedback Systems - Transactions on Automatic Control - April 1966) to the more recent concept of a passive index. We have showed that these two concepts are closely related [18]. Additionally, we have generalized the concept of a passive index to switched systems, as mentioned later in this report.

Notions of Passivity for Switched Systems

Passivity provides many benefits over general stability theory, especially in the analysis and synthesis of interconnected systems. These benefits have been further extended when applied to switched systems. Passivity can be applied to systems with naturally hybrid dynamics or systems with switching controllers. There have been a number of definitions of passivity proposed for switched systems. The definition considered in this project is the most comprehensive so far published (J. Zhao and D.J. Hill - Dissipative Theory for Switched Systems - Transactions on Automatic Control - May 2008). The switched systems in question are general nonlinear switched systems with a finite number of subsystems. The switching is assumed to take place a finite number of times on any finite interval so to avoid the Zeno phenomenon. The switched system is passive if the subsystems meet the following conditions.

1. Each subsystem is passive when it is active.
2. Each subsystem is dissipative (of a special form) when it is inactive.

Note that dissipativity is a generalization of passivity where the energy supply rate is an arbitrary function of system input rather than simply the inner product of system input and output. When passivity is defined this way, a few key results are shown for switched systems. First, passivity is preserved when passive switched systems are interconnected in negative feedback. Second, when the definitions are made slightly more restrictive, expected stability results are shown. This includes strictly passive implying asymptotic stability and output strictly passive implying L2 stability (bounded input, bounded output stability). This framework has been used extensively for this project [16][21].

Passivity Applied to Euler-Lagrange Systems with Nonholonomic Constraints

One intended application of passivity in this project is the control of networked Euler-Lagrange (EL) systems. This includes robotic manipulators and mobile robots. Passivity applied to EL systems has been well studied. However, past research has typically ignored nonholonomic constraints in these systems. However, many systems have these constraints. For example, actual wheeled vehicles have a minimum turning radius. The result is that the state of a vehicle depends on the path taken to achieve it. These constraints on the vehicle's position and velocity are nonholonomic, so a more complex model must be used. When these constraints are considered, the dynamics of the system are much more realistic. The problem considered in this project is a network of such vehicles, each with EL dynamics and nonholonomic constraints. We proposed a new setup, which allowed us to use passivity as the design and analysis tool of EL systems despite the added constraints [15].

The general problem starts with a vehicle described by EL equations with constraints. First a local state feedback is applied and the coordinate frame is redefined in order to achieve a simplified model. This simplified model is then input-output linearized to derive a model that is a simple double integrator from the input output perspective. With one last local control applied, the vehicle dynamics are locally made passive despite the nonholonomic constraints. A network of these agents is then connected over a fixed topology, specified by a graph Laplacian. At this point, a complete feedback loop is derived. This feedback loop can be appropriately subdivided to look like the interconnection of two passive systems. The feedback invariance that passivity provides allows for the stability of the loop to be inferred immediately.

This solution can be further extended when considering delays in the communication between agents. By applying a wave variable transformation to the communication channels, the networked system remains passive despite time-varying delays. This proposed setup solves the problem of output synchronization of networked EL systems subject to nonholonomic constraints. This is an extension from the previous work of which didn't consider the added constraints. There are many techniques used to preserve passivity of each agent, despite the constraints, and of the network, despite delays.

Other work on distributed systems for this project is in exploiting communication symmetries in networked dissipative systems to show stability [19]. As mentioned previously, dissipative theory is a generalization of passive theory. The symmetries are in the communication graph and include star and ring symmetries. The form of the symmetry can be used together with the dissipative property of agents to simplify the conditions for stability of a distributed system.

A Notion of Passivity Indices for Switched Systems

Another major goal in this project is to extend the applicability of passivity to switched systems that aren't necessarily passive. Traditional passivity is only a binary characterization of system behavior based on whether or not that system dissipates sufficient energy. However, there are systems that dissipate significantly more energy than is required to maintain passivity. Simply terming these systems “passive” does not describe the systems’ behavior well enough. Likewise, there are non-passive systems that would become passive with a simple loop transformation. Knowing the type and magnitude of the loop transformation would help in designing a stable system. In both cases, this information can be captured in the form of a passivity index. Using passivity indices provides more information for control design.

In order to completely characterize the level of passivity in a system, two indices are required. The first is a measure of the level of stability of the system. The second is a measure of the extent of the minimum phase property in a system. The two are independent in the sense that knowing one index does not provide any information about the other except that the other index must exist. When a system has a positive value for an index, this is termed an “excess” of that particular form of passivity. Likewise a negative value for that index is termed a “shortage.” This means that passive systems have a positive or zero value for both indices. Non-passive systems can have either index negative while the other is non-negative. There do exist systems that don’t have finite passivity indices so this theory does not apply to this class of systems.

The main difference in applying the indices to switched systems is that *the indices are no longer constant*. Each subsystem has values for the two indices and the overall switched system takes on the values of the indices over the time intervals where that subsystem is active. With this definition, the passivity indices for switched systems are piecewise constant. With the earlier assumption that there are a finite number of switches on any finite time interval, the switching signals are well behaved and the time varying indices are well defined [16]. This approach was used in resilient control to recover from cyber-attacks in [23].

The results based on the indices generalize to the case of switched systems. Conceptually, when considering the feedback interconnection of two systems, a shortage of passivity of one system can be compensated by an excess of passivity in the other system. Specifically, *a shortage of stability in one system can be compensated by an excess of the minimum phase property in the other system and the other way around* [16]-Theorem 2. Once the indices have been assessed for a given interconnection of two switched systems, the verification that the interconnection is stable is as simple as checking whether a matrix is positive definite. This means that stable feedback loops can be designed even when the systems in the loop aren't passive or even stable. This is an exciting and very promising result.

Stability of Networked Passive Switched Systems

The goal of this group in this project is to extend the theoretical foundations for passivity-based control to CPS. In order to get to this point, realistic CPS must be considered. This includes systems with network delays and switching dynamics. It was mentioned earlier that the feedback interconnection of two passive switched systems is again a passive (and stable) switched system. This holds when the two systems are interconnected with no delay. The problem investigated here is under what conditions is the interconnection is still stable when there are delays in the network.

This approach taken here is very much based on the previously discussed results. The systems of interest are passive switched systems that are interconnected over a network. The network is modeled as a time-varying delay in data transfer. It is assumed that this delay is measurable in real time (so that the system can compensate for it). It is also assumed that the network interface can be designed. This is to allow for a time-varying wave variable transformation. When this transformation is applied to the feedback interconnection of two passive switched systems over a network, the interconnection is stable [21].

A Passivity-Based Approach to Event-Triggered Network Control

Recently, several researchers have suggested the idea of event-based control as a promising technique to reduce communication and computation load for the purpose of control in many control applications. In a typical event-based implementation, the control signals are kept constant until the violation of an “event triggering condition” on certain signals which triggers the re-computation of the control actions. Compared with time-driven control, where constant sampling period is applied to guarantee stability in the worst case scenario, the possibility of reducing the number of computations, and thus of transmissions, while guaranteeing desired levels of performance makes event-based control very appealing in networked control systems (NCSs).

