Year 3 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.

The overall objectives of our research effort are:

(a) To contribute to the development and validation of new basic principles for modeling, design and performance evaluation of complex networked cyber-physical systems. These principles must be tested and shown to apply across domains of CPS applications. Most of the systems of interest are networked systems, also known as multi-agent systems;

(b) To develop model-based systems engineering (MBSE) methodologies for various classes of CPS applications, including automotive, aerospace, air-traffic management systems, robotics, collaborative robotics, energy efficient buildings, smart grid, health care, biological networks and systems, communication and sensor networks.

(c) Investigate and study in an integrated fashion the security, safety and reliability of CPS across all these application domains.

During the third year of our research project we have pushed along several frontiers towards these overall objectives. Some details are provided below. The references are given in the report sections covering books and book chapters, journal and conference publications.

This report is organized as follows. 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.

1. Theory of compositionality

1.1. Guaranteeing Passivity of a Nonlinear System through Linearization

The goal of this research is to investigate what passivity properties for a nonlinear system can be inferred when its linearization is known to be passive. For a nonlinear system which is completely reachable and passive, its linearization remains passive (W. M. Haddad and V. Chellaboina - Nonlinear Dynamical Systems and Control: A Lyapunov-Based Approach - Princeton University Press- 2008). However, the converse problem of studying passivity for a nonlinear system through its linearization has not been fully explored. To analyze the linearized system, we can take advantage of the well-established passivity theory for linear systems. It is also of practical importance because many of the controller designs for nonlinear systems are based on their linearized models.

We consider both continuous-time and discrete-time systems with feedthrough terms. Our main results show that when the linearized model is simultaneously strict passive and strict input passive, the nonlinear system is passive as well but within a neighborhood of the equilibrium point around which the linearization is done [52]. Algebraic conditions are given to show when a linear system is simultaneously strict passive and strict input passive. The results generalize to the case when the linearization is QSR-dissipative. In particular, we establish conditions under which the passivity indices of the linearized models are equivalent to those of the nonlinear systems around the equilibrium point.

We show that merely strict passivity for the linearized models may not be sufficient to guarantee local passivity of the nonlinear systems with feedthrough terms [53]. This is particularly relevant for discrete-time systems since the feedthrough terms are necessary to show passivity of the system. One set of sufficient conditions are established to guarantee local passivity of the nonlinear system when the linearization is strict passive. When the feedthrough term is zero, our results reduce to the previous results (H. Nijmeijer, R. Ortega, A. Ruiz, and A. van der Schaft - On passive systems: from linearity to nonlinearity - Proceedings 2nd IFAC Symposium on Nonlinear Control Systems- Jun 1992).

We are currently characterizing the neighborhood for which the property of local passivity for a nonlinear system implied from its linearization holds. We are also considering other approximation techniques such as model reduction that can be used to approximate large scale, complex systems (S. Gugercin and A. C. Antoulas - A survey of model reduction by balanced truncation and some new results - International Journal of Control - May 2004).

1.2. Passivity and Dissipativity of a System and its Approximation

The goal of this research is to investigate the passivity of a system as inferred from studying an approximate model of its dynamical behavior. In a large scale cyber physical system, precise knowledge of the mathematical model will be difficult to obtain. Moreover, even if such a model were obtainable, the classical tradeoff between model accuracy and tractability may lead to the use of a simpler model (W.S. Levine - Control System Fundamentals - 1st edition, CRC press - 1999). A variety of approximation methods can be used, for analysis, simulation or control design of the ‘real’ systems (A.C. Antoulas - Approximation of Large-Scale Dynamical Systems - Society for Industrial and Applied Mathematics - 2005). While it is known that under some conditions, linearization and model reduction can be performed so as to preserve passivity, the question of whether passivity of a system can be guaranteed if a system with a model ‘close’ to it is passive still remains open.

We establish relationships between passivity levels of two mathematical models, one of which could represent accurately a physical system and the other could represent an approximation. Of course, the two mathematical models can represent two different approximations of the same physical system as well. Our results [55][56][68] show that an excess of passivity (whether in the form of input strictly passive, output strictly passive or very strictly passive) in the approximate model guarantees a certain passivity index for the system, provided that the norm of the error between the two models is sufficiently small in a suitably defined sense. Further, we consider QSR-dissipative systems and show that QSR-dissipativity has a similar robustness property, even though the supply rates for the system and its approximation may be different. These results may be particularly useful if either the approximate model may be much easier to analyze, or if the accurate system model is unknown precisely.

We apply our results to particular approximation methods, such as linearization of a nonlinear system around an equilibrium point and model reduction of a higher-order system to obtain a lower-order model, sampled-data systems and quantization [54]. The analysis is extended to hybrid dynamical systems as well [54]. Since there is a rich theory of using passivity levels (or indices) to design control laws [3], our results imply that it is possible to use the (hopefully more tractable) approximate model for control design. An alternative interpretation of our results is as a robustness property for passivity and dissipativity with respect to model uncertainties (J. Bao and P. Lee - Process Control: The passive Systems Approach - 1st edition, Springer-Verlag - 2007).

1.3. Robust Nonlinear Model Predictive Control Using Passivity and Dissipativity

Model predictive control (MPC), as an effective control technique to deal with multi-variable constrained control problems, has been widely adopted in a variety of industrial applications. The success of MPC can be attributed to its effective computational control algorithm and its ability to impose various constrains when optimizing the plant behavior. Unlike the conventional feedback control, MPC allows one to first compute an open-loop optimal control trajectory by using an explicit model over a specified prediction horizon, then only the first part of the calculated control trajectory is actually implemented and the entire process is repeated for the next prediction intervals. Although MPC has many advantages, several issues, such as feasibility, closed-loop stability, nonlinearity and robustness still need to be studied. Recently, a passivity-based NMPC scheme is proposed and is shown that close-loop stability and feasibility can be guaranteed by introducing specific passivity-based constraints (T. Raff, C. Ebenbauer, and F. Allgöwer, “Nonlinear model predictive control: A passivity-based approach,” in Assessment and Future Directions of Nonlinear Model Predictive Control, ser. Lecture Notes in Control and Information Sciences, Springer Berlin / Heidelberg, 2007).

In [57], we propose a robust stabilizing output feedback NMPC scheme by using passivity and dissipativity. Instead of assuming both the nominal model and the plant are passive systems with the same dynamics as reported in the previous work, we assume that the model for prediction and the actual plant dynamics are dissipative (which are more general than passive systems since they could be non-passive), and they do not have to possess the same dynamics. Model discrepancy between the nominal model and the real system is characterized by comparing the outputs for the same excitation function. With this characterization of model discrepancy, we are able to compare the supply rate between the nominal model and the real system based on their passivity indices [53]. Then, by introducing specific stabilizing constraint into the MPC based on the passivity indices of the nominal model, we can show that the control input calculated using the nominal model can guarantee stability of the plant to be controlled.

1.4. Passivity and Dissipativity properties for Hybrid Systems and Discrete Event Systems

Many systems of interest in cyber physical systems cannot be described by traditional nonlinear models or even by switched system models. This is the case in systems with switching dynamics and different equilibria for different modes. These systems are best described by hybrid system models such as hybrid automata. These models contain both continuous states and discrete modes. In [60] new definitions were given for passivity and dissipativity for a hybrid automata model that contains continuous inputs and continuous outputs. These definitions were based on the decomposable dissipativity for switched systems mentioned earlier in this report. The notion of dissipativity was given with a result to show Lyapunov stability when the state space of the hybrid automaton is constrained. In general, Lyapunov stability isn't possible for hybrid models with different equilibria in different modes. This is why a result showing bounded stability was provided in addition. This result shows that the continuous state is attracted to a set with an upper bound which it will stay in indefinitely. This result can be applied to a large class of hybrid automata. The special case of passivity was presented and results were derived that showed that passive systems were Lyapunov stable and that the passivity property was preserved when systems are combined in feedback or parallel. As a generalization of existing definitions, they reduce to the case of dissipativity and passivity for switched systems or nonlinear systems when a system model is more restricted.

The notion of dissipativity for discrete event systems given in [60] represents preliminary work on describing the dissipativity properties for systems that evolve according to events and not based on time. Some basic definitions were given and stability results were derived to connect to existing notions of stability for finite automata and a general class of discrete event systems. While this preliminary work is promising, the more interesting case is considering discrete event system models that represent input-output mappings. These models can be used to capture computer controllers in cyber physical systems.

1.5. Experimentally Determining Passivity and Passivity Indices

In many applications, traditional system models described by differential equations may not be practical. This can be caused by a number of factors including nonlinear or time-varying dynamics that may not be modeled or logical components such as lookup tables that may not be described by either differential equation or logical models. For these systems alternative methods of determining passivity or dissipativity directly from input-output data may be used. The traditional method of control system design involves modeling the plant to be controlled, analyzing the plant, and then synthesizing a controller. Using passivity theory or theory from passivity indices does not require the use of a model. Instead, data can be collected to determine that a system is passive or that it has certain passivity indices. In most cases, there must be a significant amount of data collected in order to make these conclusions. However, the amount of data required is similar to the amount of data required to determine and verify a model.

A system is considered passive if the inner product of the system's input and output remains positive for all inputs in a set. This is tested with respect to zero initial conditions. Technically this condition must be verified for all times from the initial time to infinity. For systems that are passive with respect to a particular input, the inner product will vary with the input but will typically grow without bound. If this pattern holds for a sufficiently long initial time interval, it can be concluded that the inner product will not suddenly differ from this trend. Depending on the input, this initial time interval may be shorter or longer. Input signals can be considered with respect signal magnitude, frequency, etc.

There are a couple limitations to note with this approach. One is that this experimental result is a necessary only test for passivity. Demonstrating that a system is passive for all inputs would technically require testing an infinite set of inputs for an infinite time interval. Another is that the input set is often not a finite set in practice. An actual input to a system is likely not exactly specified in advance so will not be contained within a finite set. When the input set contains an infinite set of inputs, the test for passivity can be modified. A finite subset can be chosen that represents the diversity of the input set in terms of signal magnitude, frequency content, etc. For example, a set of inputs can be chosen to represent a range of frequencies up to some presumed maximum frequency. This maximum may be an artificial limit set by the controller or a hard constraint on the rate that an actuator can act on a system.

A similar approach can be taken to estimate passivity indices for a system. In this case the inequality to be satisfied takes the form of passivity indices for a system without internal representation. When testing this inequality, the indices can be estimated from each data set and for each time. When considering all data, this gives many upper bounds on the indices. Any algorithm that provides a final set of indices from this data must give indices that satisfy all the bounds. How the exact indices are chosen from the bounds is another problem. It is often possible to reduce one index in order to increase the other. It should be noted that the indices cannot be smaller for a restricted set of inputs than for any possible input and may be quite larger. Additionally, the algorithm may give bounds that are not tight for the indices. In this case, a buffer should be introduced to give a more conservative bound on the indices. This is especially important in the practical case when a representative sample of inputs is tested rather than the full set.

1.6. Passivity: Fundamental Theory

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 [1].

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.

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 [4]). 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.

Our work in this direction has been in two areas:

1. *Passivity for Series Interconnected Systems:* However, one 'gap' in the existing work has been that series connections were not guaranteed to preserve stability. In this direction, we provided a characterization for preserving passivity when passive systems are connected in series [8].
2. *Relation of Passivity to Conic Systems:* One fundamental contribution we have made in this project is to relate the notion of passivity to classic results on conic systems (G Zames - On the Input-Output Stability of Time-Varying Nonlinear Feedback Systems - Transactions on Automatic Control - April 1966). While rough characterizations were known, we made the relationship precise through passivity indices [6]. Roughly speaking, these indices provide an analytical characterization of 'how passive' a system is. We have shown that this is intimately related to conic systems, which allows us to use many classical results in that area. Additionally, we have generalized the concept of a passive index to switched systems, as mentioned later in this report.
3. *Relationships between Passivity and Positive Real:* While passivity is an energy-based property for nonlinear systems, positive real captures a similar property for linear time-invariant systems described by transfer functions. This connection exists in the literature but connections between the various sub-classes of passive and positive real systems were not explored. These results were studied in [58] to survey existing results and provide new results to solidify the connection.

1.7. 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 most general being published in (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 [3][9] .

Our work in this direction has encompassed the following major areas:

1. *A Notion of Passivity Indices for Switched Systems:* We have extended 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 [3]. This approach was used in resilient control to recover from cyber-attacks in [11].

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 [3 - 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.

2. *Stability of Networked Passive Switched Systems:* In this direction, we considered realistic CPS 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 [9].

3. *A New Framework for Passivity in Switched Systems:* As mentioned above, the most generalized definition of passivity for switched systems in the literature is that by Zhao and Hill. However, even that work is limited to switched systems with all modes that are passive individually. For realistic CPS, this would not be the case. A major research effort in this project has been to extend the passivity consideration for more general switched systems that include non-passive modes.

We first investigated the generalized feedback passivity of a networked control system in which the control packets may be dropped by the communication channel [42]. The system can be modeled as a discrete-time switched nonlinear system with relative degree zero that switches between two modes. At the instants when the communication link transmits the packet successfully, the system evolves in the closed-loop mode which is assumed to be non-passive but feedback passive. At these time steps, the storage function is always bounded below the energy supplied by means of feedback control. However, at the instants when a packet drop occurs, the system evolves in the open loop mode according to the free dynamics of closed-loop mode. At these time steps, the system is open loop unstable and hence the increase in storage function is not necessarily bounded by the supplied energy. We investigate the generalized feedback passivity of such a switched system through zero dynamics. We prove that if the ratio of the time steps for which the system evolves in closed-loop versus in open loop is lower bounded by a critical ratio, the system is locally feedback passive in a suitably defined sense. Moreover, this generalized definition of feedback passivity is useful since it preserves two important properties of classical passivity - that feedback passivity implies stabilizability for zero state detectable systems and that feedback passivity is preserved in parallel and feedback interconnections.

In [43][67] , we extended the above definition to general discrete-time switched systems with multiple modes. We first derive the necessary and sufficient conditions for the passivity of general switched systems with both passive and non-passive modes. By designing a suitable feedback control, some of the non-passive modes can be made passive and the above results can be further extended to switched systems with modes which can be passive, non-passive but feedback passive, or non-passive and non-feedback passive. The switched nonlinear system is proved to be locally feedback passive if and only if its zero dynamics are locally passive. A lower bound on the ratio of total activation time between (feedback) passive and non-feedback passive modes is obtained to guarantee passive zero dynamics with Lipschitz constraints. We prove that output feedback control can be used to stabilize the equilibrium point of the switched system. The compositional property of passivity remains under this generalized framework.

By introducing the new generalized definition of passivity for switched systems, we have relaxed the constraints on systems analyzed by passivity theory in the literature. Because both the stability and compositional properties are preserved using the definition, this gives us a powerful tool to investigate a broader range of systems, especially complex large-scale systems as considered in CPS.

1.8. 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. Such systems include many mechanical systems such as 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 [2].

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.

1.9. Discretization and Quantization of Passive Systems

Although traditional passivity theory has been applied successfully in various classical nonlinear systems, this property is vulnerable to discretization, quantization and other factors introduced by digital controllers or communication channels. Several preliminary results show that passivity is not preserved under discretization, which means the discretized system may not be passive even if the original continuous-time system is passive. In addition to discretization, the effect of quantization also needs to be considered when digital controllers interact with the environment by means of analog-to-digital converters or digital-to-analog converters that have a finite resolution. Moreover, quantization is necessary when the information between plants and controllers is transmitted through communication networks. Passivation techniques are needed for general nonlinear quantized systems.

In our work, the main contributions are the derivation of conditions under which the passive structure of an output strictly passive (OSP) system can be preserved under quantization and its application in stability for passive switched systems with passive quantizers [34]. The passivity preservation relies on an input/output transformation on the quantized input and output. The result shows that one can find such transformation so that the same passivity index of the original OSP system, with respect to the transformed input and output, will be recovered. The result is relatively general since we only require the system to be OSP and the quantizers to be passive, which characterize many practical quantizers. Although the passivity preserving condition is initially derived for non-switched systems, it can be extended to passive switched systems where the input/output transformation can switch between different transformations according to the current active subsystem. Therefore, passivity of passive switched systems under quantization can be guaranteed and the stability conditions in [3][9] can be applied.