Most of the results on event-triggered control are obtained under the assumption that the feedback control law provides input-to-state stability (ISS) with respect to the state measurement errors. However, in many control applications the full state information is not available for measurement, so it is important to study stability and performance of event-triggered control systems with dynamic and static output feedback controllers. In [27], a static output feedback based event-triggered control scheme is introduced for stabilization of passive and output feedback passive (OFP) NCSs. A static output feedback gain and a triggering condition are derived based on the output feedback passivity indices of the plant. In [30], a dynamic output feedback based event-triggered control scheme is introduced for stabilization of Input Feed-forward Output Feedback Passive (IF-OFP) NCSs, which expands our previous work in [27] for stabilization of more general dissipative systems. The triggering condition is derived based on the passivity theorem which allows us to characterize a large class of output feedback stabilization controllers. We show that under the triggering condition derived in [30], the control system is finite gain L2 stable in the presence of bounded external disturbances. The interactions between the triggering condition, the achievable L2 gain of the control system and the inter-sampling time have been studied in terms of the passivity indices of the plant and the controller. Based on the results in [30], we further propose a dynamic output feedback based event-triggered control set-up for NCSs which allows us to consider network induced delays both from the sampler to the controller and from the controller to the plant [28]. We show that based on the proposed set-up, finite-gain L2 stability can be achieved in the presence of arbitrary constant network induced delays or delays with bounded jitters. Extensions considering self-triggered control have also been investigated, and detailed results can be found in [24][25].

Event-based distributed control in cooperative control of multi-agent systems is of interest because of the potential to reduce communication load and implementation cost. In [29], we propose a distributed event-driven communication strategy for stabilization of large scale networked control systems with finite-gain L2 stability. Each subsystem broadcasts its output information to its neighbors only when the subsystem's local output error exceeds a specified threshold. The triggering condition is related to the topology of the underlying communication graph. We also provide analysis of the time intervals between two consecutive communication broadcasts (the inter-event time). Our analysis shows that the topology of the underlying communication graph plays an important role on the performance of the NCSs with event-driven communication.

While [29] only considers stabilization problem with an ideal network model, we continue to study event-based cooperative control problem in [26][31], where the output synchronization problem of multi-agent system with event -driven communication has been investigated. We assume all the agents in the network are lossless (lossless systems are passive systems) and we propose a set-up to achieve output synchronization of the interconnected agents with event-driven communication in the presence of arbitrary constant network induced delays. Triggering conditions to achieve output synchronization are derived based on the rectified scattering transformation applied in our proposed set-up. Whenever the agent satisfies its triggering condition, a scattering variable which contains the current output information of the agent will be sent to its neighboring agents, and the neighboring agents will extract reference information from its received scattering variables for its own control action update. The proposed set-up in [35] is an important extension of applying event-based control to cooperative control of multi-agent systems, especially when it is difficult to derive a common upper bound on the admissible network induced delays based on the triggering condition or when the network induced delays between coupled agents are larger than the inter-event time implicitly determined by the event-triggering condition. Quantization effects on output synchronization of multi-agent systems with event-driven communication have also been investigated in [31].

Event -Triggered Control in Model-Based Networked Control Systems: In addition to the above passivity based event-triggered control laws, we have been working on event-triggered control in control systems, where an explicit model of the plant is used in the controller. In this Model-Based control configuration (we have been working on such Model-Based networked control systems for several years) knowledge about the plant dynamic behavior, which is encapsulated in the plant model, is used to design controllers that require less frequent updates of feedback information [38].

Controlling Symmetric Distributed Systems using Dissipativity Theory

Symmetry, as one basic feature of shapes and graphs, has been exhibited in many real-world networks, such as the Internet and power grid, resulting from the process of tree-like or cyclic growing. Since symmetry is related to the concept of a high degree of repetitions or regularities, the study of symmetry has been appealing in many scientific areas, such as Lie groups in quantum mechanics and crystallography in chemistry. In the classical theory of dynamical systems, symmetry has also been extensively studied. For example, to simplify the analysis and synthesis of large-scale dynamic systems, it is always of interest to reduce the dynamics of a system into smaller symmetric subsystems, which potentially simplifies control, planning or estimation tasks. When dealing with multi-agent systems with various information constraints and protocols, under certain conditions such systems can be expressed as or decomposed into interconnections of lower dimensional systems, which may lead to better understanding of system properties such as stability and controllability. Then the existence of symmetry here means that the system dynamics are invariant under transformations of coordinates.

In our work, stability conditions for large-scale systems are derived by categorizing agents into symmetry groups and applying local control laws under limited interconnections with neighbors [19]. Particularly, stability for dissipative systems is considered. Dissipativity is a generalization of passivity, where the energy supplied to the system can take different forms. Several properties of dynamical systems can be captured by varying the energy supply rate. When subsystems of a symmetric system are dissipative, overall stability properties can be studied. Conditions are derived for the maximum number of subsystems that may be added while preserving stability and these results may be used in the synthesis of large-scale systems with symmetric interconnections.

Passivity indices can be used for interconnections of agents to assess the level of passivity. Motivated by the interest of sufficient stability conditions in [19], passivity indices for both linear and nonlinear multi-agent systems with feed-forward and feedback interconnections are derived with the distributed setup in [32]. For linear systems, the passivity indices are explicitly characterized, while the passivity indices in the nonlinear case are characterized by a set of matrix inequalities. We also focus on symmetric interconnections and specialize stability results to this case.

Additional work on control of symmetric systems which are not necessarily dissipative is also being pursued. Specifically, a Lyapunov-based approach focused on compositionality of symmetric systems is being considered for stability of symmetric systems. The main results prove that if a symmetric system is stable, under certain conditions the system may be "built up" by adding additional components in a symmetric manner while guaranteeing to maintain stability, in the sense of Lyapunov [39]. Extensions of these results under this grant are focused on robust robotic formation control when one or more robots in the formation may fail [40]. Current preliminary results are directed toward optimal control of symmetric distributed systems focusing on properties required for extending the optimal solution of a symmetric system to a larger one while maintaining optimality.

Dissipativity-Based Certificates for the Stabilization of Multi-Channel Systems

The goal of this research is to develop new theory, algorithms, and demonstrations related to stabilization of multi-channel systems using dissipativity-based certifications and optimization theory. The first area of this work is in reliable stabilization via rectangular dilated LMIs and dissipativity-based certifications [33][34][35]. This is a design framework for reliable stabilization of multi-channel systems developed based on a set of rectangular dilated LMIs and dissipativity certifications. We provided a less-conservative stabilization result and extended the stability condition for an additive model perturbation in the system. Moreover, the framework in which we have defined the problem provides a computationally tractable treatment for handling the issue of robust/reliable stabilization and model uncertainty.

Another area of this research is in studying feedback Nash equilibria for multi-channel systems via a set of non-fragile stabilizing state-feedback solutions and dissipativity inequalities [36]. This problem of state-feedback stabilization for a multi-channel system is considered in the framework of differential games, where the class of admissible strategies for the players is induced from a solution set of the objective functions that are realized through certain dissipativity inequalities. In such a scenario, we characterized the feedback Nash equilibria via a set of non-fragile stabilizing state-feedback gains corresponding to constrained dissipativity problems. Moreover, we showed that the existence of a near-optimal solution to the constrained dissipativity problem is a sufficient condition for the existence of a feedback Nash equilibrium, with the latter having a nice property of strong time consistency.

Related work is on robust feedback Nash equilibrium for multi-channel systems via differential games and a class of unknown disturbance observers [37]. Again the problem of state-feedback stabilization for a multi-channel system is cast in a differential-game theoretic framework. We specifically presented a sufficient condition for the existence of a robust feedback Nash equilibrium, where each agent aims to optimize different types of objective functions and when agents may unaware of all aspects or the structure of the game. We characterized the robust feedback Nash equilibrium solutions via a set of relaxed LMIs conditions and concepts from a geometric control theory, namely, a class of decentralized unknown disturbance observers where the latter are used for the game with an incomplete information.

Using Passivity in the Design and Integration of CPS

The unique challenges in CPS integration emerge from the heterogeneity of components and interactions. This heterogeneity drives the need for modeling and analyzing cross-domain interactions among physical and computational/networking domains and demands deep understanding the effects of heterogeneous abstraction layers in the design flow. To address the challenges of CPS integration, significant progress needs to be made toward a new science and technology foundation that is model-based, precise, and predictable.

We have worked toward a theory of composition for heterogeneous systems focusing on stability. We developed a passivity-based design approach that decouples stability from timing uncertainties caused by networking and computation. In addition, we developed cross-domain abstractions that provide effective solution for model-based fully automated software synthesis and high-fidelity performance analysis. The design objectives demonstrated using these techniques are group coordination for networked UAVs and high-confidence embedded control software design for a quadrotor UAV [1].

Our team has developed a passivity framework for control of multi-agent networks with applications to group coordination of unmanned aerial vehicles (UAVs). We introduced a passivity-based deployment protocol and provided the passivity and stability analysis. Additionally, we analyzed the multi-agent system at steady-state for the case where the agents were single-input, single-output (SISO) agents, and looked at deployment only for ideal regular networks. The simulations considered velocity-limited quadrotor UAVs communicating in a regular network under various network conditions.

We have extended the analytical results by showing that the outputs would asymptotically synchronize in regular networks whenever the reference inputs are identical [1]. Also, the simulations were extended to consider the combination of non-uniform constant delays, time-varying delays imposed by a disturbance node, and varying amounts of packet loss. We have further extended the approach in the following directions: (1) we consider synchronized deployment instead of deployment, (2) the steady-state results are extended to MIMO agents, (2) we characterize the class of communication networks for which the protocol achieves, (3) we improve the steady-state performance using an appropriate parameterization, and (4) we develop an efficient implementation of the deployment protocol that ensures there are no algebraic loops.

Using Passivity for Design of Wireless Network Control Systems

Wireless NCS allow for distributed deployment of control systems where information among distributed sensors, controllers and actuators are exchanged using wireless communication. The ability of using different sampling rates in wireless NCS provides the flexibility for adapting their resource needs based on the dynamic resource availability in the wireless networking environment.

In this work, we study the problem of dynamic rate adaptation for NCS so that they can fully utilize the scarce wireless resource to maximize the control performance, and at the same time, avoid network congestion [4][5]. We define the objective of sampling rate adaptation using utility-based optimal resource allocation, where a utility function is defined to quantify the relationship between the sampling rate and the robustness of the control system. To develop a distributed solution for sampling rate adaptation, we employ a price-based approach, where prices are generated at the contention regions of a wireless network to reflect the cost of unit network resource usage and used as the basis for rate adaptation. We formally prove the stability of our algorithm.

To accurately evaluate the performance of wireless NCS that employs our proposed sampling rate scheme, we implement our solution in an integrated simulation environment that consists of Matlab and ns-2. The experimental results show that our algorithm is able to provide agile and stable sampling rate adaptation for wireless NCS and enhance their robustness in dynamic wireless networking environments. Uncertainty in wireless networks such as time-varying delays and packet loss introduce undesirable effects such as instability and degraded performance in Networked Control Systems (NCS). Further, limited network resources provide constraints for communication between plants and controllers.

We have developed a framework that uses passivity combined with a self-triggered approach to design a control architecture which can tolerate time-varying delays and packet loss while minimizing bandwidth utilization [3]. We demonstrate our approach using a case study on the trajectory tracking control of a robotic manipulator over a wireless network. We provide analytical results to show passivity of the proposed networked control architecture and demonstrate tracking. Finally, we present simulation results that show the efficient utilization of network resources as well as the robustness of our design approach to network uncertainties.

Our team has investigated the use of passivity for the design of networked control systems [7]. We extended our previous work to consider control and synchronization of networked multi-robot systems [8]. The objective is to design the network so that the robots follow a reference trajectory provided by the network controller in a synchronized manner in order to achieve some global task. Instead of simply relaying an identical reference to each robot, we couple the robots' positions in a feedback manner to ensure synchronization of the global task. The theoretical foundations of our approach for digital control of multiple passive plants over networks including proofs of stability are presented in [9].

In order to apply the approach to the networked multi-robot system, we explain how to design local digital controllers that make the robotic agents passive, and the network control architecture including the network controller for the multi-robot system that preserves passivity. Finally, we address the challenges of compositional design and system integration by developing a model-based framework. In particular, we develop a prototype domain-specific modeling language and automated code generation tools for design of networked control systems on top of passivity which facilitate effective system configuration, deployment, and testing.

The prototype language for the case of linear plants that includes a code generator for simulation in Matlab/Simulink using the TrueTime toolbox is presented in [10]. In summary, our contribution lies on the application of a passivity approach for model-based compositional design of NCS to a multi-robot networked system. The networked control architecture based on passivity ensures the overall system remains stable in spite of implementation uncertainties such as network delays and data dropouts.

1.2 Component-Based Heterogeneous Network Synthesis

The objective of this part of our research is to develop new methodologies, algorithms and tools enabling the synthesis of resilient, robust, and adaptive networks. *Components* enable modularity, cost reduction, re-usability, adaptability to goals, new technology insertion, validation and verification. On the other hand *Interfaces* enable richer functionality, intelligent/cognitive networks. The desired Theory and Practice of Component-Based Networks encompasses the following elements:

- Heterogeneous components and compositionality;
- Performance of components and of their compositions;
- Methods and algorithms that enable moving back and forth from the performance - optimization domain to the correctness and timing analysis domain and also a composition theory preserving component properties as one tries to satisfy specifications in both domains.

The intended applications of the desired theory encompass a wide variety of networks: from communication to social, from cellular to transportation, from nano to macro networks. The desired theory is a critical theory and methodology for Networked Embedded Systems, Cyber-Physical Systems, Systems Biology.

In our research we emphasize several different linked views of networks:

- as distributed, asynchronous, feedback (many loops), hybrid automata (dynamical systems);
- as distributed asynchronous active databases and knowledge bases;
- as distributed asynchronous computers.

Some of the key questions/problems we study are:

- Can we develop a taxonomy of network structure vs. network functionality?
- Can we develop a theory of modularity and compositionality for networks?