1.10. Dissipativity-Based Certificates for Reliable 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 main goal is reliable stabilization, i.e., the system remains stable (or additionally satisfies some performance guarantee) even if some components fail. Our work in this direction is along the following lines:

1. *Reliable stabilization using dilated LMIs:* The first area of this work is in reliable stabilization via rectangular dilated LMIs and dissipativity-based certifications [21][22][23][66] . 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 stabilization results that were less conservative than those existing in the literature. Further, we 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. For instance, in [39], we used a

rectangular dilated LMIs framework to provide a relaxed sufficient condition for the simultaneous stability of a multi-channel system both when all of the controllers work together and when one of the controllers ceases to function due to a failure.

2. *Game-theoretic tools for robust stabilization:* 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 [24][36][40]. 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.

3. *Reliable Performance:* Beyond stability, we also considered the problem of reliable disturbance decoupling to guarantee a certain level of performance. In [38], the problem of reliable disturbance decoupling for a generalized multi-channel system was posed in a game-theoretic framework. Specifically, we linked the problem of stabilization of the multi-channel system to certain properties of controlled invariant subspaces that are associated with the problem of disturbance decoupling, where the structure induced from this family of invariant subspaces is used for a game-theoretic interpretation of the problem. We also provided a sufficient condition for the existence of a set of feedback equilibria that maintain the robust stability of the system under possible single-channel controller/agent failure as well as in the presence of unknown disturbances in the system [41].
4. *Robustness against Attacks:* A related problem is that of ensuring reliability when the faults arise due to adversaries that are trying to strategically harm the control objective. We considered the problem of ensuring stability in the face of an adversary that poses a Denial-of-Service attack on the control packets [25]. By assuming a Markov modulated attack, we provided the optimal controller design to defend against such an attack.

1.11. 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. Our work in this direction has been along the following lines:

1. *Stability conditions using symmetry and dissipativity:* 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 [7]. 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. It is important to note that no restrictions were placed on the actual dynamics which may be different. The results are robust under parameter variations, therefore apply to heterogeneous systems as well, as long as they satisfy the dissipativity inequalities. Moreover, approximate symmetry with respect to not exactly symmetric interconnections are also considered and more robustness of the results are derived. Other work on distributed systems for this project is in exploiting communication symmetries in networked dissipative systems to show stability [7]. We consider a symmetric communication graph (for example a star or a ring topology). The form of the symmetry can be used together with the dissipativity property of agents to simplify the conditions that guarantee stability of a distributed system. Symmetry and dissipativity in the design of large-scale complex control is studied in [61].

2. *Passivity indices in 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 [7], passivity indices for both linear and nonlinear multi-agent systems with feed-forward and feedback interconnections are derived with the distributed setup in [20]. 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, with extensions of network delays. Normally dissipativity and passivity cannot be preserved if random delays are introduced into the network. Scattering transformations are used to force the energy stored in the delayed network to

be non-negative, and feedbacks and the presence systems to be L_2 stable, therefore preserving the stability results with updated output feedback passivity index.

3. *Symmetry without dissipativity:* 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 [27][65]. Extensions of these results under this grant are focused on robust robotic formation control when one or more robots in the formation may fail [28]. 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. Other current efforts are directed toward extending the results to non-symmetric systems. These efforts include a) conditions for stability of perturbed symmetric systems, where the dynamics of the system have a symmetric "kernel" but with additive non-symmetric components [78], b) bounds on solutions for perturbed stable symmetric systems [79] and c) bounds on solutions for stable symmetric systems subjected to persistent nonautonomous input signals [80].

1.12. Event-Triggered 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).

Our work in this direction has been along the following lines:

1. *Event-triggered control for passive systems:* 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 [15], 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 [18], 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 [15] 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 [18], 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 [18], 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 [16]. 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 [12][13].

2. *Event-triggered distributed control of large scale systems:* 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 [17], 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 [17] only considers stabilization problem with an ideal network model, we continue to study event-based cooperative control problem in [14][19], 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 [34] 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 [19].

3. *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 [26].

4. *Formation Control of Multi-agent Systems with Event-driven Communication and Passivity:* Existing results on distributed coordination control of multi-agent systems critically rely on maintaining a connected communication network among the agents, either for all time or over sequence of bounded time intervals. However, for a given set of initial conditions, those assumptions on connectivity of the networks are difficult to verify. In particular, connectivity of the initial network cannot guarantee connectivity of the network in future times. Motivated by the importance of network connectivity in the control of multi-agent systems, many researchers have emphasized connectivity preservation in networked dynamical systems. While connectivity preservation for coordinated control of mobile agents has been extensively studied in the literature, one should notice that continuous or frequent communications between coupled agents are still required in most of these works; moreover, the control action updates and the data transmissions between agents are usually assumed to be implemented in a synchronous fashion. Note that multi-agent dynamic systems are distributed systems which usually act in an asynchronous manner and in general, it is difficult to implement synchronous motions on them. However, analyzing the dynamics of asynchronous systems is more difficult compared to their synchronous counterparts.

The objective of this work [35] is to study formation control of multi-agent systems with connectivity preservation where the data transmissions between coupled agents are triggered in an event-driven combined with a time-driven way. By “event-driven”, we mean there exists a triggering condition for each agent so that whenever an agent satisfies its triggering condition, it will send its current state information to its neighbors at that time (event-time). From this perspective, communications among coupled agents are scheduled by demand. By “time-driven”, we mean that there exists an upper bound on the inter-event time of each agent. Hence, in our set-up, the agent will transmit its current state information to its neighbors whenever it satisfies its own triggering condition or if the time elapsed form the last event time is going to exceed the agent’s maximal admissible inter-event time. The distributed control action is generated based on the local information sent by the neighboring agents. We have derived the triggering condition to achieve both formation control and connectivity preservation, provided that the initial deployment of the agents are within the communication radius of their neighbors.

A multi-agent system, in general, can be defined as a network of a number of loosely coupled dynamic units that are called agents. In real-life, each agent can be a robot, a vehicle, or a dynamic sensor, etc. The main purpose of using multi-agent systems is to collectively reach goals that are difficult to achieve by an individual agent or a monolithic system. When the main problem of interest in control of multi-agent systems is to establish a well-structured motion, the term swarm or sometimes formation is used. There exists a number of different formation coordination and control approaches investigated in the system and control literature. Most of these work assumed a synchronous implementation strategy regarding the control action updates and the scheduling of data transmissions among the coupled agents. Note that multi-agent dynamic systems are distributed systems which usually act in an asynchronous manner and in general, it is difficult to implement synchronous motions on them. However, analyzing the dynamics of asynchronous systems is more difficult compared to their synchronous counterparts.

In this work, we propose a distributed event-driven control strategy for formation control of networked passive systems. The distributed triggering condition is derived based on the observation that the entire networked control system is Output Strictly Passive (OSP) with some error signal as input and some disagreement signal as output when an ideal network model is assumed. We further propose a set-up to render the entire networked control system OSP in the presence of constant network induced delays and derive a triggering condition to achieve distance-based formation when delays are considered.

5. *Analytic Performance Expressions for Event triggered Estimation:* Most of the work available in the literature has focused on either designing event triggered schemes to transmit data to guarantee stability, or designing sub-optimal schemes to approximate the optimal event triggered schemes. In [51], we provided analytical expressions for performance with level triggered event triggered schemes for communication in an estimation problem. These results provided an analytic way to trade-off performance with communication rate.

6. *Event-triggered Estimation over Shared Communication Medium:* To further integrate the event-triggered research with CPS, we considered the performance of event-triggered schemes when multiple processes share one communication medium [50]. Such a situation in natural in large CPS. We considered various contention resolution mechanisms along with CSMA. Performance expressions were analytically calculated. The surprising result was that for many natural choices of contention resolution mechanisms, a simple time-triggered scheme based on round robin transmissions can provide better performance with the same communication rate. This result provides caution to designers in view of the recent spurt of interest in event-triggered schemes.

1.13. Model-based Control of Networked Systems.

The main goal in this research topic is to reduce the necessary network bandwidth for control of uncertain Networked Control Systems (NCS). In the Model-Based Networked Control Systems (MB-NCS) framework we implement a nominal model of the plant at the controller/actuator side to approximate the plant behavior so that the sensor is able to send data at lower rates, since the model can provide information to generate appropriate control inputs while the system is running in open loop mode. We have obtained the following results in this direction:

1. *Model-Based Event-Triggered (MB-ET) control:* The use of event-triggered control techniques has gained significant attention for the design control systems with non-periodic communication. The use of event-triggered control in embedded control systems and CPS has the main purpose of reducing computational effort and task delays by updating the controller only when the output of the system changes by a given amount. In

NCS the use of event-triggered updates is used in order to reduce network bandwidth following the same idea. Stabilization of uncertain systems subject to quantization and network induced delays has been studied in [29]. Tracking control of discrete-time systems with network delays has been considered in [30]. Similar strategies have been considered in [31] for stabilization of distributed coupled subsystems. Centralized and decentralized control techniques were provided in that paper.

2. <u>*Adaptive stabilization:*</u> The use of parameter estimation techniques is used in [32] in order to estimate the current parameters of the plant and to upgrade the model of the system. A more accurate model provides an improved control action and longer open-loop mode time intervals can be obtained.

3. <u>*Model-based control of dissipative nonlinear discrete-time systems:*</u> The MB-ET approach has been extended in [33] to study uncertain nonlinear dissipative discrete-time systems that are also affected by external disturbances. The design of dissipative controllers for MB-NCS is made possible by modeling the model-based networked architecture as a standard negative feedback interconnection and by implementing the model as a difference (input-output) equation which can be updated using the system's output measurements directly without need of state observers. Communication rates are reduced significantly with the MB-NCS framework and then further reduced by implementing non-periodic event-triggered communication. The main result of [33] demonstrates boundedness of the average output squared with a constructive bound. This bound can be made quite small by varying the design parameters of the controller and varying the acceptable error threshold. This work was extended in [59] to also stabilize the internal state of a nonlinear system from the input-output representation. This new approach also considers non-vanishing input disturbances. While the addition of these disturbances hurts the upper bound on the output and state as time goes to infinity, it doesn't prevent a boundedness result from being demonstrated.

4. <u>*Model-based Scheduling for Networked Control Systems:*</u> When communication networks are used to close the control loop, we have to consider the possible communication delays and packet dropouts when design the control system. The previous work on MB-NCSs is focused on reducing the data transmissions between the sensor and the network controller so that the networked control system can run open-loop for a longer time. The roles of the communication networks could be considered as time-delay operators, in general. However, in the presence of time-varying network induced delays, the data packets transmitted by the sensor could arrive at the controller node in a wrong order, which implies that a data packet arriving later due to long delay may not contain new information about the plant. Moreover, packet dropouts are very likely to occur due to long delays or data flow congestions. Hence, how to deal with the outdated data received by the network controller and the data-loss in the communication networks are important issues that need be addressed in the context of MB-NCSs. These are the main problems investigated here. We have derived a systematic model-based scheduling strategy to achieve ultimate boundedness stability in the sensor-actuator networked control systems, which could be applied to both linear and nonlinear networked control systems.

Further recent results in this field are published in [1][5][10][63][64][68][70][71][74] [93].

1.14. Anytime Control

In CPS, one of the major approximations that breaks down as compared to classical control is that of availability of ample computational resources at every time step to be able to implement any control algorithm with a control input being calculated at every time step. In CPS, the microprocessor may share many tasks and interrupts may take priority over the control task. We addressed the problem of designing control algorithms that can function in spite of time-varying and uncertain computational resource availability in our work on anytime control (this work was started under a different NSF grant). Anytime algorithms are algorithms that provide a solution with minimal processor availability, and refine the solution as more processing resources become available. We provided an anytime control algorithm for linear systems in [44][45] that was based on refining the model of the process gradually as more processing resources became available. Assuming a stochastic model of processor availability, optimal controller design was obtained and stability and performance analysis provided. In [46], we extended the algorithm to a constrained linear system using the receding horizon control methodology. The constrained system framework is naturally more conservative even without additional processing constraints. However, we were able to provide stability proofs and demonstrate marked improvement in performance with the anytime algorithms. Finally, using a Lyapunov function based methodology, we provided some of the first available anytime control algorithms for non-linear systems in [47][48][49]. The basic idea is to calculate and store future control inputs when processor is available and use such stored inputs when processor is not available. Once again, stability proofs were provided and performance expressions for the linear case obtained.

1.15. Performance-aware Passivity-based Adaptive Sampling in Networked Control Systems

While NCS certainly provide numerous benefits, the complexity of their modeling, analysis and design raises several challenges which need to be overcome to fully utilize the benefits. Two significant challenges in the design and operation of NCS are the impact of network effects and limited network resources. The network effects consist of network uncertainties, such as time-delays and the possible loss of packets, introduced due to the use of a communication network. These network effects pose considerable concerns due to their significant impact on overall system stability, performance and safety. On the other hand, the limited network resources often lead to limited information exchange over the communication network. The limited network resources imply that the frequency of information exchange between the components of the NCS is limited. This limitation has a direct impact on the achievable stability and performance of the NCS. Attaining desirable trade-off between satisfying the communication constraints as a result of the limited network resources without sacrificing stability and ultimately performance of the overall system is a challenging problem.

We developed a performance-aware adaptive sampling framework for passivity based networked control system. The framework, presented in [94], integrates the nice properties or passivity and adaptive sampling in order to simultaneously address the design challenges involving uncertainties and constrained resources in wireless communication network. Hence, while passivity provides the desirable robustness to network effects, adaptive sampling provides the desirable "sample and sent when necessary" approach for efficient utilization of limited network resources. A pair of sample-and-hold components, a variable passive sampler and a variable passive hold, are introduced that facilitate the integration of non-uniform sampling while at the same time ensuring passivity. The stability of the overall networked control system is derived and trajectory tracking is demonstrated for the case where the performance objective is tracking. A case study for the trajectory tracking control of a four degree-of-freedom robotic manipulator over a wireless network is used to demonstrate the efficacy of the approach.

1.16. End-to-end reliability analysis of wireless real-time mesh networks

State-of-art wireless real-time mesh networks, such as WirelessHART or ISA100.10a offer a high probability of successful delivery of packets within a certain application-mandated deadline. These soft guarantees are required to be kept despite the well-known uncertainties of wireless communications, in the presence of fading, interference, node failure etc. The high reliability, among others, stem from eliminating link-layer contention by centralized planning of resource allocation and by using redundant routing.

Often, application design, such as design of control loops, is decoupled from the underlying communication layers by assuming reliable delivery within the given deadline. Thus, the probability analysis of successful delivery plays a central role in integration of CPS applications with such wireless communications platforms. This kind of analysis and application co-design in the literature most often assumes uncorrelated, identically distributed packet losses over the constituent links, independently of the underlying deployment geometry and propagation environment.

In order to obtain a more realistic view of the end-to-end flow reliabilities in real-time mesh networks we analyzed the per-link outage probabilities under the assumption of Nakagami-m multipath fading channels and distance-dependent average path losses [83]. The per-link outage probabilities can then be used to characterize the end-to-end reliability either for a specific geometry, or by assuming random geometrical distribution of nodes.