The reasons for emphasizing *component-based design for networks* are: Top-down design methods are rigid and costly because reuse of previous work is not clear and mandated. Wireless networks are inherently dynamic and require adaptivity and agility. Component-based design provides required flexibility and agility. Components can be evolved and modified without starting the design process from scratch, i.e. we can reuse components in new designs. It is much easier to identify low performing components and redesign them. Additional reasons for emphasizing *component performance models* are: Feasibility of Component Based Design depends on *Compositionality*. Compositionality is principally the ability to compute or estimate system level properties from local properties of components. Due to horizontal and vertical couplings in wireless networks it is not possible to explicitly determine and quantify these relations. Therefore we need to develop numerical and analytical models which enable us to compute system level properties from components properties and to perform also associated sensitivity analysis.

Model-based CPS Exploration

The interaction of connected components creates complexity impeding the analysis of large systems. Thorough exploration, appearing as formal verification, optimization or constraint satisfaction typically has a complexity that is either a high order polynomial or an exponential function of system size. However, for a large class of systems the essential complexity is linear in system size and exponential in *treewidth* which makes the previous notion of exponential complexity in system size an accidental overestimate.

We demonstrated in [41] how this reduced complexity can be achieved using summary propagation on factor graphs. We described summary propagation in terms of operations belonging to a commutative semiring-weighted relational algebra. We showed how by appropriate selection of the commutative semiring, the same solution applies to propositional satisfiability, inference on Bayesian networks and a mixed integer linear optimization problem motivated by the power restoration problem for distributed, autonomous networks. This solution leads to a non-iterative distributed algorithm that operates on local data. While weighted relational algebraic operators are used as the basic means of calculation, the algorithm presented works only on factor graphs that are trees. This requires the calculation of a non-unique structure called a *join tree*, which can be trivially generated from a unique structure called a *clique separator gra*ph, which can be computed in linear time from a SysML Parametric Diagram description of the system for chordal systems. Interesting artifacts arise from this structural analysis, which may be interpreted as interfaces and components. The framework also contains mathematical artifacts that may be interpreted as hierarchy and abstraction. We also developed a tool to assist in the structural analysis described.

Our contribution [41] is elucidating and advocating the use of *chordality* and the *sum-product algorithm* in the analysis of structured systems. We developed an analysis method for optimization, logical and probabilistic inference on a certain class of systems, where exploiting the logical system topology localizes the curse of dimensionality. The complexity of analysis using this framework grows exponentially in the size of local neighborhoods but only linearly in overall system size making it well suited to component based analysis. As an example application, we developed a novel distributed algorithm that uses local information for optimal power restoration that also provides a space of possible computational and communication topologies that are consistent with the algorithm. Finally, we showed how SysML Parametric Diagrams can be used to capture factor graphs and describe an algorithm for “refactoring” Parametric Diagrams into factor join trees for efficient summary propagation.

Distributed Topology Control for Stable Path Routing

We introduced and investigated [42] the stable path topology control problem for link-state routing in mobile multihop networks. Topology control in wireless multi-hop networks has been a topic of active research in recent years. Different topology control mechanisms have been proposed for various purposes, including connectivity, energy-efficiency, throughput and robustness to mobility. In particular, several topology control algorithms, both centralized and distributed, that are aimed to reduce the broadcast storm problem have been developed.

Broadcasting in a network is the process by which a packet sent from one station reaches all other stations in the network. Several routing protocols in Mobile Ad Hoc Networks (MANETs) are proactive link state protocols, which broadcast the link state information. However, in these networks, the link states are highly dynamic, and consequently, a large number of packets, corresponding to every link state change, is broadcast in the network. This problem is referred to as the broadcast storm problem. We adopt a graph pruning approach to reduce the broadcast storm problem for link state routing: by selecting a subset of the graph topology to be broadcast, the broadcast storm can be reduced. Several of the pruning mechanisms proposed in the literature are distributed localized algorithms. These local pruning algorithms have access to only their local neighborhood information (typically two-hop neighborhood information), which they prune to reduce the broadcast storm. Although there are a number of metrics that capture the link dynamics, few algorithms use these link metrics for topology control in routing. Even those that do are only heuristic methods; they do not offer proof guarantees for stability of the routing paths. We formulated the topology control problem of selective link-state broadcast as a graph pruning problem with restricted local neighborhood information.

One important metric for routing in wireless multi-hop networks is path stability. Although path stability has been studied for many reactive distance vector schemes, there is little work that addresses topology control for stable paths in link state routing. We introduced a new topology control algorithm that guarantees stable path routing: a mechanism that prunes the initial topology (to reduce the broadcast storm) while guaranteeing that the stable paths (for unicast routing) from every host to any target station are preserved in the pruned topology. Topology control for stable paths has a two-fold advantage: First, these long lived paths are cheaper to maintain because they are less likely to change. Second, it offers the higher layer traffic long lived sessions and consequently yields improved traffic carrying performance. We developed [42] a multiagent optimization framework where the decision policies of each agent are restricted to local policies on incident edges and independent of the policies of other agents. We showed that under a condition called the *positivity condition*, these independent local policies preserve the stable routing paths globally. We also provided an efficient and distributed algorithm, which we call the *Stable Path Topology Control Algorithm*, to compute this local policy that yields a pruned graph. Using simulations, we demonstrated that this algorithm, when used with the popular ETX metric, outperforms topology control mechanisms commonly used for Mobile Ad Hoc Networks (MANET).

These results [42] provide a novel and formal solution to the design of one of the key components in our component-based formalism of distributed MANET routing, the component we have named the Selection of Topology Information to Disseminate Component (STIDC). Furthermore, these results [42] have several generalizations and extensions to networked systems other than MANET, which we are currently pursuing.

Multi-metric Network Problems

The recent decades have witnessed a paradigm shift in system theory: ubiquity of inexpensive communication and computing devices has spawned several applications that are necessarily distributed among physically separated processors. Many CPS classes and associated applications are networked systems. These applications range from distributed databases, transitive security authentication schemes to distributed estimation and control protocols. Since all these applications are built over an underlying communication network, these systems are aptly called *networked systems*. The heterogeneity of devices, which constitute the networked system, and the varied functions that they support have created several interesting problems that did not exist in traditional system theory. For instance, a distributed sensor network is a networked system that performs sensing, control and actuation. To perform this primary functionality, this networked system also supports several communication and security protocols. Further, for these distributed systems, the capabilities and functionalities of the different constituent component subsystems differ significantly. Typically there are different sensor nodes to sense different physical parameters. Certain nodes, which are not energy-limited, might support stronger communication and security mechanisms. In essence, a networked system performs several function computations over a distributed heterogeneous platform. We find that methods from traditional system theory are handicapped to handle this heterogeneity.

Different applications of such a networked system perform computations with different functional metrics. In many cases, the aggregate metric for a particular computation is obtained as composition of local metrics that are measurable by the different constituent subsystems. The rules of composition, to compute this aggregate metric, differ among different computations. For instance, for the routing computation, the metric is typically the interface delay. In this case, the composition of the metrics is additive across the different subsystems. However, for a trust/security computation, a possible metric is the strength of the cryptographic key between a pair of subsystems, and this follows a bottleneck composition. Consequently, for a multi-functional heterogeneous networked system, the different computations can be formulated as a multi-metric network problem with different rules of composition for each of the metrics [43]. Several computations, such as authentication mechanisms, are specified as logical rules over functional metrics. In these cases, the metric sets are not necessarily totally ordered. We have illustrated with examples from trust evaluation schemes that we need a partially ordered set to describe these metrics. We have demonstrated [43] that for many applications, the composition rules on these metrics follow the semiring axioms.

In the multi-metric setting, the different metrics (for the different computations) are not trivially comparable. For example, metrics such as delay, used in routing, cannot be compared with logical trustworthiness metrics, used in trust evaluation. To handle this, we introduced [43] composition methods from multi-criteria optimization theory that provide tradeoff methods for the different functionalities: different tradeoff methods arise from different vector orders. We developed a common framework where several multi-criteria tradeoff methods can be viewed as instances of *idempotent semiring algebraic path problems* on labeled multigraphs. Applying different vector-orders to this framework, we showed [43] that we can obtain Pareto, lexicographic and max-order solutions. Although the different multi-metric tradeoffs can be encompassed in this idempotent framework, we illustrated, using an example, that these tradeoff methods under some composition rules are in general computationally intractable. Consequently we identified [43] a class of semiring rules for which the corresponding multi-metric tradeoff problems can be solved at affordable computational complexity. We demonstrated that this class encompasses many CPS applications and problems of interest.

Security and Trust

In [44] we developed a novel application of these new methodologies [43] for the important problem of trusted routing, formulating it as a transaction of services over a complex networked environment. We presented definitions from service-oriented environments that unambiguously capture the difference between trust and reputation relations. We showed that the trustworthiness metrics associated with these relations have a linear order embedded in them. Identifying this order structure permits us to treat the trusted routing problem as a bi-objective path optimization problem. We considered *bottleneck trust* and developed polynomial time algorithms to obtain the optimal routing paths in various bi-objective settings. In developing these algorithms, we identified an interesting decomposition principle for (min; +) and (min; max) semirings, which yields a distributed solution.

In a different application of the methods of [43][44] we addressed in [45] security and trust problems arising in the critical area of state estimation in electric power grids in general and in the Smart Grid in particular, a CPS area of major interest. We assumed that the monitoring of the electrical grid is done by a network of agents with both computing and communication capabilities. We proposed a security mechanism aimed at protecting the state estimation process against false data injection originating from faulty equipment or cyber-attacks. Our approach [45] is based on a multi-agent filtering scheme, where in addition to taking measurements, the agents are also computing local estimates based on their own measurements and on the estimates of the neighboring agents. We combine the multi-agent filtering scheme with a *trust-based mechanism* under which each agent associates a trust metric to each of its neighbors. These trust metrics are taken into account in the filtering scheme so that information transmitted from agents with low trust is disregarded. In addition, a mechanism for the trust metric update is also introduced, which ensures that agents that diverge considerably from their expected behavior have their trust values lowered.

Consensus in Networked Multi-Agent Systems with Adversaries

In the past decade, numerous consensus protocols for networked multi-agent systems have been proposed. Although some forms of robustness of these algorithms have been studied, reaching consensus securely in networked multi-agent systems, in spite of intrusions caused by malicious agents, or adversaries, has been largely overlooked.

In this work, we consider a general model for adversaries in Euclidean space and introduce a consensus problem for networked multi-agent systems similar to the Byzantine consensus problem in distributed computing. We present the Adversarially Robust Consensus Protocol (ARC-P), which combines ideas from consensus algorithms that are resilient to Byzantine faults and from linear consensus protocols used for control and coordination of dynamic agents. We show that ARC-P solves the consensus problem in complete networks whenever there are more cooperative agents than adversaries. Finally, we illustrate the resilience of ARC-P to adversaries through simulations and compare ARC-P with a linear consensus protocol for networked multi-agent systems. Our results are reported in [6].

Component-based Architectures for CPS

System design for Wireless Sensor Networks (WSNs) is a complicated process because of the wide variety of WSN applications, the heterogeneity of low-level implementation details, and the complex and heterogeneous interactions with their physical environments. Current ad hoc design methods (both simulation-based and testbed-based) for WSNs are far from satisfactory and cannot estimate system performance thoroughly and with the required accuracy. Furthermore, these ad hoc methods restrict design space exploration and the evaluation of new technology insertion. In [46] we proposed a model-based system design framework for WSNs, which is a systematic methodology applying Systems Engineering principles to support system requirements, design, analysis, and verification/validation processes during all design life cycles in WSNs. First, we described [46] a hierarchy of model libraries to model various behaviors and structures of WSNs, including physical environments, physical systems, communication protocols, computation components, system services and WSN applications. Main design considerations and challenges were also discussed. Next, based on our model libraries, we introduced a system design flow for WSN applications and discussed its advantages. Specifically, our framework can enhance collaboration between different design entities and stakeholders, reduce development risk, improve system performance and increase productivity by guaranteeing reusability, composability and compositionality. Finally, we provided a part of the physical environments and physical systems model libraries, which are described using the Systems Modeling Language (SysML), to illustrate the basic model principles. Specifically, main components of sensor motes, their relationships and behaviors were modeled independently with upper layer communication and computation mechanisms, which is different from other sensor mote models in the literature. In addition, the dynamics of major deployment environments of WSNs were modeled [46] by related parameters, which can also be extended to describe other environments. By generating C/C++ simulation codes directly from the SysML models, the performance of a single mote was evaluated.

Several of these advances were presented in the invited plenary address [47] at the First IEEE International Conference on Cyber Technology in Automation, Control and Intelligent Systems (IEEE-CYBER 2011). The following is a brief summary of this plenary address. Advances in Information Technology have enabled the design of complex networked systems, with large number of heterogeneous components and capable of multiple complex functions. These advances have at the same time increased the capabilities of such systems and have increased their complexity to such an extent that systematic design towards predictable performance is extremely difficult if not unfeasible today. This is especially manifested in the area of cyber-physical systems, of all scales, that have become ubiquitous. In addition, the need for systems that can rapidly adapt to new situations and change their structure and behavior accordingly has also increased dramatically. We presented methodologies that show promise in addressing these challenges. They include model-based systems engineering, component based synthesis and architectural design towards efficiency and adaptability. We demonstrated their effectiveness in various applications: collaborative robotics, collaborative heterogeneous sensor networks, cybersecurity of critical infrastructures, human-machine teams and organizations, and composite trust.

Autonomous Collaborating Swarms

A very important class of networked CPS is autonomous collaborating swarms. Networked systems of autonomous agents have emerged in a variety of applications such as collaborative robotics, mobile sensor networks and disaster relief operations. Complex phenomena are often observed in these systems due to the large number of agents, nonlinear interactions, locality of information transmission, and changes in the connectivity of the agents. Similar to their natural counterparts, engineered autonomous agents are capable of developing emergent behaviors such as herding, collaborative decision making based on local communication. The speed of developing emergent behaviors and their robustness to agents' failures depend on the underlying network connectivity and feasible communications. We have investigated such systems from a model-based systems engineering perspective. More specifically we have studied the interdependence of structure and behavior in a networked system of autonomous vehicles. During the reporting period we investigated several key challenges associated with this class of CPS. Our emphasis has been on system concepts and synthesis, including system architecture and the effects of various topologies and networks on performance.