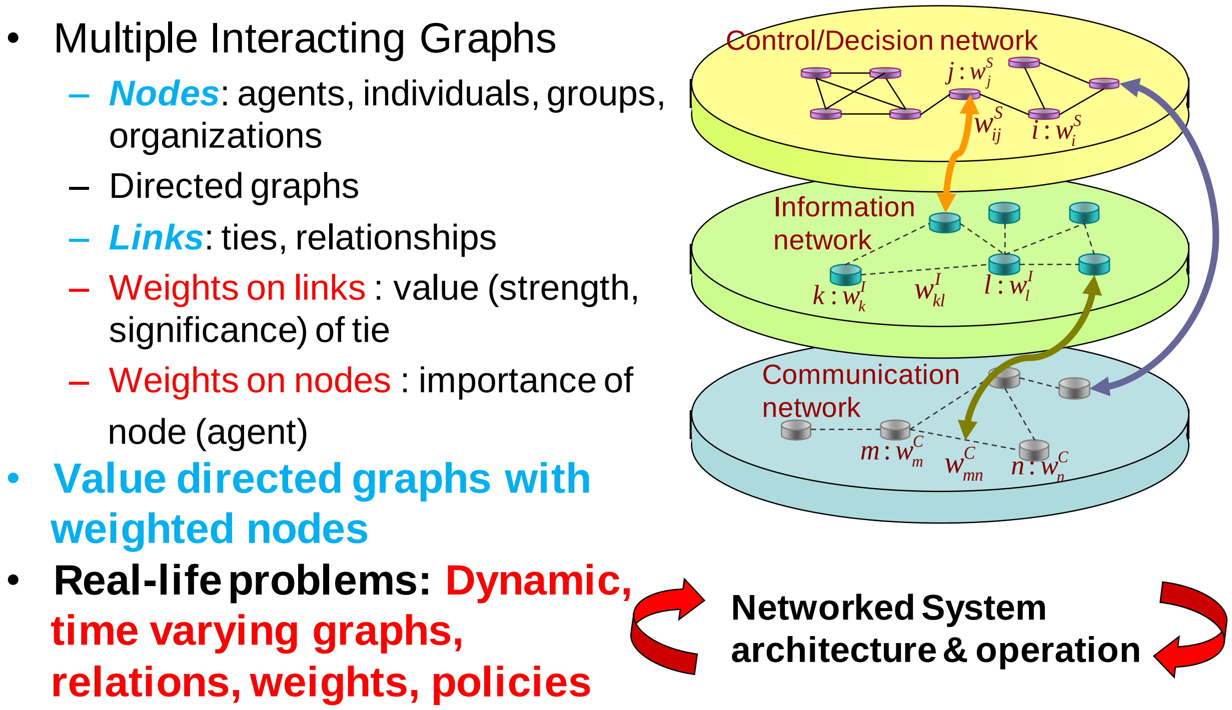
Closed-form expressions can be obtained for the per-link outage probabilities for specific path loss exponent values, if the path loss increases proportionally with the square or the fourth power of the distance. These cases can be seen as limiting cases for practically observed path loss exponent values. We adopt a linear programming-based formulation to select optimum redundant routes with maximum end-to-end reliability, based on the per-link outage values.

The insights gained from analytic expressions can be incorporated into design decisions about link scheduling, routing and deployment constraints, such as when to adopt redundant multipath routing or how to allocate retransmission slots in a realistic scenario

1.17. Multiple Graph Models for Networked CPS

A very important class of networked CPS is autonomous collaborating multi-agent systems, which for large populations are also called 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 continued our investigation of 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, and have developed certain new fundamental principles. Our emphasis continues to be on system concepts and synthesis, including system architecture and the effects of various topologies and networks on performance.

We have abstracted the collaboration between the agents into three interconnected levels, as shown in Figure 1 below. At each point of time, three *multigraphs* describe the network of moving vehicles: a *communication multigraph (network)*, an *information multigraph (network)* and a *cognitive/collaboration multigraph (network)*. The first two multigraphs describe the information exchange in the network whereas the *cognitive multigraph* is specific to the particular collaborative activities that the nodes perform and determines the desired collaboration activity; it is also described often as the *control/decision multigraph (network)*. Our research is focused on the following challenging question: Given a preferred emergent behavior, which connectivity and communication graphs can satisfy the requirements given by the corresponding collaboration 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. Small World-like graphs, Expander Graphs and Motif-based topology design have emerged from our framework and research.



- Multiple Interacting Graphs
  - ***Nodes***: agents, individuals, groups, organizations
  - Directed graphs
  - ***Links***: ties, relationships
  - Weights on links : value (strength, significance) of tie
  - Weights on nodes : importance of node (agent)
- **Value directed graphs with weighted nodes**
- **Real-life problems: Dynamic, time varying graphs, relations, weights, policies**

Networked System architecture & operation

Figure 1: Multiple interacting multigraphs model of networked CPS

Recently [121], using this framework, we were able to resolve a long standing problem in distributed control: the so-called "vehicle platooning coordination using only local information" (see [1]; P. Varaiya, "Smart Cars on Smart Roads: Problems of Control," *IEEE Transactions on Automatic Control*, 38(2), 195–207, 1993; H. Hao, P. Barooah, J.J.P. Veerman, "Effect of Network Structure on the Stability Margin of Large Vehicle Formation with Distributed Control", IEEE CDC 2010; P. Seiler, A. Pant, K. Hedrick, "Disturbance Propagation in Vehicle Strings", *IEEE Trans. Automatic Control*, 2004; B. Bamieh, M.R. Jovanović, P. Mitra, S. Patterson, "Coherence in Large-Scale Networks: Dimension-Dependent Limitations of Local Feedback", *IEEE Trans. Automatic Control*, 2012). The long standing problem considered in [121] is an excellent example of the **interaction between the control and communication graphs** (networks) in our new framework.

Most of the literature in distributed control is devoted to:

(i) Given a distributed plant and an information exchange pattern amongst the control stations, when is the optimal controller linear or the synthesis convex?

(ii) Sufficiency conditions like *nested information structures* and *quadratic invariance* that give an affirmative answer are known.

In our work instead we focused on the following design question:

Given a plant with a set of (decentralized) control stations, design a "minimal" information exchange pattern that provides desirable control performance.

The main obstacles towards answering this question are:

(a) Optimizing over information patterns is combinatorially hard, which leads to the significance of understand features of the 'right' information pattern.

(b) Given an information pattern, the optimal controller is not necessarily linear/convex, which leads to making context dependent simplifying assumptions.

The simple problem studied in [121] captures all these "hard" characteristics of the fundamental question of understanding the interrelations between the collaboration and communication graphs. The vehicle platooning problem considers an Intelligent vehicle Highway System (IVHS) where a number of vehicles heading to a common destination form a platoon or a road train, as shown in Figure 2. The advantages are: improved highway throughput, and reduced fuel consumption. The latter has been demonstrated recently in real experiments with platooning trucks in commercial routes between Sweden and Denmark. At high speeds, with close spacing and multiple vehicles, distributed automatic control is needed.

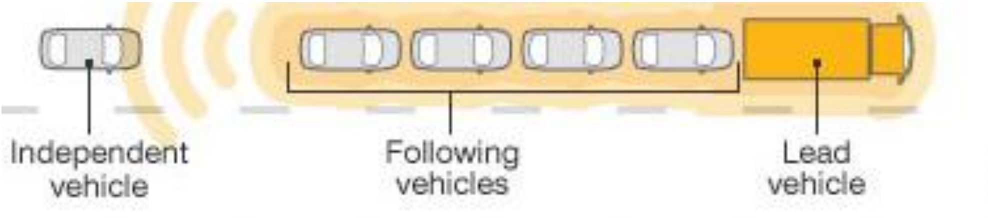


Figure 2: Vehicle platooning

In the simplest, and most common formulation of the problem, the vehicles have identical linear dynamics ($\ddot{x}_i = u_i$) and only the lead vehicle is given the desired trajectory information $x_d(t)$. The control objective of the problem is to maintain through regulation prescribed reference inter-vehicle spacing. Symmetric control is applied between the vehicles based on only local information. That is *i* applies a linear feedback control:

$$u_i = \frac{1}{deg(i)} \sum_{j \in \mathcal{N}(i)} [-k(x_i - x_j - \Delta_{i,j}) - b(\dot{x}_i - \dot{x}_j)]$$
$$+ \delta(1,i)[-k(x_1 - x_{1,d}) - b(\dot{x}_1 - \dot{x}_{1,d})]$$

Prior results are all negative (see the references given at the beginning of this subsection above). Namely if the information is restricted to the *nearest neighbor type*, then:

- The least damped eigenvalue of the closed loop matrix scales as **$O(1/N^2)$**.
- **String instability** is inevitable- disturbances acting on an individual grow without bounds in the size of the platoon.
- It is **not possible to achieve coherence** or resemblance to a rigid lattice as the formation moves.

That is the bottom line is: **nearest neighbor type information patterns** (so common in multi-agent networked systems control) **lead to inadequate control performance!**

Following a novel approach in [121] based on the fundamental formulation depicted in Figure 1, we developed a state space formulation of the distributed control of a 1-D vehicle platoon. The objective was to understand the effects of the underlying information exchange pattern between the vehicles on the control performance of the platoon. The symmetric control case is considered where each vehicle gives equal weight to all the information available to it in determining its control law. We showed that ***expander families of graphs*** when used as information patterns result in stability margins decaying to zero at rate at most $O(1/N)$; an improvement over the previously known $O(1/N^2)$ decay with nearest neighbor type information patterns! Our careful analysis [121] of the nontrivial gap in performance suggests that the lower bound is not tight and that our conclusion of an at most $O(1/N)$ decay rate for the stability mar gin may be pessimistic i.e. the decay rate may be slower. In Figure 3 (from [121]) we compare the stability margin with expander as the information pattern against the nearest neighbor type information pattern along the same axis. Notice that the decay rate in the case of the former is slower than the latter, providing validation to our argument of using an expander as the information pattern. The main goal of [121] was to bring forth the possibility of more general, albeit simple, information patterns in the vehicle platoon problem and present an analysis where different kind of patterns can be compared.

We have also tried to address the issue of reducing the load on the communication network while improving control performance. It is clear that optimizing a cost of communication over the set of all possible information patterns is NP hard; instead we argue that expander families, due to their sparsity, lower the demand on the communication network while their spectral properties help improve control performance. How can the relative distance and velocity information between far away vehicles in the platoon be communicated? Current vehicle-to-vehicle wireless communication technologies make the implementation of longer inter-vehicle communication implementation straightforward. A promising implementation approach is to use substantial quantization to send the necessary information, thus implementing quantized controls.

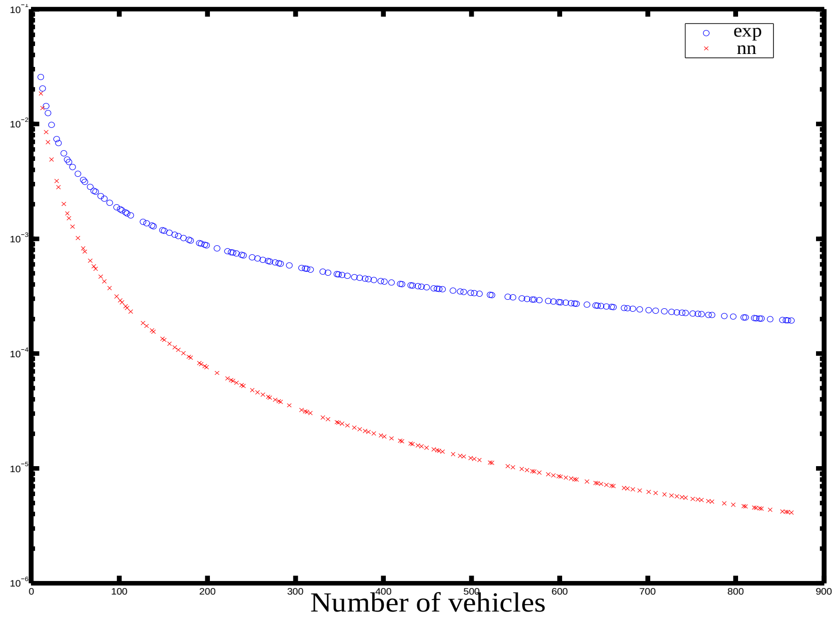


Figure 3: Experimental verification that expanders outperform nearest neighbor type information patterns. Plot of stability margins with expanders serving as information patterns is above that with nearest neighbor type

Several open questions remain. For example the asymmetric control case has to be analyzed for more general information patterns. Also the relation between information pattern and other important metrics of control performance such as string stability, coherence has to be investigated. Another important question is the choice of the right expander family for the platoon control problem. More generally how to synthesize the right expander family? Formulating a way incorporating communication network constraints in the problem of choosing expanders. Investigating more general scenarios for answering the question "**the right information pattern for a given collaborative control task**." We will address some of these questions in future work.

1.18. Resilient Control of Multiagent Networks

A multi-agent network, or networked multi-agent system, consists of a set of individuals called agents, or nodes, equipped with some means of sensing or communicating along with computational resources and possibly actuation. The agents share information in order to achieve specific group objectives. Some examples of group objectives include consensus, synchronization, formation control, and cooperative load transport. In order for the group objectives to be achieved, distributed algorithms are used to coordinate the behavior of the agents.

Perhaps the most fundamental challenge in the design of networked multi-agent systems is the restriction that the coordination algorithms use only local information. In this manner, the algorithms and feedback control laws can be distributed.

A second challenge lies in the fact that the network itself is dynamic. Since the distributed algorithms depend directly on the network, this additional source of dynamics can affect the stability and performance of the networked system.

A third challenge is caused by uncertainties introduced in the network and in the implementation of the control algorithms. As described above, the network is a dynamical system. Depending on the different time constants involved, delays in sensing or communication may lead to instability. Moreover, information may be lost in the network, and the implementation of the control algorithms may be subject to quantization. How these concerns affect stability and performance is a difficult problem.

Finally, multi-agent networks, like all large-scale distributed systems, have many entry points for malicious attacks or intrusions. If one or more of the agents are compromised in a security breach, what assurances are possible concerning the status of the global objective? For the success of the global objective, it is important that the cooperative control algorithms are designed in such a way that they can withstand the compromise of a subset of the nodes and still guarantee some notion of correct behavior at a minimum level of performance. We refer to such a multi-agent network as being resilient to adversaries. Given the growing threat of malicious attacks in large-scale cyber-physical systems, this is an important and challenging problem.

Synchronization, for instance clock synchronization, is important for coordinated behavior of multiple CPSs. Several synchronization applications can be cast into consensus problems. The formulation of resilient synchronization problems and the design of controllers that ensure correct operation in the presence of adversaries are important for security.

<u>Adversary models:</u> the adversary models studied in our work have two aspects: a threat model and scope of threat model. The threat model defines the behavioral semantics of the individual compromised nodes. The scope of threat model defines the topological semantics of the adversary model. That is, the scope of threat model may stipulate the total number of adversaries (nodes), or the number of interactions among other nodes (directed edges) that are allowed under the model. The scope, in terms of either nodes or directed edges, may be limited by global or local bounds, and the scope may also be fractional in nature.

Resilient Consensus in the Presence of Adversaries: Continuing our previous work, in [88] we study the problem of reaching consensus asymptotically in the presence of adversary nodes whenever the network is asynchronous under a local broadcast model of communication. The type of adversary considered is omniscient and may collude with other adversaries to achieve the goal of disrupting consensus among the normal nodes. The main limitation on the behavior of the adversary nodes is that whenever the adversary nodes communicate with neighbors, they must broadcast their messages so that all neighbors receive the same information. The asynchronous consensus algorithm studied here uses local strategies to ensure resilience against the adversary nodes. The class of topologies studied are those that are robust. Network robustness formalizes a notion of redundancy of direct information exchange between subsets of nodes in the network, and is an important property for analyzing the behavior of resilient distributed algorithms that use only local information.

In [91], we address the problem of resilient in-network consensus in the presence of misbehaving nodes. Secure and fault-tolerant consensus algorithms typically assume knowledge of nonlocal information; however, this assumption is not suitable for large-scale dynamic networks. To remedy this, we focus on local strategies that provide resilience to faults and compromised nodes. We design a consensus protocol based on local information that is resilient to worst-case security breaches, assuming the compromised nodes have full knowledge of the network and the intentions of the other nodes. We provide necessary and sufficient conditions for the normal nodes to reach asymptotic consensus despite the influence of the misbehaving nodes under different threat assumptions. We show that traditional metrics such as connectivity are not adequate to characterize the behavior of such algorithms, and develop a novel graph-theoretic property referred to as network robustness.

In [92], we study the continuous-time consensus problem in the presence of adversaries. The networked multi-agent system is modeled as a switched system, where the normal agents have integrator dynamics and the switching signal determines the topology of the network. We consider several models of omniscient adversaries under the assumption that at most a fraction of any normal agent's neighbors may be adversaries. Under this fractional assumption on the interaction between normal and adversary agents, we show that a novel graph theoretic metric, called fractional robustness, is useful for analyzing the network topologies under which the normal agents achieve consensus.

Resilient Synchronization in the Presence of Adversaries: Synchronization, like consensus, is a group objective where the agents seek to agree on their state values. Synchronization differs from consensus in the fact that the state values dynamically change in the absence of influence from neighboring agents in the network. Whereas consensus is an agreement process on values, synchronization is an agreement process on the underlying dynamics.

A major challenge in the synchronization objective in multi-agent networks is the design of local coupling rules (controllers) that facilitate synchronization of the agents' dynamics. Another major challenge is achieving synchronization resiliently in the presence of compromised nodes, or adversaries.

In [89], we study local interaction rules that enable a network of dynamic agents to synchronize to a common zero-input state trajectory despite the malicious influence of a subset of adversary agents. The agents in the networked system influence one another by sharing state or output information according to a directed, time-varying graph. The normal agents have identical dynamics modeled by linear time-invariant systems that are weakly stable, stabilizable, and detectable. The adversary agents are assumed to be omniscient and can take any uniformly continuous state or output trajectory. We design dynamic state and output control laws under the assumption that there is either an upper bound on the number of neighbors that may be adversaries, or an upper bound on the total number of adversary agents in the network. The control laws use only local information (i.e., information from neighbors in the network) and are resilient in the sense that they are able to mitigate the malicious influence of the adversary nodes and facilitate asymptotic synchronization of the normal agents. The conditions on the network topology required for the success of the synchronization control laws are specified in terms of network robustness.

Network robustness formalizes the notion of redundancy of direct information exchange between subsets of nodes in the network, and is a fundamental property for analyzing the behavior of certain distributed algorithms that use only local information. Network robustness is a novel graph theoretic property that provides a measure of redundancy of directed edges between all pairs of nonempty, disjoint subsets of nodes in a graph.
The robustness of a graph has been shown recently to be useful for characterizing the class of network topologies in which resilient distributed algorithms that use purely local strategies are able to succeed in the presence of adversary nodes. Therefore, network robustness is a critical property of resilient networked systems. While methods have been given to construct robust networks, algorithms for determining the robustness of a given network have not been explored. In [90], we study algorithms for determining the robustness of a network. In this paper we introduce several algorithms for determining the robustness of a network, and propose centralized, decentralized, and distributed algorithms.

1.19. Generalized Consensus Problems and Networked CPS

Analytically, swarm optimization methods and generalized consensus problems provide foundational methods for many coordination problems in multi-agent systems (and swarms). In a certain precise sense generalizations of the consensus problem provide a very useful and generic abstraction for many distributed control and inference problems in networked CPS. During the reporting period we made significant advances in this area and in different directions. First, we analyzed a significantly generalized version of the consensus problem of a group of dynamic agents, whose communication network is modeled by a directed time-varying graph, and the agents move in a convex metric space [116]. A convex metric space is a metric space on which we define a convex structure. Using this convex structure we define convex sets and in particular the convex hull of a (finite) set. Under minimal connectivity assumptions, we show that if at each iteration an agent updates its state by choosing a point from a particular subset of the convex hull generated by the agent’s current state and the states of his/her neighbors, then the asymptotic agreement is achieved. In addition, we derived bounds on the distance between the consensus point(s) and the initial values of the agents. As an application example, we used this framework to introduce an iterative algorithm for reaching consensus of opinion. In this example, the agents take values in the space of discrete random variable on which we define an appropriate metric and convex structure. For this particular convex metric space we provided a more detail analysis of the convex hull generated by a finite set points. In addition we performed many numerical simulations of the consensus of opinion algorithm, which validated the analytical performance predictions. During the reporting period we completed the analysis and applications of this generalization of distributed consensus problems [116].

During the reporting period we also completed our investigation of the convergence of linear consensus distributed algorithms under Markovian random graphs [115]. In [115] we developed a complete analysis of the linear asymptotic consensus problem for a network of dynamic agents whose communication network is modeled by a randomly switching graph. The switching is determined by a finite state Markov process, each topology corresponding to a state of the process. This generalization provides a good abstraction for understanding the interactions of the control graph (here determined by the consensus logic and algorithm) and the communication graph (here determined by this random graph model). We addressed the cases where the dynamics of the agents is expressed both in continuous time and in discrete time. We showed [115] that, if the consensus matrices are doubly stochastic, average consensus is achieved in the mean square sense and the almost sure sense if and only if the graph resulting from the union of graphs corresponding to the states of the Markov process is strongly connected. The aim of this work [115] was to show how techniques from the theory of Markovian jump linear systems, in conjunction with results inspired by matrix and graph theory, can be used to prove convergence results for stochastic consensus problems. Our results are the most general known for this type of stochastic consensus problems.

In a further generalization of the consensus paradigm of problems, and in a sense extending in a combined manner the previous two results and research we investigated [124][117] a generalized gossip algorithm on convex metric spaces. In this work [124][117] we introduced and analyzed a randomized gossip algorithm for solving the generalized consensus problem on convex metric spaces, where the communication between agents is based on a set of Poisson counters. We studied the convergence properties of the algorithm using stochastic differential equations theory. In particular we showed that the distances between the states of the agents converge to zero with probability one and in the *rth* mean sense. In the special case of complete connectivity and uniform Poisson counters, we derived upper bounds on the dynamics of the first and second moments of the distances between the states of the agents. In addition, we introduced instances of the generalized consensus algorithm for several examples of convex metric spaces together with numerical simulations. This two-way generalization of the consensus problem can model many phenomena involving information exchange between agents such as cooperative control of vehicles, formation control, flocking, synchronization, parallel computing, etc., when stochastic phenomena and or communications are present. Distributed computation over networks has a long history in control theory.

Network topologies change with time (as new nodes join and old nodes leave the network) or exhibit random behavior due to link failures, packet drops, node failure, etc. This motivated the investigation of consensus algorithms under a stochastic framework. In addition to network variability, nodes in sensor networks operate under limited computational, communication, and energy resources. These constraints have motivated the design of gossip algorithms, in which a node communicates with a randomly chosen neighbor. In [124][117] we introduced and analyzed a generalized randomized gossip algorithm for achieving consensus. We presented instances of the generalized gossip algorithm for three convex metric spaces defined on the set of real numbers, the set of compact intervals and the set of discrete random variables. These results complement our previous results regarding the consensus problem on convex metric space, where only deterministic communication topologies are studied [116].

During this reporting period these generalization were applied to several distributed inference problems involving networked CPS. In [112] we analyzed the consensus-based distributed linear filtering problem, where a discrete time, linear stochastic process is observed by a network of sensors. We assumed that the consensus weights are known and we first provided sufficient conditions under which the stochastic process is detectable, i.e. for a specific choice of consensus weights there exists a set of filtering gains such that the dynamics of the estimation errors (without noise) is asymptotically stable. Next, we developed a distributed, sub-optimal filtering scheme based on minimizing an upper bound on a quadratic filtering cost. In the stationary case, we provided sufficient conditions under which this scheme converges; conditions expressed in terms of the convergence properties of a set of coupled Riccati equations. In related work [113] we introduced a consensus-based distributed filter, executed by a sensor network, inspired by the Markovian jump linear system filtering theory. We showed that the optimal filtering gains of the Markovian jump linear system can be used as an approximate solution of the optimal distributed filtering problem. This parallel allows us to interpret each filtering gain corresponding to a mode of operation of the Markovian jump linear system as a filtering gain corresponding to a sensor in the network. The resulting approximate solution can be implemented distributively and guarantees a quantifiable level of performance [113].

In a series of papers we investigated during this reporting period, important generalization of the distributed consensus problem under increasingly realistic assumptions of nonlinearity, vanishing communications and delays. These realistic assumptions are of common occurrence in networked CPS. Thus in [119] we revisited the classical multi-agent distributed consensus problem under the dropping of the assumption that the existence of a connection between agents implies weights uniformly bounded away from zero. We formulated and studied the problem by establishing global convergence results in discrete time, under fixed, switching and random topologies. We studied the application of the results to flocking networks. In [119] the weight functions are allowed to vanish at a certain rate. A key technical tool we used in the proofs is the *coefficient of ergodicity*, which is a measure of the contraction rate of nonnegative matrices. Application of our results include networked CPS with random failures, flocking networks (natural, artificial, hybrid). We also investigated our models, approach and results in relation to the nonlinear consensus problem studied by Smale in flocking and language learning.

In [133] we studied linear time invariant (LTI) continuous time consensus dynamics in the presence of bounded communication delays. Contrary to traditional Lyapunov based methods, we approached the problem using Fixed Point Theory. This method, allows us to create an appropriate complete functional metric space and through contraction mappings to establish the existence and uniqueness of a solution of this model. We explored the case of constant as well as distributed delays. The crucial factor when one models the dynamics of multiple agents, is the amount of symmetry the designer is willing to sustain. The more symmetrical the proposed model is, the easier the mathematical manipulation is and the stronger (or more elegant) the results are. The price for this is the distance from Reality. The more symmetrical a system is, the more ideal hence the less realistic is. An excellent example of this general principle is the Consensus Dynamics, especially in the LTI case. Although the step from symmetric to asymmetric weights affects only the consensus point; the step from synchronous to asynchronous communication can be really hard to analyze using a Lyapunov method. The Fixed Point Theory comes to fulfill this gap since it does not require a, usually too insightful, construction of a Lyapunov candidate, at the expense of harder analysis and perhaps a bit stronger assumptions. The main advantage of this approach is that it cannot lead to a dead-end. Here the researcher is free to choose his own space of functions and search for an existence of a solution of the model he proposes. In this work, we considered simple consensus models. We exploited the heritage of the solutions of the synchronous version (i.e. convergence to a common value with exponential rate) and we asked whether similar behavior can be found in the delayed case and at what cost. What is, in our opinion, very interesting, is that through the procedure of constructing a contraction mapping, we were able to understand the interplay between symmetry and sufficient conditions.

In [134] we investigated the time varying counterpart of the study in [133]. In this work, we revisited the linear time varying (LTV) consensus model in the presence of bounded communication delays. We proved exponential convergence of the autonomous agents to a common value under conditions related to the topology of the communication graph, the nature of the time-varying weights, the maximum allowed delay and the rate of convergence of the non-delayed system. Contrary to a (common) Lyapunov based approach, the main novelty of our work is the use of Fixed Point Theory. Our goal was to bypass the main problem of Lyapunov theory, which is to come up with a good candidate function. The main advantage of contraction mappings is that one needs not to worry about it. Indeed the more asymmetric such a multi-agent system is the more difficult is the construction of a Lyapunov candidate function is even more difficult (if not impossible) in the case of multi-agent dynamics. It should be noted that the more asymmetrical assumptions one makes for the delays, the stronger (and more restricting) the assumptions get. We also investigated in [134] extensions to multiple delays and weaker connectivity assumptions.

Motivated by non-linear flocking models and recent results in opinion dynamics, in [135] we analyzed the asymptotic behavior of a non-smooth, non-linear flocking model with bounded interactions range. In this work, we investigated a second order problem, with a different approach (differential inclusions) and our aim was to answer a different set of questions. Based on state dependent communication graphs we analyzed a family of nonlinear flocking models by establishing sufficient initial conditions so as connectivity, and thus asymptotic flocking, is ensured. We investigated models with non-linear uniformly bounded connection rates with and without delays. Our major contribution is that we eliminate the assumption of connectivity and we establish initial condition requirements for it, so that asymptotic flocking can occur. Our results extend to the case where there is delay in the communications between agents. That is unlike the vast majority of works in the literature, here we did not assume a priori connectivity of any kind. The goal was to derive an estimation of the set of initial data such that the agents would coordinate their velocities so as to form a unified flocking body. The analysis includes models without and with delay. We believe that there are broad classes of initial graph topologies which favor efficient computations. In the future we plan to investigate the same model in the presence of uncertainties, e.g. potential functions which typically model collision avoidance standards. Another, and most challenging future direction, is the case of non-uniform weights. It should be noted that there is yet to be found a Lyapunov functional to study the convergence of non-linear flocking models (in the sense of Cucker-Smale) with delays. The Lyapunov-Krasovskii functional often used is not applicable when the connectivity weights are not bounded from below.

In [136] we considered a generic non-linear consensus model and proved convergence results to a common value together with prescribed rate of convergence. Instead of a Lyapunov approach we employed again a functional metric space and made a fixed point theory argument using contraction mappings. This work was restricted to the case of static networks. Fixed Point Theory does not require one to look for a global energy function that takes care of the asymmetry of the dynamical system. The price one pays is much more work in the analysis and clearly more conservative assumptions. These assumptions however reflect exactly this lack of both symmetry and linearity in our model. The more asymmetric is the system the harder the analysis becomes. It should also be noted that these results are far from global. On the other hand, the advantage of this approach is that it reveals a great deal of the system's aspects and hence gives the designer the ability to implement elaborate control techniques. For example one can ask for rate bounds given the necessary delay and vice versa. Another example could be, given an initial condition, how should the rate function of the non-linear part, behave so that consensus is achieved with pre-assigned rate and delay. We further discussed extensions to problems with asymmetric limiting weights, multiple delays, fully non-linear functions (beyond passive nonlinearities), switching networks.

Finally in [143] we considered a multi-agent non-linear delayed model which sustains consensus type solutions. We use fixed point arguments to establish sufficient conditions for existence and uniqueness of solutions that converge exponentially fast to a common value with prescribed rate. The conditions depend on the communication topology, the non-linearity of the model as well as the delay in the propagation of information. Furthermore we test the robustness of our results in the presence of independent time varying perturbations both deterministic and stochastic. A very interesting extension would be the study of this model in the presence of state dependent stochastic perturbations (which readily arise in the case of communication noise, for example). This issue is left for future work.

1.20. Distributed Optimization in Networked CPS

Networked CPS almost certainly include a distributed, non-collocated version of the sense-decide-actuate paradigm from feedback control. The interplay between the cyber and physical aspects of CPS on one hand puts constrains on these functions but on the other hand can be exploited to advantage. At the heart of these problems are distributed optimization algorithms utilizing local information and their properties. During this reporting period we continued our in-depth investigation of such distributed optimization algorithms for networked CPS.

In [122] we investigated the problem of multi-agent optimization for convex functions expressible as sums of convex functions. Each agent has access to only one function in the sum and can use only local information to update its current estimate of the optimal solution. We considered two consensus-based iterative algorithms, based on a combination between a consensus step and a subgradient decent update. Intutively the subgradient decent update can be thought of as each agent taking the best next action based on her/his available information, while the consensus step can be thought of as the collaborative effort between the agents. The main difference between the two algorithms is the order in which the consensus-step and the subgradient descent update are performed. We obtained [122] upper bounds on performance metrics of the two algorithms. We showed that updating first the current estimate in the direction of a subgradient and then executing the consensus step ensures a tighter upper bound compared with the case where the steps are executed in the reversed order. WE investigated differences in convergence rates and the role of the communication topologies. In support of our analytical results, we gave some numerical simulations of the algorithms as well.

In [141] we investigated distributed optimization problems with equality constraints enforced by networks. We introduced two discrete-time, distributed optimization algorithms executed by a set of agents whose interactions are subject to a communication graph. The algorithms can be applied to optimization problems where the cost function is expressed as a sum of functions, and where each function is associated to an agent. In addition, the agents can have equality constraints as well. The algorithms are not consensus-based and can be applied to non-convex optimization problems with equality constraints. We demonstrate that the first distributed algorithm results naturally from applying a first order method to solve the first order necessary conditions for a lifted optimization problem with equality constraints; the solution of our original problem is embedded in the solution of this lifted optimization problem. Using an augmented Lagrangian idea, we derive a second distributed algorithm that requires weaker conditions for local convergence compared to the first algorithm. For both algorithms we address the local convergence properties. Distributed algorithms for solving constrained optimization problems have already been studied in the literature. The focus has been on convex problems: the cost and constraint sets are assumed convex. The algorithms are based on a combination of a consensus step (to cope with the lack of complete information) and a projected (sub)gradient descent step. They assume that either all agents use the same constraint set or each agent has its own set of constraints. In our work we did not make any convexity assumptions on the cost and constraint functions, but we assumed they are continuously differentiable. We proposed [141] two distributed, discrete-time algorithms that, under suitable assumptions on the cost and constraint functions, guarantee convergence to a local minimizer (at a linear rate), provided that the initial values of the agents are close enough to a (local) minimizer and a sufficiently small step-size is used. The most interesting aspect of these algorithms is that ***they are not heuristic algorithms***, but they follow naturally from using a first order numerical method to solve the first order necessary conditions of a ***lifted optimization problem*** with equality constraints; the solution of our original problem is embedded in the solution of this lifted optimization problem.

In a non-traditional problem area we investigated connections between optimization and security-privacy for networked systems. In [144] we investigated, in a novel manner, privacy preserving solution methods based on optimization. Ensuring privacy is an essential requirement in various contexts very relevant to CPS, such as social networks, healthcare data, ecommerce, banks, and government services. Here, different entities coordinate to address specific problems where the sensitive problem data are distributed among the involved entities and no entity wants to publish its data during the solution procedure. Existing privacy preserving solution methods are mostly based on cryptographic procedures and thus have the drawback of substantial computational complexity. Surprisingly, little attention has been devoted thus far to exploit mathematical optimization techniques and their inherent properties for preserving privacy. Yet, optimization based approaches to privacy require much less computational effort compared to cryptographic variants, which is certainly desirable in practice. In our recent work [144], a unified framework for transformation based optimization methods that ensure privacy was developed. A general definition for the privacy in the context of transformation methods was proposed. A number of examples were provided to illustrate the ideas. It is concluded that the theory is still in its infancy and that huge benefits can be achieved by a substantial development.