In [48] we presented the analysis of a discrete-time, decentralized, stochastic coordination algorithm for a group of mobile nodes, called an autonomous swarm, on a finite spatial lattice. All nodes take their moves by sampling in parallel their locally perceived Gibbs distributions corresponding to a pairwise, nearest-neighbor potential. The algorithm has no explicit requirements on the connectedness of the underlying information graph, which varies with the swarm configuration. It was established that, with an appropriate annealing schedule, the algorithm results in swarm configurations converging to the (global) minimizers of a modified potential energy function. The extent of discrepancy between the modified and original potential energy functions is determined by the maximum node travel between time steps, and when such distance is small, the ultimate swarm configurations are close to the global minimizers of the original potential energy. Simulation results were presented to illustrate the capability of the sampling algorithm in approximating global optimization for swarms.

Situational awareness requires maintaining a reasonable level of communication connectivity in networks of autonomous vehicles. It is difficult to overcome deep fading of time-varying wireless channels in a dynamic and resource constrained environment. Moreover, other system constraints such as the energy consumption and total operation time make the design of communication protocols for such a system more challenging. In [49] we considered the problem of efficient communications of a group of autonomous vehicles with energy consumption and total operation time constraints in an adversarial environment. We showed that the policy of continuously attempting to communicate reliably over the course of the mission may lead to considerable system degradation. We proposed an adaptive algorithm to make communication attempts opportunistically, based on the qualities of the wireless channels as the vehicles move throughout the terrain. We compared the proposed algorithm with a non-opportunistic algorithm in which the vehicles blindly attempt to communicate regularly throughout the course of the mission. We showed that the proposed algorithm can significantly improve the system performance, both in terms of operation time when the agents transmit situational information and data throughput when additional data transmission is necessary.

Motif-based Network Design

Networks of mobile autonomous vehicles rely heavily on wireless communications as well as sensing devices for distributed path planning and decision making. Designing energy efficient distributed decision making algorithms in these systems is challenging and requires that different task-oriented information becomes available to the corresponding agents in a timely and reliable manner. We have developed [50][51][52] a systems engineering oriented approach to the design of networks of mobile autonomous systems, in which a cross-layer design methodology determines what structures are to be used to satisfy different task requirements. We identified a three-tier organization of these networks consisting of connectivity, communication, and action graphs and studied the interaction between them [50][51][52]. It is expected that in each functionality of a network, there are certain topologies that facilitate better achievement of the agents' objectives. Inspired from biological complex networks, we proposed [50][51] a bottom-up approach in network formation, in which small efficient subgraphs (motifs) for different functionalities of the network are determined. The overall network is then formed as a combination of these sub-graphs. We showed that the bottom-up approach to network formation is capable of generating efficient topologies for multi-tasking complex environments.

We have abstracted the collaboration between the vehicles into three interconnected levels. At each point of time, three graphs describe the network of moving vehicles: a *connectivity graph*, a *communication graph*, and an *action graph*. The first two graphs describe the information exchange in the network whereas the *action graph* is specific to the particular collaborative activities that the nodes perform and determines the desired collaboration activity. We considered [51] a challenging question: Given a preferred emergent behavior, which connectivity and communication graphs can satisfy the requirements given by the corresponding action graph? We have considered top-down as well as bottom-up approaches to this problem. In the top-down design, an optimization framework is developed that outputs efficient topologies given a single performance metric. Given different performance metrics, graphs that satisfy a favorable trade-off are selected as the candidates for the system structure. The focus of the bottom-up approach has been to discover how local preferences and decisions will result in the emergence of real world networks with certain requirements. Motif-based topology design was proposed [50][51] in this framework. The designed links are realized via low power wireless media. The lower level design addresses challenges emanating from realizing the ideal graph topologies and consists of physical layer, MAC layer and network layer constraints. In order to design realistic and efficient networks, we have considered the interdependence of these two levels of design and develop a framework to capture the design requirements effectively [50][51].

To design efficient local connectivity patterns, we have used [50][51] the idea of network motifs, which was first proposed in the context of biological networks. Network motifs are task specific local connectivity patterns, which exist with much higher frequency in real biological networks compared to those in random networks. These are sub-networks of low number of nodes (usually 3-4) whose persistence in networks performing similar tasks in different contexts, imply their efficiency in the sense that they optimize certain performance metric in a local scale. We use a simulation test bed to find network motifs for local level communication structures in a collaborative vehicles framework. Here, the group mission consists of several tasks that the agents participate in. The tasks include search operation, data gathering/processing, target finding and leader follower explorations. Each task gives rise to certain motifs that are specific to that task and the partial knowledge of the environment specifications that the agents operate in. In this way, given the subtasks that are necessary for the mission accomplishment, the most efficient task-specific local topologies are extracted [50][51]. Switching suitable graphs when the mode of operation is changing can be handled by solving the resulting reachability problem using methods for symbolic planning such as graph grammars. Based on such switching, we also addressed [50][51] the effects of split/merge operations on the spectral characteristics of the resulting connectivity graphs.

In [52] we reviewed the different design aspects of networks of collaborative moving vehicles. We addressed the different graph structures that are necessary for modeling collaborative vehicle networks. We surveyed the existing methods addressing geometric connectivity, Physical and Data Link Layer, and routing issues for networks of collaborative vehicles and showed the limitations of designs that address only single layer issues. We provided a systems engineering framework for the design of such systems and present the current challenges in the design of energy efficient communication networks for collaborative vehicles.

CPS and Systems Biology

Biological systems represent a very challenging class of CPS because the cyber part is implemented via different physical layers (chemical, biological) and the physical part is based on complex biology, physics, chemistry and biochemistry. Furthermore most biological systems are networked systems. The significance of studying biological systems and networks from a CPS perspective is two-fold: (a) Bringing the quantitative methods of engineering, mathematics, and model-based systems engineering to biological systems is of fundamental importance to biology and medicine and indeed forms the basis of the new science of Systems Biology; (b) Understanding biological systems and networks as networked CPS may provide inspiration for the development of new methods and algorithms for broad classes of CPS.

In a series of papers [53][54][55][56][57] we developed the first-ever systems biology model used to study the role of cholesterol in Alzheimer’s Disease (AD). This model was developed to help ask several questions: (1) What are the key nodes and regulatory points in the described network? (2) Does inhibition of BACE activity by cholesterol fit with the known data? (3) How does varying the expression levels of LRP-1 alter steady state levels of Aβ? A simplified network describing the interactions between the cholesterol and beta amyloid (Aβ) synthesis pathways was generated using information available from literature and the KEGG database. A system of non-linear differential equations was developed and modeled using several different initial conditions. Rate constants were approximated using ratio-metric data from the literature, or by fitting parameters to obtain a stable simulation within given biological constraints. Simulations demonstrated the importance of negative feedback control by cholesterol in the regulation of beta amyloid levels. Additionally, the effect of reduced LRP-1 levels and oscillatory cholesterol generation was studied. Biological experiments with mice supported the research.

A topological network describing the interactions between the simplified proteomic, lipidomic and metabolic pathways have been derived [57]. The network was simplified to include only those molecules that are most relevant from a biological standpoint and directly relevant to the questions that we were trying to ask. There are 15 rate constants and a total of 17 molecules in the network. The degree of each major node was calculated by determining the total number of edges in and out of a node, including inhibitory interactions. The nodes with highest degree (AcetylCoA and cholesterol) were expected to play key roles in the overall behavior of the system. All molecules were assumed to reside in one of two compartments: the brain (limited concentration levels) and blood (infinite sink for any molecule being transported across the BBB). Within the brain, the cholesterol was subdivided between astrocytes and neurons, while the ApoE pool was subdivided into astrocytic and free ApoE. Simulation results with this network model, showed several unexpected phenomena, including a decrease in APP and Aβ when the transfer rate of cholesterol between astrocytes and neurons is decreased. These results show that cholesterol and LRP levels play significant roles in the development of increased Aβ levels in the brain, one of the key markers for AD. Future models should study these effects in further detail and incorporate aspects of inflammation that are believed to play a role in AD pathogenesis.

2. Tools and tool architectures

2.1 Compositional Framework for Tool Integration

Our goal is to develop theory and tool infrastructure for the rapid and inexpensive design, construction and integration of tool chains for different CPS domains. The outcome of this research activity will be an open *System Integration Tool Suite* that will consist of the tool components produced by the project team. The tool chain will be incrementally integrate these components into the CPS-VO Repository and distribute them in an open-source, well-documented form.

Our research have been built on Vanderbilt's Model-Integrated Computing tool suite that includes metaprogrammable tools for modeling (Generic Modeling Environment – GME), model data management (Unified Data Model tool – UDM), model transformation (Graph Rewriting and Transformation tool - GReAT). The new approach we follow builds on these tools to create Semantic Backplane that constitutes a "language engineering environment" where domain-specific modeling languages (DSMLs) and tool chains can be rapidly designed and evolved.

The functions of the Semantic Backplane are Metamodeling, Metamodel Analysis and Verification and Metageneration. These functionalities are supported by Languages, Models and Tools as discussed below.

<u>*Tools:*</u> The Semantic Backplane includes the MIC tool suite: (a) GME configured for building metamodels using the metamodeling language MetaGME, (b) the GReAT model transformation tool suite for specifying model transformations and compiling the specifications into executable Model Transformation Tools, and (c) the Unified Data Model (UDM) tool suite for specifying and generating model management backends . A recently completed component of the Semantic Backplane tool suite is the translator toward FORMULA , a tool that can be used for formally verifying and validating metamodels and specifications of model transformations. (FORMULA is the continuation of research started at Vanderbilt on structural semantics at Microsoft Research (MSR)). There is ongoing collaboration between Vanderbilt and MSR in developing and using

FORMULA in various foundational aspects of model-based design, particularly as a formalism for describing formal semantics of modeling languages. FORMULA now is included in the Microsoft Visual Studio distribution.

Languages: The Semantic Backplane includes language for metamodeling – MetaGME – and language for specifying model transformations – GreAT. The languages are functionally complete: Metamodels specified in MetaGME are used for configuring metaprogrammable tools and can be translated into alternative metamodeling languages (used in the Eclipse Modeling Framework, the UML tool suites or MOF). Model transformations specified in GReAT can be compiled into fast Model Transformation Tools. For metamodel analysis and verification we use FORMULA. The Semantic backplane tools include translator that translate metamodels (and GReAT model transformations in the future) into FORMULA.

Models: The modeling languages and model transformations deployed in CPS integration tool chain are specified by MetaGME metamodels and GReAT. If formal verification of metamodels and model transformations are required, the metamodels can be translated into FORMULA. The metamodels, transformation models and FORMULA specifications provide the core semantic foundations that keep the evolution of integration tool chains sound.

Specifying DSML semantics is an essential task for meaningful integration and exchange of models in complex tool chains. Without semantics models become loose artifacts open to misinterpretation. This problem compounds as models are integrated and exchanged. However, providing a framework for specifying and composing semantics is challenging for several reasons: (1) Unlike traditional programming languages that share the Turing machine as a common foundation, DSMLs vary in the nature of their semantics. (2) Direct specification of semantics as mathematical formulas, e.g. by logic, sequent calculi, or trace algebras, requires expertise as a mathematician and language designer. (3) Manual composition of DSMLs semantics by manipulation and (semi-automated) correctness proofs is not practical.

In general, models represent a structure (e.g. a mechanical assembly) and associated behaviors. Accordingly, specification of modeling languages requires support for specifying both *structural* and *behavioral* semantics. In earlier work we have developed a process, called *semantic anchoring*[1] that allows the precise mapping of highly domain specific notations to mathematically sound semantic domains. In this project we are working on the following new approaches:

Structural Semantics defines the set of well-formed models that can be created in a DSML. The set of well-formed models can be defined by a type language and a constraint language. MetaGME uses UML class diagrams as type language and the Object Constraint Language (OCL). We have completed the formalization of structural semantics using the mathematical framework of Structured Logic Programming (SLP). The degree to which we can reason about metamodels depends on the expressiveness of the constraint logic. Some examples are: (1) Models of component-to-CPU deployments where legal models must be schedulable. (2) Models of dataflow systems where legal models never deadlock and always use bounded memory. (3) Models of system state where legal models are those states satisfying invariants. Prior work at Vanderbilt led to the first version of FORMULA (Formal Modeling Using Logic Programming and Analysis) that used non-recursive Horn logic, for deciding well-formedness or mal-

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[1] Jackson, E., Porter, J., Sztipanovits, J.: "Semantics of Domain Specific Modeling Languages" in P. Mosterman, G. Nicolescu: Model-Based Design of Heterogeneous Embedded Systems. pp. 437-486, CRC Press, November 24, 2009

formedness of model instances[2]. Lately, this work has been extended at Microsoft Research to an extended Horn logic with stratified negation[1]. The current version of FORMULA combines algebraic data types (ADTs) and first-order logic with fixpoints (FPL).

As part of our current research activities related to structural semantics, we have completed a MetaGME to FORMULA translator and working on tools for the targeted language engineering environment that offers capabilities to answer the following questions:

(1) Consistency checking – Does there exist a legal model? (2) Synthesis – Does there exist a model that has a certain property?, (3) Design space exploration – Do there exist many models that have a property?, (4) Model checking – Does there exists an initial model and sequence of steps where a property holds over the steps?

Behavioral Semantics is represented as a mapping of the model into a mathematical domain that is sufficiently rich for capturing essential aspects of the behavior (such as dynamics). In other words, the explicit representation of behavioral semantics of a DSML requires two distinct components: (a) a mathematical domain and a formal language for specifying behaviors, and (b) a formal language for specifying transformation between domains. In our previous work on semantic anchoring, we formalized behavioral semantics based on Abstract State Machines (ASM) and represent model transformations as graph transformation (taking advantage of the GReAT model transformation tool of the MIC tool suite). Based on this approach, we have developed a semantic anchoring tool suite that enables the compositional specification of behavioral semantics[1] - an essential requirement for creating an open DSML-based modeling language framework. In this project we experiment defining behavioral semantics in FORMULA. This would greatly simplify specification complexity and allow more extensive invariant verification.