We use the term "efficient" to mean the effective implementation of transformation and cryptographic methods in general. For many non-trivial problems, cryptographic treatments require very large circuit representations, resulting in explosions in associated computation due to integers involving thousands of bits. These properties are directly reflected in the case of protocol complexity as well. Moreover, in the case of linear programming (LP), cryptographic protocols are often collaboratively executed in each iteration step of the simplex algorithm. Thus, they are inherently restricted to LPs. More recently, the first cryptographic method for handling interior-point method has been proposed. Still the high computational complexity for cryptographically secured iterations in both the simplex and interior-point methods is unavoidable. Transformation methods can use the state-of-the-art interior-point solvers, which can be implemented by using floating-point arithmetic. The underlying machinery for interior-point methods for optimization based approaches are built on linear algebra, which is very efficiently implemented compared to cryptographic treatments. Moreover, an interior-point method can solve important classes of convex optimization problems with a number of operations that grows no faster than a polynomial of the problem dimensions and $\log(1/\varepsilon)$, where $\varepsilon > 0$ is the accuracy required. Roughly speaking, within 10 and 100 iterations (Newton steps) of the interior-point method, a solution of practical use can be obtained. Therefore, transformation based algorithms are very effective compared to cryptographic methods.

1.21. Distributed Control Algorithm in Networked CPS with Indirect and Direct Communications

In networked CPS, the three layers of Figure 1 are not always clearly delineated. This is true at any scale, although it is easier to understand this fact for the smaller scales. Indeed at very small scales what is cyber and what is physical, what is control and what is communication is not so clear; the components executing these functions can often execute both. But a little reflection one could easily see that this is true at all scales. The agents in a networked CPS can communicate directly, via the communication graph, indirectly via the sensors they have available or indirectly through the interactions of the system to their individual actions. This is a central and distinguishing property of CPS and represents a fundamentally new concept with far reaching implications. During this reporting period we investigated such problems and obtained a couple of important foundational results.

Several learning rules (or, interchangeably, algorithms) have been proposed in the evolutionary games literature that help agents learn Nash equilibria (NE) in games with special structure like potential, weakly-acyclic, congestion games, etc. Thus, designing utilities with such special structure facilitates direct use of these algorithms. Another desirable feature of some of these learning rules is payoff-based implementation i.e. no knowledge of the payoff structure is needed and an agent adjusts its play based on observed payoffs alone. However, there are situations where this paradigm of designing utilities with special structure is too restrictive. To illustrate this point, consider the problem of maximizing the total power production of a wind farm 9a common part of smart-grids, an important class of networked CPS). Aerodynamic interactions between different wind turbines are not well understood and there are no good models to predict the effects of one turbine's actions on the power production of other turbines downstream. The information available to each turbine is its own power output and a decentralized algorithm that maximizes the total power production of the farm is sought. Since there are no good models for the interactions, there is little hope to design utilities with special structure that are functions of such individual power measurements. This points towards the need for algorithms that are applicable when there is little structural information about the utilities (for instance, a turbine can be assigned its individual power as its utility which, in turn, can depend on the actions taken by others in complex ways). To summarize, we require a decentralized, payoff-based algorithm that:

- requires little assumptions on the structure of the utilities; and
- helps agents learn a solution concept that corresponds to desirable system-wide behavior.

A fully decentralized learning rule which addresses exactly these concerns has been recently proposed by Young t al, with the objective of making the agents learn to play efficient actions that maximize the sum of the individual utilities i.e. the welfare function. Roughly speaking, this algorithm prescribes certain probability distributions for the agents to pick actions from; the distributions depend on the measured payoffs and a certain noise parameter e. It was proved by Young et al that for a sufficiently small ε, the realized actions of the agents in the limit are drawn from a distribution close to one with support over efficient actions. These results are based on the theory of perturbed Markov chains that was developed by Young to explain equilibrium section in evolutionary games. While this learning rule and related results are encouraging, they have the following shortcomings:

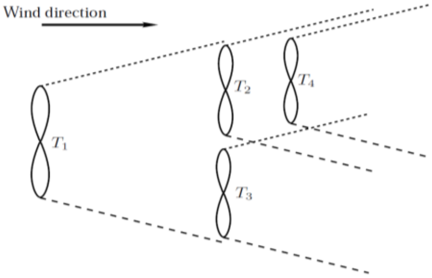
1) Viewed as an algorithm, an adequate notion in which the individual actions converge to the efficient ones is absent.
2) There are results regarding perturbed Markov chains that suggest that the expected waiting time before efficient actions are picked associated with a small ε can be too long.

In [132] we investigated a decentralized algorithm achieving Pareto optimality in a multi-agent system utilizing only the effects of agent actions on an individual utility function. Utility functions are not needed to have a functional form, they can be just measurements. In [132] we considered N agents, each picking actions from a finite set and receiving a payoff according to its individual utility function that may depend on the actions picked by others. An agent has no knowledge about the functional form of its utility and can only measure its instantaneous value. It was assumed that all agents pick actions and receive payoffs synchronously. For this setting, a fully decentralized iterative algorithm for achieving Pareto optimality i.e. picking actions that maximize the sum of all utilities was proposed by Marden, Young et al. that lacks convergence guarantees. By scheduling a certain noise parameter to go to zero along iterations of this algorithm, we derived conditions that guarantee convergence in probability. The contribution of our work is analogous to that of proving convergence of Simulated Annealing. We modified the learning rule of Young et al by allowing the parameter ε to decrease to zero along the iterations of the algorithm ("annealing") and derive conditions on the rate of decrease of ε that guarantee convergence of the resulting algorithm w.p. 1. A sufficient condition for ergodicity of perturbed Markov chains with certain time decreasing perturbations was also derived in the process. While this directly addresses the first of the two concerns raised above, it is also a step towards the second.

This work initiated a novel and fundamental investigation of the interaction between control and communication graphs and established that it is possible to develop simple distributed and asynchronous algorithms, for networked CPS, that ***learn what is best for the team***. Figure 4, Figure 5, and Figure 6 illustrate several networked CPS examples where our results can be applied.

Example: Maximizing Power Production of a Wind Farm

A Wind Farm. Courtesy:http://www.dis.anl.gov/



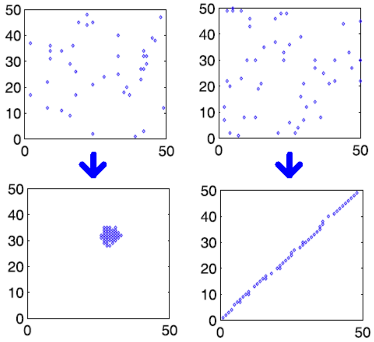
Schematic representation of a wind farm depicting individual turbine wake regions.

- Aerodynamic interaction between different turbines is not well understood.
- Need on-line decentralized optimization algorithms to maximize total power production.

Assign individual utility
$u_i(t)$ = power produced by turbine *i* at time *t*
such that maximizing $\sum_i u_i(t)$ leads to desirable behavior.

Figure 4: Networked CPS: Wind farms

Example: Formation Control of Robotic Swarms



Simulation results demonstrating rendezvous and gathering along a line

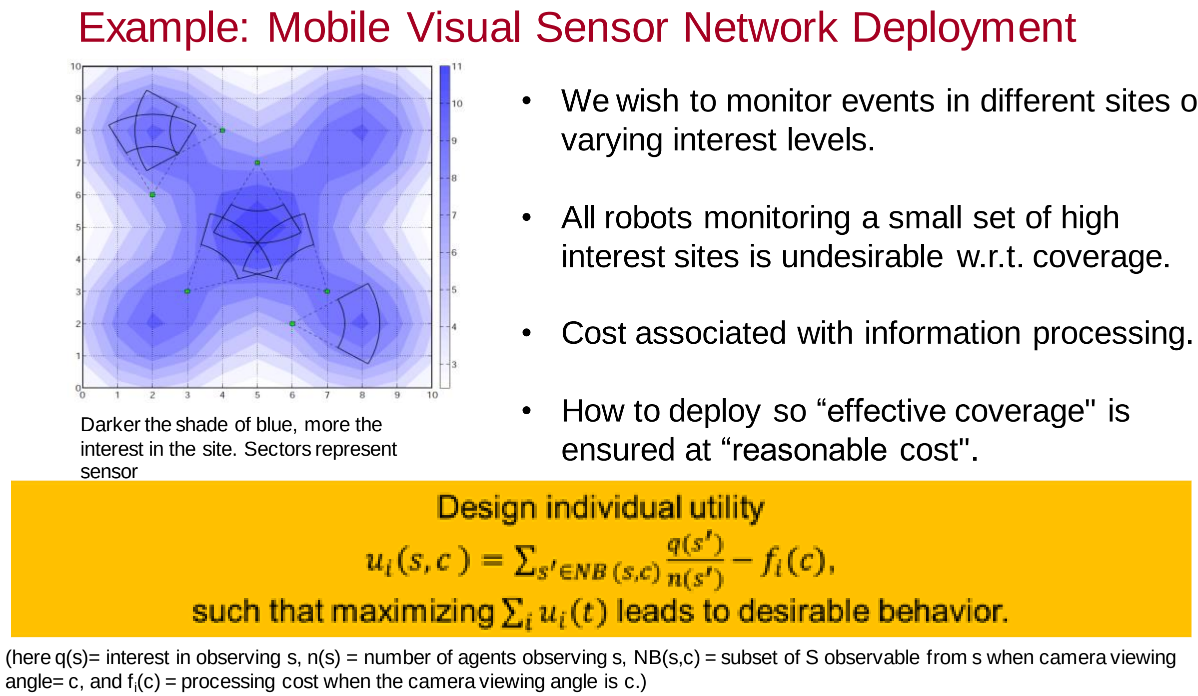
- Deploy a robotic swarm in unknown environment: obstacles, targets etc. have to be discovered.
- The swarm must form a prescribed geometric formation.
- Robots have limited sensing and communication capabilities.

For rendezvous, design individual utility

$$u_i(s_i) = \frac{1}{|\{s_j \in S: \left\| s_i - s_j \right\| < r\}|} - \alpha \, dist_r(s_i, obstacle),$$

such that minimizing $\sum_i u_i(t)$ leads to desirable behavior.

Figure 5: Networked CPS: Robotic swarms



Example: Mobile Visual Sensor Network Deployment

Darker the shade of blue, more the interest in the site. Sectors represent sensor

- We wish to monitor events in different sites of varying interest levels.
- All robots monitoring a small set of high interest sites is undesirable w.r.t. coverage.
- Cost associated with information processing.
- How to deploy so “effective coverage" is ensured at “reasonable cost".

Design individual utility

$$u_i(s,c) = \sum_{s' \in NB(s,c)} \frac{q(s')}{n(s')} - f_i(c),$$

such that maximizing $\sum_i u_i(t)$ leads to desirable behavior.

(here q(s)= interest in observing s, n(s) = number of agents observing s, NB(s,c) = subset of S observable from s when camera viewing angle= c, and $f_i(c)$ = processing cost when the camera viewing angle is c.)

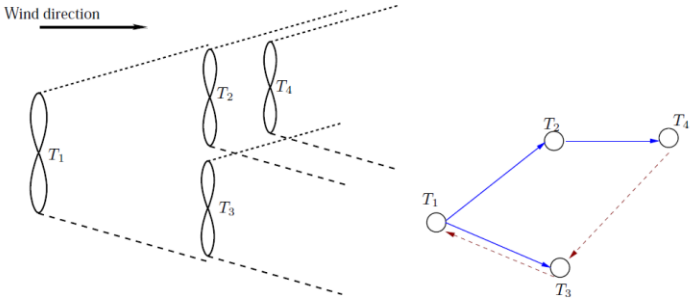
Figure 6: Networked CPS: Mobile Wireless Sensor Nets

Figure 7 illustrates the fundamental concept of indirect communications via the Interaction Graph, vs. direct communications via the Communication Graph.

Like agents, system designer does not know exact functional form of the payoffs.
→ The system designer may have “coarse information" about which agents' action can affect which others.

***Interaction graph* models such coarse information**: It’s a directed graph where a link from i to j implies actions of agent i affect the payoff of agent j.

***Communication graph* models explicit inter agent communications**: It’s a directed graph where a link from i to j implies agent i can send information to agent j.



The wind farm example is considered in the figure:

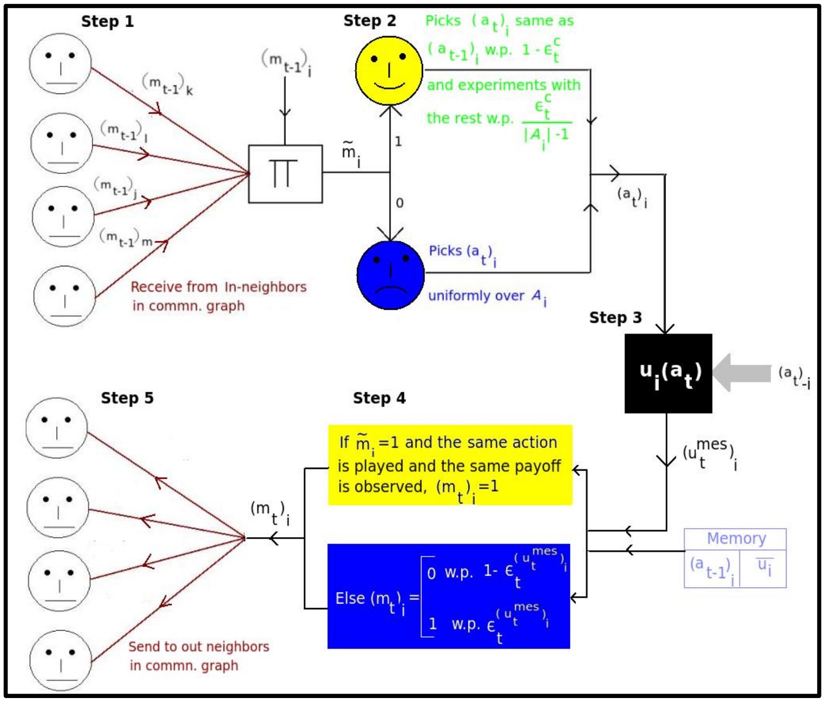
- blue lines are edges in the interaction graph and,
- the red lines in the communication graph.

Figure 7: Indirect vs. direct Communications in networked CPS

By restricting the rate of decrease in the annealing schedule, we derived the convergence guarantee we set out for in [132]. From a practical viewpoint, while an annealing scheme seems natural, the value of our result lies in giving the system designer the freedom to choose amongst annealing schedules without worrying about adverse effects on the convergence of the algorithm. Along the way, we also derived conditions for ergodicity of perturbed Markov chains with time-decreasing noise, which can be used to derive similar conditions for other algorithms based on the theory of perturbed Markov chains.

In [142]we closed this circle of studies by showing that with one bit of communication we can supplement missing indirect interactions between agents with direct communications and can develop simple distributed algorithms that can learn what is best for the team. In [142] our algorithm of [142] was modified to incorporate exchange of certain bit-valued information between the agents over a directed communication graph (see Figure 7). The notion of an interaction graph is then introduced to encode known interactions between the agents through the system physics and dynamics. Restrictions on the payoff structure are eliminated and conditions that guarantee convergence to welfare minimizing actions w.p. 1 were derived under the assumption that the union of the interaction graph and communication graph is strongly connected. The key concepts of the algorithm and its improvements are shown in Figure 8.

Based on Marden et al[5], endow each agent with a state $x_i = (a_i, m_i); m_i \in \{0,1\}$ is the mood of agent i, with 1 corresponding to a "content" agent and 0 to a "discontent" one.



Differences from the algorithm in [5] :

- No explicit inter-agent communication is used in [5].
- Some assumptions on utilities are made in [5] to prove feasibility.
- ε_t is held constant for some $\epsilon > 0$ in [5].

[5]. Marden, Young and Pao, "Achieving Pareto optimality through distributed learning", 2012.