Common Semantic Domains are essential for relating various domain specific dialects of the same fundamental modeling approaches. This is absolutely important in the heterogeneous CPS integration context. In earlier work[1] we have developed an approach called semantic anchoring that we use as specification strategy in the Semantic Backplane. Semantic anchoring is based on the recognition that although DSMLs use many different modeling abstractions, model composition principles, and notations for accommodating needs of domains and user communities, the fundamental types of behaviors are more limited. Broad categories of component behaviors can be represented by behavioral abstractions, such as FSM, Timed Automaton, and Hybrid Automaton. This observation led us to propose a semantic anchoring infrastructure8 that includes the following two elements: (1) formal specification of a basic set of behavioral abstractions – called Semantic Units and (2) specification of transformations. While we will use our earlier semantic anchoring infrastructure for this purpose, but we plan to migrate to FORMULA if the ongoing exploration efforts will meet our expectations.

In summary, we plan to use the Semantic Backplane as foundation for tool integration the following ways in the project:

1. Syntactic integration: translation of models across language variants and syntactically different dialects [59][12].
2. Semantic anchoring: keeping the semantic specification of model elements explicit by defining their transformation to their semantic units.

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[2] Jackson, E., Sztipanovits, J.: ‘Formalizing the Structural Semantics of Domain-Specific Modeling Languages,” *Journal of Software and Systems Modeling* pp. 451-478, September 2009

3. Semantic linking: keeping track of dependencies among model elements deployed in multiple tools [60].
4. Semantic interfaces: keeping the relationship between the semantics of domain specific languages used by modeling, analysis and simulation tools and their abstracted semantic interface explicit and sound.
5. Semantic co-operation: keeping the relationship between the behavioral semantics of domain specific languages used by simulation tools and their abstracted semantic interface toward simulation composition platform explicit and sound.

High-Confidence Embedded Control Software Design

Traditional design methods are not suitable for high-confidence embedded software due to the lack of a formal semantic model for software analysis and automatic code generation. Further, designed embedded software is hard to reuse. In order to automatically generate high-confidence and reusable embedded software, we propose a Transaction Level Modeling (TLM)-centric, platform-based, time-triggered and component-oriented method [11]. In our method, we start with a specification model (SM) of the control system using Simulink. After validation of this SM by simulation, we import the model into an automated embedded software development environment. The environment uses a suite of domain-specific modeling languages (DSMLs) called the Embedded Systems Modeling Language (ESMoL) to integrate analysis and code generation tools. Modeling, analysis, simulation, and code generation are all related to a single design model. The design language is specific to distributed embedded control systems. ESMoL is a suite of DSMLs which function together as a system level design language (SLDL), providing a single multi-aspect design environment [12].

In the ESMoL environment, we establish a TLM based on the imported SM. The TLM captures the hardware platform of the system, the mapping of tasks to the processors and messages to the communication ports, and the scheduling information of the tasks. Based on this TLM, we perform embedded software synthesis which consists of code generation and binary generation. We evaluate the binary code on the target platform to check performance with requirements.

2.2 Multi-model Simulation Environment for Incremental System Integration

Our goal is to support the CPS integration process with a virtual prototyping system including heterogeneous, multi-model simulators capturing essential aspects of systems dynamics. We planned to leverage in this effort our previous results on model-based integration of simulation engines that were based on DoD's High-Level Architecture (HLA). This effort will result in a reusable multi-model simulation integration framework that we can use to rapidly configure our integration experiments. We will also develop the techniques for ensuring model continuity and the seamless evolution of integrated systems from simulation to full implementations.

Networked Control System Wind Tunnel

We have developed a simulation tool for NCS that integrates ns-2, the most widely used open-source network simulator, with Matlab/Simulink, a software tool extensively for control design and simulation of control systems. We have finalized the first version of the Networked Control System Wind Tunnel (NCSWT), an integrated simulation environment for NCS [13]. The NCSWT integrates MATLAB/Simulink and ns-2 according to the High Level Architecture standard. We demonstrate the convenience and efficiency of the NCSWT using several case studies where realistic network effects such as data drops and delays are introduced. We also demonstrate the flexibility and power of the tool in modeling realistic NCS. Currently, we are working on a new Linux-based version aiming at considerably improving performance. In addition, we introduce a model integration language that enables the rapid modeling and synthesis of NCS architectures.

3. Experimental Validation and Evaluation

Open Automotive Experimental Platform

We have completed an initial plan for building an open automotive experimental platform at the Institute for Software Integrated Systems (ISIS) at Vanderbilt University. The platform's objective is to provide a realistic automotive test-bed for testing the design and integration methodologies developed in the project. The test-bed consists of a computer host connected to four Electronic Control Units (ECUs) using a time triggered network. The host provides simulation capabilities for a complete vehicle in a modular and reconfigurable way. The test-bed includes a software stack with a RTOS, drivers for the time triggered network, and a virtual machine that allows time triggered execution in order to provide real-time simulation capabilities. A tool chain for embedded software control is also under development.

In addition, we have developed Adaptive Cruise Control and Lane Centering Control algorithms for testing purposes and we have created a virtual experimental platform to assess control composition and control-software integration before we start the experimental studies.

Quadrotor UAVs

Traditional design methods are not suitable for high-confidence embedded software due to the lack of a formal semantic model for software analysis and automatic code generation. Further, designed embedded software is hard to reuse. In order to automatically generate high-confidence and reusable embedded software, we propose a Transaction Level Modeling (TLM)-centric, platform-based, time-triggered and component-oriented method [11]. We use this new method to generate the control software for a quadrotor helicopter.

In our method, we start with a specification model (SM) of the control system using Simulink. After validation of this SM by simulation, we import the model into an automated embedded software development environment. The environment uses a suite of domain-specific modeling languages (DSMLs) called the Embedded Systems Modeling Language (ESMoL) to integrate analysis and code generation tools. Modeling, analysis, simulation, and code generation are all related to a single design model. The design language is specific to distributed embedded control systems. ESMoL is a suite of DSMLs which function together as a system level design language (SLDL), providing a single multi-aspect design environment [12]. In the ESMoL environment, we establish a TLM based on the imported SM. The TLM captures the hardware platform of the system, the mapping of tasks to the processors and messages to the communication ports, and the scheduling information of the tasks. Based on this TLM, we perform embedded software synthesis which consists of code generation and binary generation. We evaluate the binary code on the target platform to check performance with requirements.

Networked Multi-Robot System

We have demonstrated the passivity-based approach using an experimental Networked Multi-Robot System (NMRS) [8]. The experimental setup consists of two CrustCrawler robotic arms and one Novint haptic paddle connected using a networked computing platform. The computing platform consists of five networked Windows PCs with Matlab/Simulink. The robotic arms and the haptic paddle are connected to three respective PCs via USB interface utilizing Matlab/Simulink APIs. The goal in our experiments is for the tip of the end effectors of the robots to follow the trajectory of the human-controlled haptic paddle in a synchronized and stable manner. We have obtained extensive experimental results that demonstrate the approach using both wired and wireless networks and considering the effect of persistent and intermittent link failures. Further, we have performed a comparison study, which compares our approach to an approach that does not use network feedback. The comparison study illustrates the need for network feedback whenever synchronization of the robot arms is desired. The detailed approach that includes the experimental evaluation is presented in [8].

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