Figure 8: The distributed asynchronous algorithm and its extension

Our key result [142] and its major advantages are shown below:

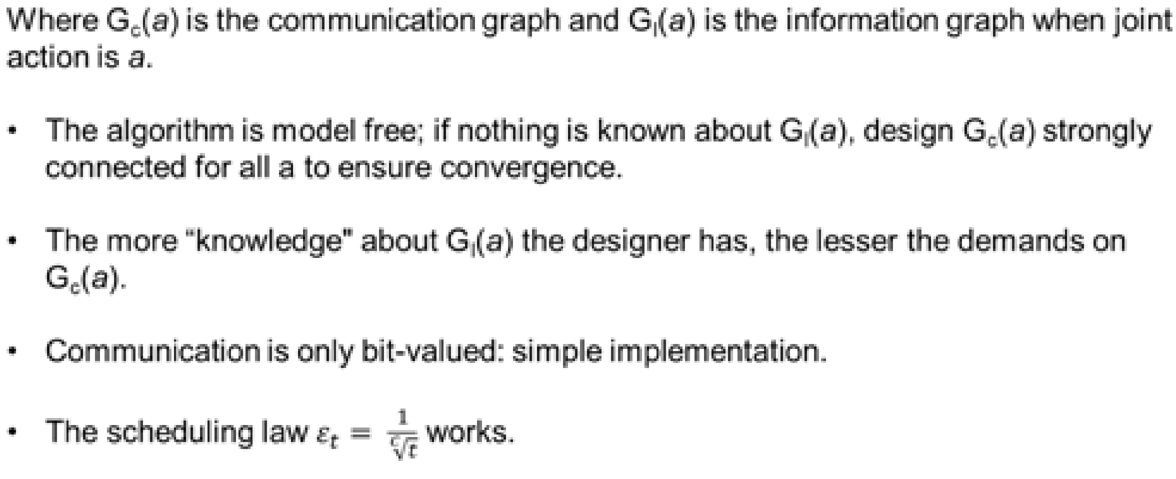
<u>Theorem</u>[6]

Assume

1. $\sum_{t=1}^{\infty} \varepsilon_t^c = \infty$ *and* ;
2. *for each* $a \in A, G_c(a) \cup G_I(a)$ *is strongly connected.*

Then,

$$\lim_{t\to\infty} P(a_t \in A^*) = 1.$$



Where $G_c(a)$ is the communication graph and $G_I(a)$ is the information graph when joint action is a.

- The algorithm is model free; if nothing is known about $G_I(a)$, design $G_c(a)$ strongly connected for all a to ensure convergence.
- The more "knowledge" about $G_I(a)$ the designer has, the lesser the demands on $G_c(a)$.
- Communication is only bit-valued: simple implementation.
- The scheduling law $\varepsilon_t = \frac{1}{\sqrt[c]{t}}$ works.

[6]. Menon, Baras, “A Distributed Learning Algorithm with Bit-valued Communications for Multi-agent Welfare Optimization”, CDC 2013.

Future directions along this fundamental for CPS line of research include:

- Nothing about the rate yet! How long does it take to converge?
- What effect does the structure of communication have on the rate of convergence?
- Similar algorithms for the continuous actions space setting?
- With some model information, gradient descent etc. can help converge faster.

1.22. Multi-criteria Design of Wireless Communication and Sensor Networks

Mobile broadband wireless networks and wireless sensor networks (WSN) are perhaps the most ubiquitous class of networked CPS. Challenging design problems arise in the design and operation of such networks due to the several performance metrics and constraints that modern environments impose. During the reporting period we investigated several such fundamental problems.

In [123] we investigated ways to minimize aggregation latency in WSN used in power grids. Wireless Sensor Networks (WSN) have been widely recognized as a promising technology that can enhance various aspects of today’s electric power systems, making them a vital component of the smart grid. Efficient aggregation of data collected by sensors is crucial for a successful WSN-based smart grid application. Existing works on the Minimum Latency Aggregation Scheduling (MLAS) problem in WSNs usually adopt the protocol interference model, which is a tremendous simplification of the physical reality faced in wireless networks. In contrast, the more realistic physical interference model has been proven to have the potential to increase network capacity. In our work [123] we proposed a distributed algorithm to minimize the data aggregation latency under the physical interference model, which jointly considers routing, power assignment and transmission scheduling. Thus this work addressed a challenging multi-metric problem. We theoretically proved that our algorithm solves the MLAS problem correctly and the latency is bounded by $3(K + 1)^2(\Delta + \log(\sqrt{2} / (K+1))) + 6K^2 + 4K + 2$, where K is a model-specific constant and Δ is the logarithm of the ratio between the lengths of the longest and shortest links in the network. Simulation results demonstrate that our algorithm can significantly reduce the aggregation latency compared to other schemes under the physical interference model. In networks where *n* nodes are uniformly distributed, our algorithm achieves an average latency between O($\log^3$ n) and O($\log^4$ n). We also discussed [123] how to improve the energy efficiency through load-balancing techniques.

In [126] we introduced HybridStore, our new data management system for hybrid flash-based sensor devices. One of the main challenges in wireless sensor networks is the storage and retrieval of sensor data. Traditional centralized data acquisition techniques suffer from large energy consumption, as all the readings are transmitted to the sink. In long-term deployments, it is preferable to store a large number of readings in situ and transmit a small subset only when requested. This framework becomes practically possible with the new generation NAND flash that is very energy efficient with high capacity. Recent studies show that the NAND flash is at least two orders of magnitude cheaper than communication and comparable in cost to computation. Therefore, extending the NAND flash to off-the-shelf low-end sensor platforms can potentially improve in-network processing and energy efficiency substantially. This trade-off is an excellent example of the fundamental interplay between the cyber and physical parts in networked CPS (here WSN), and demonstrates that careful joint design of the cyber and physical parts can substantially improve the overall performance of the networked CPS. However, due to the distinctly different read and write semantics of the NAND flash, and tightly constrained resource on sensor platforms, designing an efficient resource-aware data management system for flash-based sensor devices is a very challenging task.

Existing works do not take advantage of both the on-board random-accessible NOR flash that is quite suitable for index structures, and external economical energy-efficient NAND flash with high-capacity, which is ideal for massive data storage. In our work [126], we proposed HybridStore, a novel efficient data management system for resource-constrained sensor platforms, which exploits both the on-board NOR flash and external NAND flash to store and query sensor data streams. In order to completely avoid expensive in-place updates and out-of-place writes to an existing NAND page, the index structure is created and updated in the NOR flash. To handle the problem that the capacity of the NOR flash on low-end sensor platforms is very limited (512KB to 1MB), HybridStore divides the sensor data stream into segments, the index of which can be stored in one or multiple erase blocks in the NOR flash. Since the NAND flash is much faster and more energy-efficient for reading, the index of each segment is copied to the NAND flash after it is full. Therefore, all NAND pages used by HybridStore are fully occupied and written in a purely sequential fashion, which means it can support both raw NAND flash chips and FTL-equipped flash packages efficiently.

HybridStore can process typical joint queries involving both time windows and key value ranges as selection predicate extremely efficiently even on large-scale datasets, which sharply distinguishes HybridStore from existing works. The key technique is a novel index structure that consists of the inter-segment skip list, and the in-segment β-Tree and Bloom filter of each segment. The inter-segment skip list can locate the desired segments within the time window of a query, and skip other segments efficiently. The β-Tree of a segment is the key data structure to support value-based queries. It exploits a simple prediction-based method to split each node in the tree adaptively to generate a rather balanced tree, even when key values are very unevenly distributed. The Bloom filter of a segment facilitates value-based equality queries inside that segment, which can detect the existence of a given key value efficiently. Our index can eliminate a substantial number of unnecessary page reads when processing joint queries.

In addition, HybridStore can trivially support time-based data aging without any extra overhead, because no garbage collection mechanism is needed here, which will induce extensive page reads and writes to move valid pages within the reclaimed erase blocks to new locations. HybridStore can be used as a storage layer to provide a higher level abstraction to applications that need to handle a large amount of data. For example, the design and implementation of Squirrel can become much simpler if HybridStore is adopted for storage management.

In [138] we developed coordinated scheduling and power control for downlink cross-tier interference mitigation in heterogeneous cellular networks. As smartphones and tablet PCs are widely spread throughout the world, mobile data and video traffic demand has been increasing considerably. To accommodate the higher cellular capacity demand, heterogeneous cell deployment is considered as an efficient approach compared to macro-cellular based solutions. The cellular network structure consisting of different types of base stations (BSs) is often known as a heterogeneous cellular network, and it is implemented by deploying low-powered BSs such as pico BSs (PBSs), femto BSs, or relay BSs in a relatively unplanned manner within the macro BS (MBS) transmission coverage. These overlaid small cells are known to provide spatial diversity and cell splitting gains. In 3rd Generation Partnership Project (3GPP) standardization, heterogeneous cellular networks (HetNets) have been discussed as one of key network models for 4G Long Term Evolution Advanced (LTE-A) systems. In heterogeneous cellular networks, the deployment of low-powered picocells provides user offloading and capacity enhancement. The expansion of a picocell's coverage by adding a positive bias for cell association can maximize these effects. Under this circumstance, downlink cross-tier interference from a macro base station to pico mobile stations in the expanded picocell range deteriorates those pico mobile stations' performance significantly. In our work [138], a coordinated scheduling and power control algorithm was proposed, whereby the macro base station reduces its transmission power for those victim pico mobile stations in the expanded picocell range only on a set of resource blocks to minimize performance degradation at the macro base station. First, the transmission power level is calculated by mobile stations' channel condition and QoS requirements. Then, a set of resource blocks is determined by solving a binary integer programming to minimize the sum of transmission power reduction subject to victim pico mobile stations' QoS constraints. To reduce computational complexity, we utilize a heuristic algorithm, i.e., max-min greedy method, to solve the problem. Through system level simulations, we show that average and 5%-ile throughputs of victim pico mobile stations are significantly improved.

In [140] we investigated a related problem of minimizing energy consumption in cellular networks by enabling device-to-device (D2D) relays. The number of smartphones being adopted as well as the amount of traffic generated by them is increasing exponentially. As smartphones become more capable, they consume more energy. At the same time, battery technology could not keep pace. As a result, short battery life is determined to be the number one factor limiting the usefulness of these devices. It is very important that we study every aspect of smartphone operation and come up with energy efficient designs. Previous studies in smartphone battery consumption have identified the screen and radio communication as the biggest power consumption components. In our work, we focused on reducing power consumed by radio communication. Enabling relays in cellular networks has been shown to provide coverage extension, increase throughput by providing multipath diversity, and reduce transmission power of mobile devices. Both LTE and WiMAX introduce relay nodes as part of the standard. However, these specialized relay nodes have to be deployed, and thus incur cost to network operators. Instead, we can make use of the abundant availability of phones and letting devices in the vicinity of a cellular user to act as relays for that user's transmission. In our work, we exploited device-to-device (D2D) communications underlaying cellular networks to reduce the aggregated transmission power of smartphones in a cell. D2D are local connections that can be set up with the assistance of the base station. These low-power connections can be used as relays for normal cellular links, hence reducing the overall power consumption of all users. We formulated the relay selection decision at the base station as a Binary Mixed Integer Programming problem. Since this class of convex problems is known to be NP-hard, we proposed a heuristic suboptimal algorithm which has linear time complexity. We showed through simulations that our suboptimal algorithm achieves very close to optimal performance. We also showed that enabling D2D relays has major benefit in term of reducing transmission power by mobile users.

1.23. Composable Security for Networked CPS

Security and trust is a cross-cutting challenge for all CPS and in particular for networked CPS. During this reporting period we continued the investigation of CPS security and trust as a premier and significant (in terms of its ubiquitous relevance for everyday life and work) example of compositionality and the science of integration for CPS. We investigated several interrelated problems towards developing stronger and more resilient secure protocols for autonomic networks (infrastructure networks, manufacturing networks, power networks, smart grids, communication networks, sensor networks, intelligent collaborative robotic networks, social networks, economic networks). All these networks can be considered as networked systems or as networked embedded systems. All are excellent examples of networked CPS.

In [114] we investigated the dynamics of selfish response to epidemic propagation. Countermeasures to an infection can be centrally enforced, or the decision for their adoption can be left to individual agents such as individual home computer users or companies. However, when it is up to individual agents to invest in protection against infection, contradicting incentives appear. Although agents want to be safe against viruses, they would prefer to avoid paying the cost of security. Security may not only cost money, it may also reduce the utility of the network, for example, by isolating the agent from the rest of the network. Moreover, it may reduce the utility of the device, for example, by slowing it down. To complicate things further, user incentives may change with time, as the information available to them changes. There exist security advisories that provide information about current and newly emerging threats in popular technology products. Such information influences user decisions and incentives by changing their perception of the risks involved. On the one hand, if users receive news of an ongoing epidemic, they are much more willing to protect themselves. On the other hand, when the infection has subsided and there is no clear danger, complacency may set in with a consequent reduction in the time and resources spent to ensure safety.

An epidemic that spreads in a network calls for a decision on the part of the network users. They have to decide whether to protect themselves or not. Their decision depends on the tradeoff between the perceived infection and the protection cost. Aiming to help users reach an informed decision, security advisories provide periodic information about the infection level in the network. In [114] we studied the best-response dynamic in a network whose users repeatedly activate or de-activate security, depending on what they learn about the infection level. Our main result is the counterintuitive fact that ***the equilibrium level of infection increases as the users' learning rate increases***. The same is true when the users follow smooth best-response dynamics, or any other continuous response function that implies higher probability of protection when learning a higher level of infection. In both cases, we characterize the stability and the domains of attraction of the equilibrium points. Our finding also holds when the epidemic propagation is simulated on human contact traces, both when all users are of the same best-response behavior type and when they are of two distinct behavior types.

Cyber-attacks on the sensors and controllers of power grids are becoming an increasing threat. Power grids are premier examples of networked CPS. Combining cyber and physical means can increase the security of such distributed sensor and control system. In [118] we investigated trust-based multi-agent collaborative filtering for increased smart grid security. In [118] we addressed the problem of state estimation of the power system for the Smart Grid. 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 injections originating from faulty equipment or cyber-attacks. Our approach 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 combined 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 was also introduced, which ensures that agents that diverge considerably from their expected behavior have their trust values lowered.

In large distributed networked CPS, we believe it is impossible to achieve an acceptable level of security without allocating some security functionality to the physical part of the system (i.e. hardware, signal processing, physical characteristics of the system). These physical layer security scheme can strengthen considerably the security and trust of networked CPS and are an indispensable component of CPS security schemes. In [120] we provided an excellent such example were we discovered and developed an effective scheme using a physical layer security scheme to enhance the location privacy of the ubiquitous LTE paging system. User location privacy is a growing concern in cellular networks. It has been recently (2012) shown that the paging architecture in GSM networks leaks user location information. In our work [120], we first proved theoretically that LTE networks also have the same vulnerability. We then proposed a solution making use of a novel signal processing technique, physical layer identification. The idea is to embed users' unique tags onto the downlink paging signal waveforms so that the tags are stealthy and robust. We showed that our scheme not only improves users' privacy, but also saves system bandwidth. We have applied for a patent for this important discovery.

Expanding on the use of physical layer techniques, in [137] we developed distributed trust-based routing algorithms for mobile adhoc networks (MANET). One critical threat to the performance of such networks (MANET) is the adversarial behavior of nodes. Being highly dependent on cooperation of other nodes in the network, even restricted adversarial behavior can cause significant degradation. The lack of centralized authorities, coupled with an open medium further presents adversaries with a large attack surface. There has been tremendous research effort on analysis of adversarial models and mechanisms to secure these network. Establishing trust and security in ad-hoc networks has been a long studied problem. Several methods have been proposed for evaluation and dissemination of trust in such networks, with the goal of providing secure data paths. In [137] we proposed a mechanism to utilize trust metrics derived from various methods for secure routing. Our scheme can be used with existing on-demand routing protocols with minimal modification. We highlighted scenarios that establish the need for associating trust with a link, rather than just a node. Our scheme [137] incorporates both link and node trust to avoid adversarial paths in a distributed manner. We validated via simulation, the security properties of our scheme in an ad-hoc networks.

In our work [137], we presented a distributed scheme for secure routing of data in an ad-hoc networks. The aim of our scheme is to neutralize the advantage gained by the adversary through actions such as creation of wormholes, or rushing attacks. We used the notion of point-to-point trust, as developed by a variety of methods, and extended it to the network layer without cooperation between nodes. Our scheme combines metrics obtained from multiple layers (physical, application) to secure the network layer. The security guarantees provided by our scheme are probabilistic in nature, rather than provable, as provided by cryptographic methods. To the best of our knowledge, the attacks studied in our work do not have provably secure distributed solutions. Our scheme can be used as a component in tandem with other higher layer methods to build provide comprehensive security.

Security, resilience and safety are closely interrelated concepts, especially for networked CPS. An excellent example is presented by smart manufacturing, where teams of autonomous robots and humans cooperate for maximum flexibility. Safety is of paramount importance in such systems. Another example is provided by the increasing use of unmanned air vehicles (UAVs) over commercial air space for various non-military monitoring applications. Set valued dynamics is an important method for analyzing and evaluating safety in such dynamic networked CPS. Reachability analysis provides one of the fundamental methods. In [125] we investigated reachability for linear discrete time set-dynamics driven by random convex compact sets. This work addresses the important problem of safety tolerance robustness under random perturbations and environments. In our work [125] we studied linear set-dynamics driven by random convex compact sets (RCCSs), and derived the set-dynamics of the expectations of the associated reach sets as well as the dynamics of the corresponding covariance functions. We established that the expectations of the reach sets evolve according to deterministic linear set-dynamics while the associated dynamics of covariance functions evolves on the Banach space of continuous functions on the dual unit ball. The general framework was specialized to the case of Gaussian RCCSs, and it was shown that the Gaussian structure of random sets was preserved under linear set-dynamics of random sets.

These new results obtained during this reporting period, together with our results on this topic during the previous reporting periods, demonstrate the fundamental principle that we are trying to establish for many CPS and their performance. Namely, that the synergistic use of the physical part of the components with their cyber part, can lead to *significantly better* performance. Network security is a challenging area to establish the validity of this principle. Furthermore, incorporating hardened nodes (via hardware enhancements) in a network provides the means to establish composable security for networked CPS.

2. Tools and tool architectures

2.1. Co-simulation framework for time-triggered CPS

A co-simulation framework for design of time-triggered cyber-physical systems is proposed [75][76][77]. A virtual prototyping approach, which uses SystemC to model the cyber part and simulators of physical systems to model the physical part of a CPS, forms the core of the proposed framework.

We use this framework to establish a virtual automotive platform which can be used to study the integration of automotive CPS at early design stages. The virtual automotive platform includes the following three CPS design layers:

Software layer: each task takes the corresponding generated C code from MATLAB/Simulink model to realize its functionality. All the tasks belonging to the same PE are grouped into one task set class. When integrating all the models, the task set will be instantiated and registered to the RTOS model of the corresponding PE, and an off-line defined schedule table for TT activations is also registered to the RTOS model.

Network/platform layer: (1) a PE model for TT computation, (2) a clock model for driving TT operations, (3) a network model compliant with the TTEthernet protocol for TT communication between different nodes, and (4) sensor and actuator models for interaction with the physical environment.

Physical layer: Integrating CarSim into the co-simulation framework is achieved by a wrapper module that takes charge of synchronization between the SystemC simulation kernel and CarSim VS solver. Different dynamics variables reference to the variables in the internal mathematical model through VS APIs. These dynamics variables are revealed by the wrapper module to the sensors/actuators of the network/platform layer through shared variables.

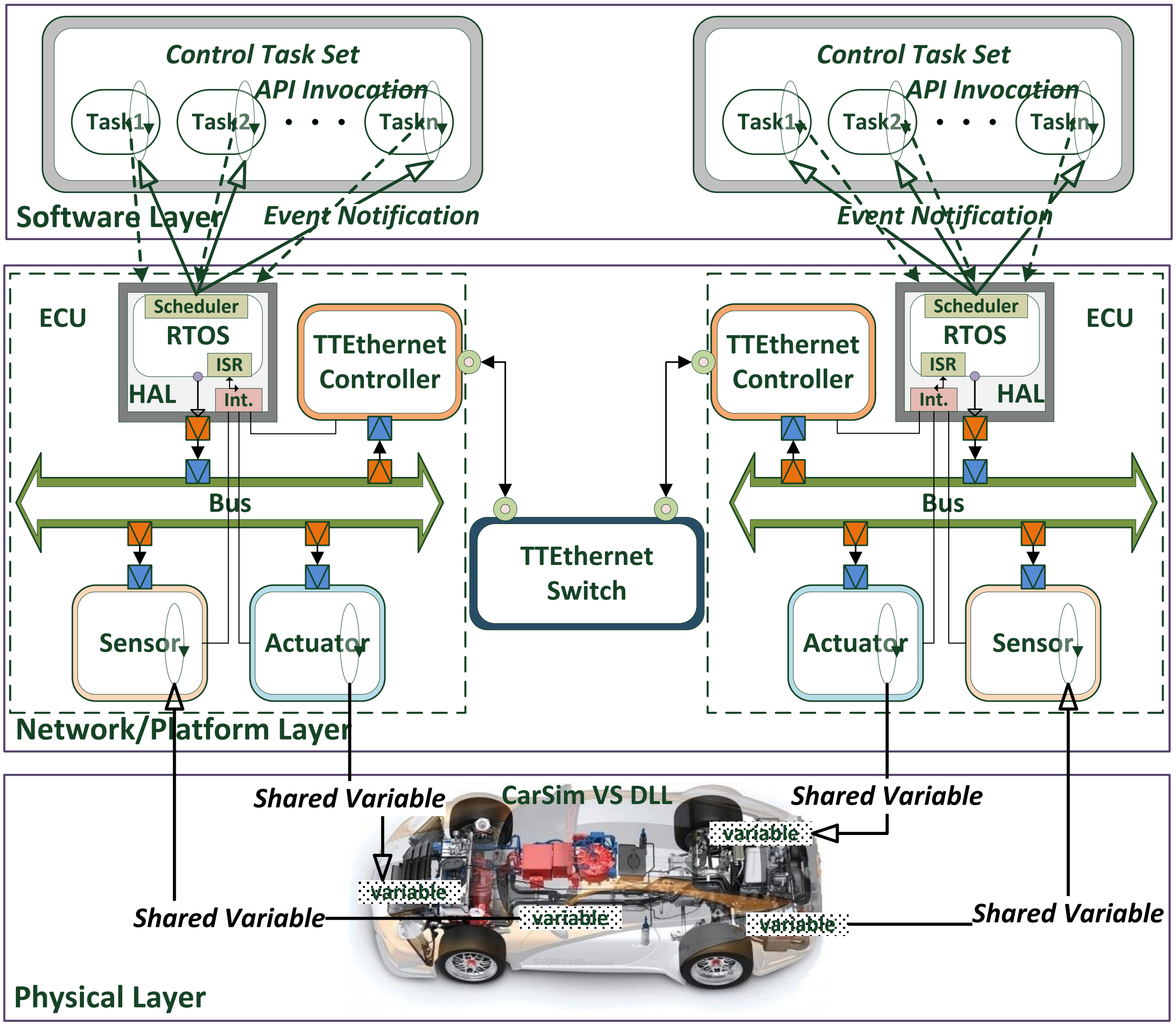


Figure 9: Co-simulation framework for automotive CPS

In order to improve the usability of the framework, we integrate it with our model-based design tool called ESMoL, as shown in Figure 10.

The first four steps belong to using ESMoL to facilitate high-confidence control software design. Step 1 is to specify the control functionality in the MATLAB/Simulink environment. The Simulink model will be imported into the ESMoL automatically to become the functional specification for instances of software components. Step 2 is to specify the non-functional parts of the system in ESMoL. Step 3 translates the ESMoL model into the simpler ESMoL_Abstract model using the Stage1 interpreter of ESMoL. Step 4 is to take the scheduling problem specification generated from ESMoL_Abstract model and use a tool of ESMoL called SchedTool to solve the scheduling problem. Step 5 is to generate C code from MATLAB/Simulink model using Real Time Workshop (RTW) toolbox. Step 6 uses Stage2 interpreter of ESMoL to generate the virtual prototype. Finally, the co-simulation results of the holistic system provide performance feedback for engineers to revise their designs, which is the Step 7.

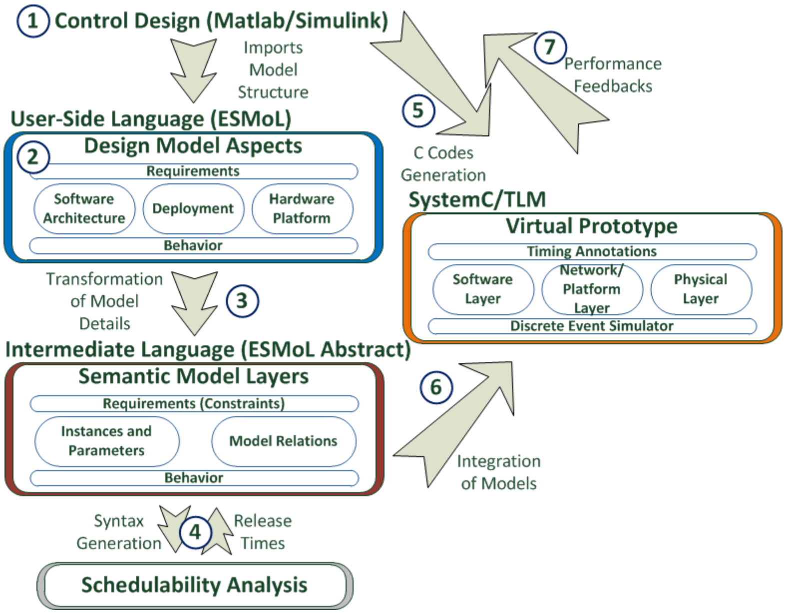


Figure 10: ESMoL integration

An Adaptive Cruise Control (ACC) case study is done on this virtual automotive platform and the results are compared to the results from a hardware-in-the-loop simulator. It exhibits similar results with good simulation efficiency.

2.2. System simulation framework for wireless CPS

Integration of algorithms and designs at various layers of the network stack within a high-reliability wireless real-time network is especially challenging. Simulation is an important tool at every stage of the design process. The designer needs to validate the complete system under a wide variety of deployment scenarios (deployment geometries, environment characteristics, traffic needs), while keeping the computational complexity reasonable, in order to be able to run a sufficiently large number of Monte Carlo trials, thus ensuring credible simulation results. Also, the simulation needs to retain and reproduce the most important features of the physical environment, such as those of the wireless propagation channel between the nodes of the network.

To address these needs, we proposed a system simulation framework for realistic performance evaluation of highly deterministic and high-reliability multihop wireless sensor and control networks, with emphasis on wireless cyber-physical systems that contain physical systems tightly integrated with the communications platform [81][82]. Exploiting common design restrictions in state-of-art wireless real-time networks, specifically the centralized planning of resource scheduling and routing and limited network size, the proposed simulation methodology allows highly accurate simulations with significantly lower computational effort compared to traditional packet-level simulators.

Based on the principles of the proposed framework, we also developed a concrete simulator implementation to simulate wireless networked control systems over WirelessHART, a state-of-art multi-hop industrial wireless mesh networking technology for real-time networks [82]. The implemented simulator aims at facilitating the cross-layer integration and optimization of components of wireless real-time networks, such as resource allocation algorithms and routing technologies, and also enables validation of application performance, such as stability and performance of feedback control loops over wireless multihop networks.

2.3. Integration and analysis of CPS using generalized bond graphs

We also research the possibility to model and analyze the integration of Cyber-Physical Systems using Generalized Bond Graphs with Port Hamiltonian System formulation. The first results of our research in this direction are published in [97].

The Modelica Standard Library (MSL) has provided inspiration in this work; within MSL, the user can connect different components together to form a system. However, once a system is built using MSL components, all that can be done is simulation; the underlying dynamic equations of each component are designed with only simulation in mind.

Our method is based on a modeling scheme in which components are connected together through an exchange of power (through ports), as opposed to the traditional exchange of signals. Current port-based modeling techniques, such as Modelica, compile equations from a set of connected components which then are used to simulate the system. We modify these existing techniques so that each component now contains information pertaining to structural properties.

Central to each component is a Dirac structure, which contains all power conserving interconnections within the component. By using the Dirac structure as a strict mathematical construct, we can analyze certain structural properties of systems such as controllability, observability, and passivity. One of the main benefits of using Dirac structures is that it allows compositionality; composing two Dirac structures creates another Dirac structure.

Currently we are able to determine the controllability and observability given the Dirac structure of a component. We are working towards applying passivity-based control analysis to the Dirac structure of a component. Recently, we extended our method to a Port Hamiltonian system library (written in Modelica) for simulation and analysis of a radio-controlled car. We hope that a library like this can be extended to other domains beyond just mechanical/electrical.

2.4. Model-Based Systems Engineering for CPS

The wide distribution of software-based process control systems and the existing level of networking and communication mean that there is broad scope for CPS to be used in the affected application domains. The integration of these two capabilities is a catalyst that will ignite demand. This would indicate a fast and extensive change, which will be of great importance, especially for the USA as a centre for high technology. If a successful contribution is to be made in shaping this change, the revolutionary potential of CPS must be recognized and incorporated into internal development processes at an early stage. For that *Interoperability and Composability of CPS* is critical, as well as their capability to be adapted flexibly and application-specifically as well as extended at the different levels of abstraction. This requires cross-domain concepts for architecture, communication and compatibility at all levels. The effects of these factors on existing or yet undeveloped systems and architectures represent a major challenge. CPS create core technological challenges for traditional system architectures, especially because of their high degree of connectivity. This is because CPS are not constructed for one specific purpose or function, but rather are open for many different services and processes, and must therefore be adaptable. In view of their evolutionary nature, they are only controllable to a limited extent. This creates new demands for greater interoperability and communication within CPS that cannot be met by current closed systems. In particular, the differences in the characteristics of embedded systems in relation to IT systems and services and data in networks lead to outstanding questions in relation to the form of architectures, the definition of system and communication interfaces and requirements for underlying CPS platforms with basic services and parallel architectures at different levels of abstraction.

To summarize and emphasize, the complexity of the subject in terms of the required technologies and capabilities of CPS, as well as the capabilities and competences required to develop, control and design/ create innovative, usable CPS applications, demand fundamentally integrated action, interdisciplinarity (research and development, economy and society) and vertical and horizontal efforts in:

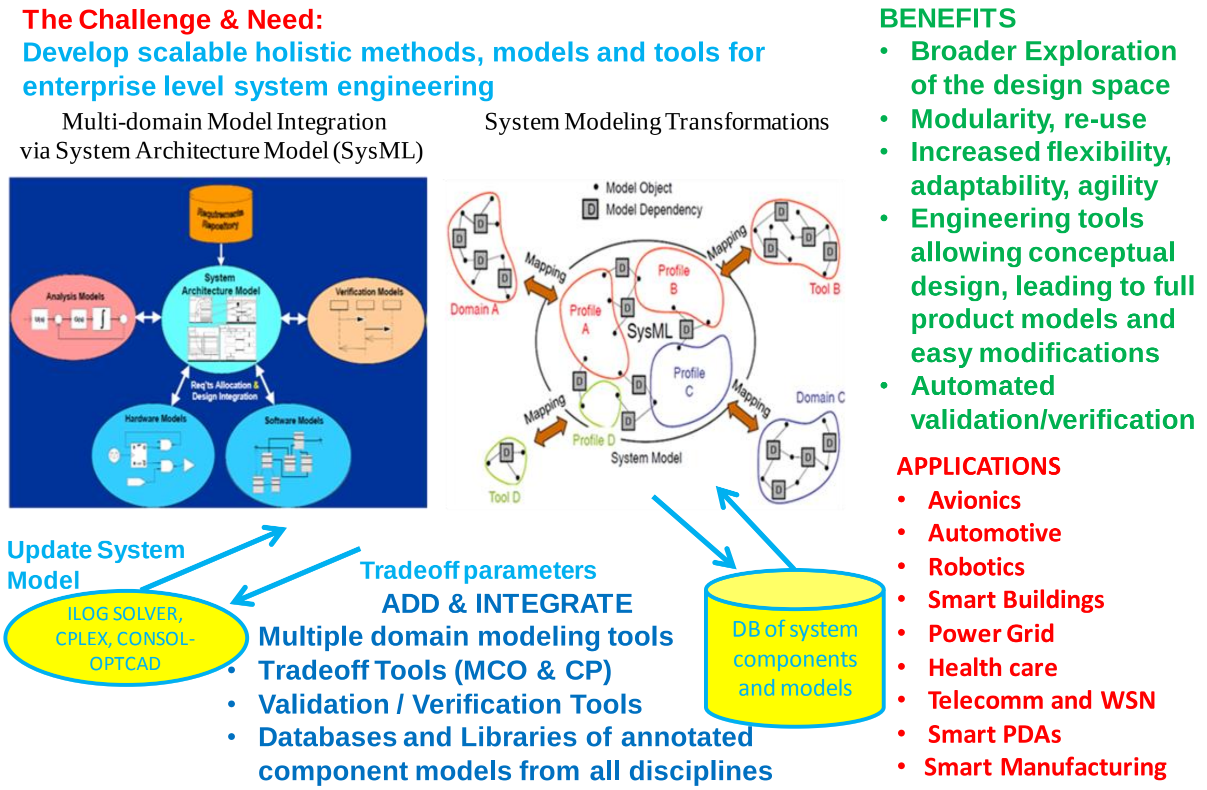
- The creation of open, cross-domain platforms with fundamental services (communication, networking, interoperability) and architectures (including domain-specific architectures)
- The complementary expansion and integration of application fields and environments with vertical experimentation platforms and correspondingly integrated interdisciplinary efforts
- The systematic enhancement with respect to methods and technologies across all involved disciplines to create innovative CPS

The aim of our research is precisely to clarify these objectives and systematically develop detailed recommendations for action. Our overall approach and steps are illustrated in Figure 11. During the reporting period we continued our efforts in two essential problems:

(i) The creation of a framework for developing cross-domain integrated modeling hubs for CPS.
(ii) The creation and demonstration of an initial framework for linking the integrated CPS modeling hub of (i) with powerful and diverse tradeoff analysis methods and tools for design exploration for CPS.

Regarding problem (i) in our work and research so far we have addressed the challenge of developing model-based systems engineering (MBSE) procedures for the design, integration, testing and operational management of cyber-physical systems, that is, physical systems with cyber potentially embedded in every physical component. Thus in the emerging framework for standards for integrated modeling hubs for CPS, MBSE methods and tools are prominent.

High levels of MBSE productivity will be achieved through the use of high-level visual abstractions coupled with lower-level (mathematical) abstractions suitable for formal systems analysis. Recent research has demonstrated the use of SysML as a centerpiece abstraction for team-based system development, with a variety of interfaces and relationship types (e.g., parametric, logical and dependency) providing linkages to detailed discipline-specific analyses and orchestration of system engineering activities. During the reporting period we have successfully integrated (and demonstrated the use of, in real industrial CPS problems) various environments with SysML: Modelica, MATLAB (Stateflow / Simulink, Mathematica, Maple etc.). CPS puts additional significant challenges in this integration of models view due to the fundamental heterogeneity of CPS components and the hybrid (logic-analog nature of CPS). Our research effort during this reporting period continued the development of new foundations for this model integration and towards a framework for standardization in these so-called ***CPS modeling integration hubs***. So far we have developed such CPS modeling integration hubs for power grids, microrobotics, energy efficient buildings, wireless sensor networks and vehicle management systems for next generation all-electric aircraft.



The Challenge & Need:

Develop scalable holistic methods, models and tools for enterprise level system engineering

Multi-domain Model Integration via System Architecture Model (SysML)

System Modeling Transformations

Update System Model

Tradeoff parameters

ADD & INTEGRATE

- **Multiple domain modeling tools**
- **Tradeoff Tools (MCO & CP)**
- **Validation / Verification Tools**
- **Databases and Libraries of annotated component models from all disciplines**

BENEFITS

- **Broader Exploration of the design space**
- **Modularity, re-use**
- **Increased flexibility, adaptability, agility**
- **Engineering tools allowing conceptual design, leading to full product models and easy modifications**
- **Automated validation/verification**

APPLICATIONS

- **Avionics**
- **Automotive**
- **Robotics**
- **Smart Buildings**
- **Power Grid**
- **Health care**
- **Telecomm and WSN**
- **Smart PDAs**
- **Smart Manufacturing**

Figure 11: Linking Design Space Exploration Tools with SysML – Integrated CPS Modeling Hub

Although progress to date in MBSE, facilitates the integration of system component models from different domains, we still need an integrated environment to optimize system architecture, manage the analysis and optimization of diverse measures of effectiveness (MoE), manage the various acceptable designs and most than anything else perform tradeoff analysis. Thus the next steps in the development of methodologies and tools to address our vision towards a highly automated environment for the synthesis and design validation for CPS are (in our opinion): (a) Integration of combined multi-metric optimization and constrained based reasoning methods and tools with the integrated system modeling environment facilitated by SysML, thus enabling broad exploration of the design space; (b) Linkage of the combined system modeling and design exploration integrated methodology and environment with libraries of component models properly annotated. During the reporting period we continued our efforts in (a), and initiated efforts in (b) for the area of wireless sensor networks.

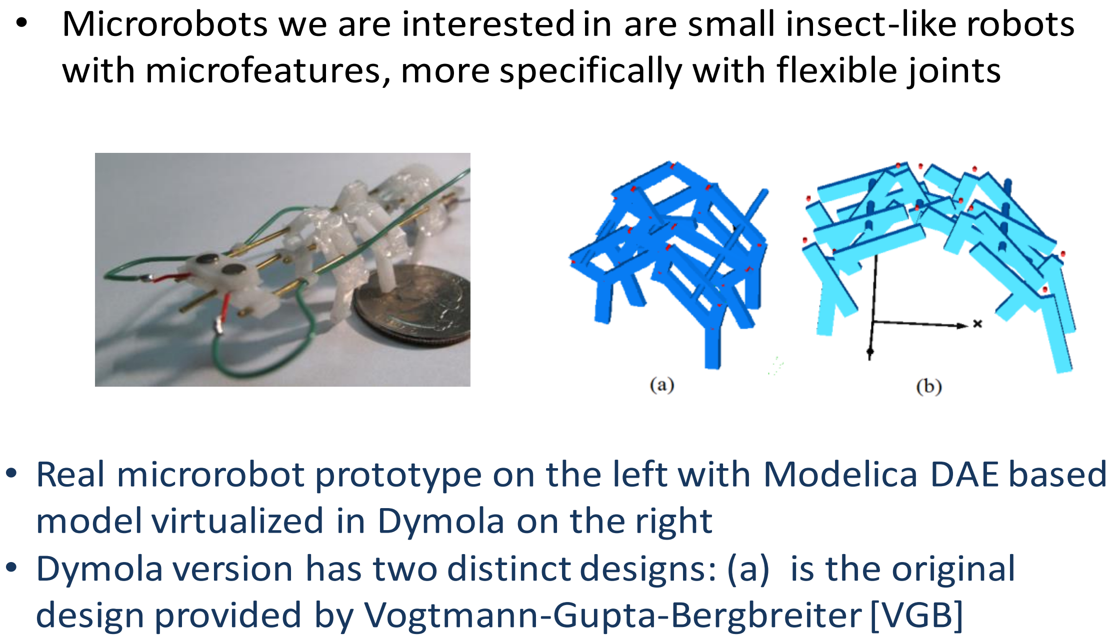
Regarding problem (ii) during this reporting period we further developed and demonstrated the first ever integration of a powerful tradeoff analysis tool (and methodology) with our SysML-Integrated system modeling environments for CPS synthesis. Primary applications of interest that we worked within this framework during the reporting period were: microgrids and power grids, wireless sensor networks (WSN) and applications to Smart Grid, energy efficient buildings, microrobotics and collaborative collaborative robotics and the overarching (for all these applications) security and trust issues including our pioneering and innovative work on compositional security systems.

At the University of Maryland we have developed sophisticated multi-criteria optimization tools, the most prominent one is CONSOL-OPTCAD, that incorporate duality methods of analysis (involving both numerical and discrete variables) for problems such as IPPD, as well as innovative visualization techniques to help engineers understand the impact of design choices. We have continued the development of methodologies which extend these sophisticated techniques for tradeoff analysis of system metrics and specifications, and implement them in software environments where the benefits of SysML and our analysis/visualization techniques for optimization and tradeoff can co-exist. A key component of the emerging framework is a metamodeling environment with its associated languages and its semantics based on sophisticated versions of annotated block diagrams and bond graphs.
Additional challenges that we initiated addressing during this reporting period are the following. First there is the challenge of *systematic architecture optimization*, and exploration of a broad set of system design alternatives. This is best accomplished by evaluating system architectures through measures of effectiveness (MoE). The latter can be effectively accomplished by a combination of industrial strength multi-objective optimization algorithms, constrained based reasoning algorithms and dynamic system simulations as needed. In our work and research so far the key diagrams are the Requirements Diagram (RD) and the Parametric Diagram (PD); both new diagrams introduced by SysML. The tradeoff analysis methodology that we have developed and used at the Institute for Systems Research of the University of Maryland, is based on the integrated and interoperable use of constrained based reasoning and multi-criteria optimization. It is capable of performing trade-off analysis for both the behavioral and the structural model of a system and its components, as well as of the allocation of behavioral components to structural components.

Our research addresses the fundamental CPS challenge of connecting multiple development environments, so as to provide a unified system view, while at the same time facilitating holistic (i.e. system level traceability and impact analysis). This will accomplish system architecture management across disciplinary domains. The approach undertaken in our research represents a substantial and innovative extension of the current state of the art in Model-Based Engineering (MBE). Our approach and results todate address the following applications and challenges for CPS synthesis: (a) Broader exploration of the design space; (b) Dramatically increased flexibility and adaptability to changing environments, without time-consuming redesign; (c) Need for modifiable systems, reconfigurable or upgradable by reference to virtual models, by plug-replacing subcomponents; (d) Heterogeneous CPS model integration; (e) Engineering tools, technologies and methods that enable conceptual design – system design and production, that are useful for full product models and allow easy modification and upgrades.

During the reporting period we developed and applied such tool environments to two generic CPS examples: microgrids and microrobots.

In [128] we introduced the idea of the "modeling hub" in order to realize the vision of Model-Based Systems Engineering and especially we focus on the trade-off path of this hub. For that purpose the design capabilities of SysML were extended by integrating it with Consol-Optcad, a powerful multi-criteria optimization tool for trade-off analysis. The integration and its implementation was applied to analyze a multi-criteria optimization problem concerning power allocation and scheduling in a microgrid. In the future we intend to expand the capabilities of this integration by making Consol-Optcad able to handle mix integer problems, which represent the majority of problems that industry usually faces. Making a two-way transformation is also planned for the near future, as it will give the capability of a true interaction between SysML and Consol-Optcad without human intervention. Finding a way to incorporate structural changes and geometry to the design space exploration process is another very challenging task that can expand the usefulness of the integration. Finally, we plan to integrate IBM CPLEX and IBM-ILOG Solver in our modeling hub -- tools that are used widely in industry with excellent results in many domains.



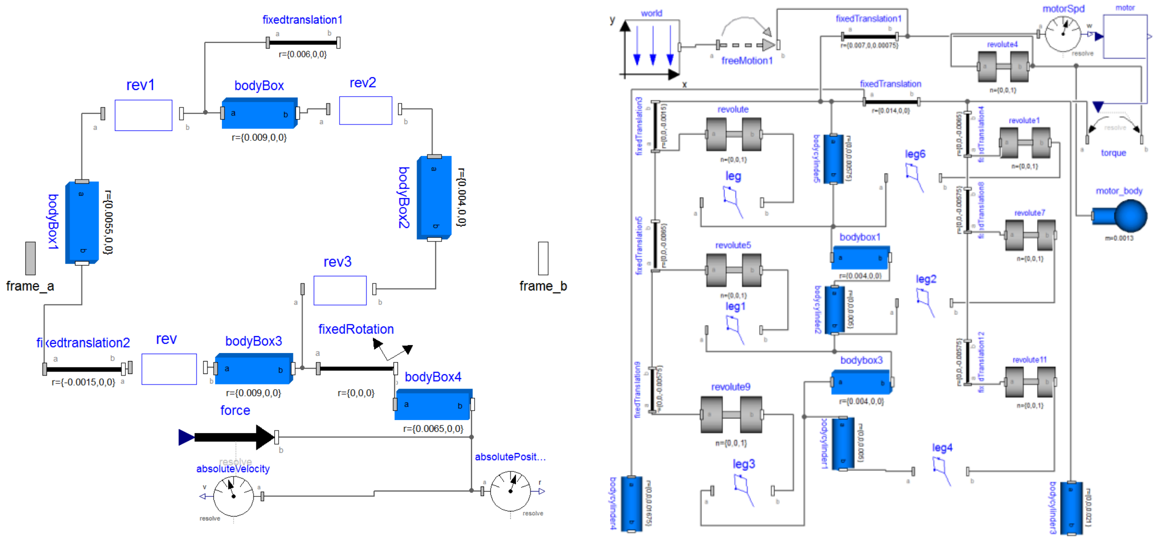
- Microrobots we are interested in are small insect-like robots with microfeatures, more specifically with flexible joints

- Real microrobot prototype on the left with Modelica DAE based model virtualized in Dymola on the right
- Dymola version has two distinct designs: (a) is the original design provided by Vogtmann-Gupta-Bergbreiter [VGB]

Figure 12: Microrobots of interest as CPS

In [111] we described this new methodology and environment for Cyber Physical Systems (CPS) synthesis and demonstrate it in the design of microrobots viewed as CPS. The microrobots of our study are shown in Figure 12. Various types of microrobots have been developed in recent years for applications related to collaborative motion such as, sensor networks, exploration and search-rescue in hazardous environments and medical drug delivery. However, control algorithms for these prototypes are very limited. Our new approach for modeling and simulation of the complete microrobotics system allows the robots to complete more complex tasks as per specifications. Since the microrobots tend to have small features, complex micro-structures and hierarchy, the control laws cannot be designed separately from the physical layer of the robots. Such a type of microrobot is indeed a CPS, as control in the cyber side, and the material properties and geometric structure in the physical side, are tightly interrelated. This design approach is important for microrobots, capable of collaborating and completing complex tasks. An important innovation in this work was the treatment of material properties and geometric configurations as design variables. Figure 13 illustrates a Modelica model of the microrobot. In this particular work we demonstrated how the interplay between the cyber part (here the control algorithm) and the physical part (here the material selection and the geometric configuration of the legs) can lead to various improved solutions with respect to stable motion of the microrobots. For instance, similar performance results could result with two different selections of the controller, material and geometry. Thus design space exploration also includes what part of functionality will be allocated to the physical part and what to the cyber and why?

- Leg Model
- Overall Model



Structure of the leg model in Modelica block diagram. The joints rev, rev1, rev2 and rev3 are the joints with flexible material.

Simplified structure of the robot using the leg submodel. Highlighted submodel is an electrical motor model, includes a Pulse Width Modulation controller, which is the Cyber part of the robot.

Figure 13: Modelica model of microrobot

In [139] we developed HybridSim, a modeling and co-simulation toolchain for cyber-physical systems. Many CPS, such as Smart Buildings, are subject to very expensive deployment costs and complex network interactions. Thus comprehensive modeling and simulation of such systems are crucial to ensure that they function as intended before deployment. Given the multi-domain nature of CPS, it is more appropriate to use a heterogeneous simulation environment to study system dynamics. In our work [139], we designed and implemented an integrated modeling and co-simulation toolchain, called HybridSim, for the design and simulation of CPS. Firstly, HybridSim can transform and import existing system components from multi-domains into SysML, which enables systems engineers to design CPS with only these imported SysML blocks. Secondly, HybridSim can generate Functional Mock-up Units (FMUs) and configuration scripts directly from SysML designs. Finally, HybridSim can co-simulate these FMUs according to the Functional Mock-up Interface standard to synchronize their corresponding simulators and exchange information between them. We demonstrated the convenience and efficiency of HybridSim using a comprehensive hydronic heating system model for Smart Buildings as the case study to investigate the impact of packet loss and sampling rate introduced by the communication network.

Finally in [127] we investigated ontologies of time and time-based reasoning for MBSE of CPS. Our work is concerned with the development of Model-Based Systems Engineering (MBSE) procedures for the behavior modeling and design of Cyber-Physical Systems. This class of problems is defined by a tight integration of software and physical processes, the need to satisfy stringent constraints on performance, safety and a reliance on automation for the management of system functionality. To assure correctness of functionality with respect to requirements, there is a strong need for methods of analysis that can describe system behavior in terms of time, intervals of time, and relationships among intervals of time. Accordingly, in our work [127] we investigated temporal semantics and their central role in the development of a new time-based reasoning framework in MBSE for CPS. Three independent but integrated modules compose the system: CPS, ontology and time-reasoning modules. This approach is shown to be mostly appropriate for CPS for which safety and performance are dependent on the correct time-based prediction of the future state of the system. A Python-based prototype implementation has been created to demonstrate the capabilities of the ontological framework and reasoning engine in simple CPS applications.

2.5. Compositional Analysis of Dynamic Networked CPS and Complexity Reduction

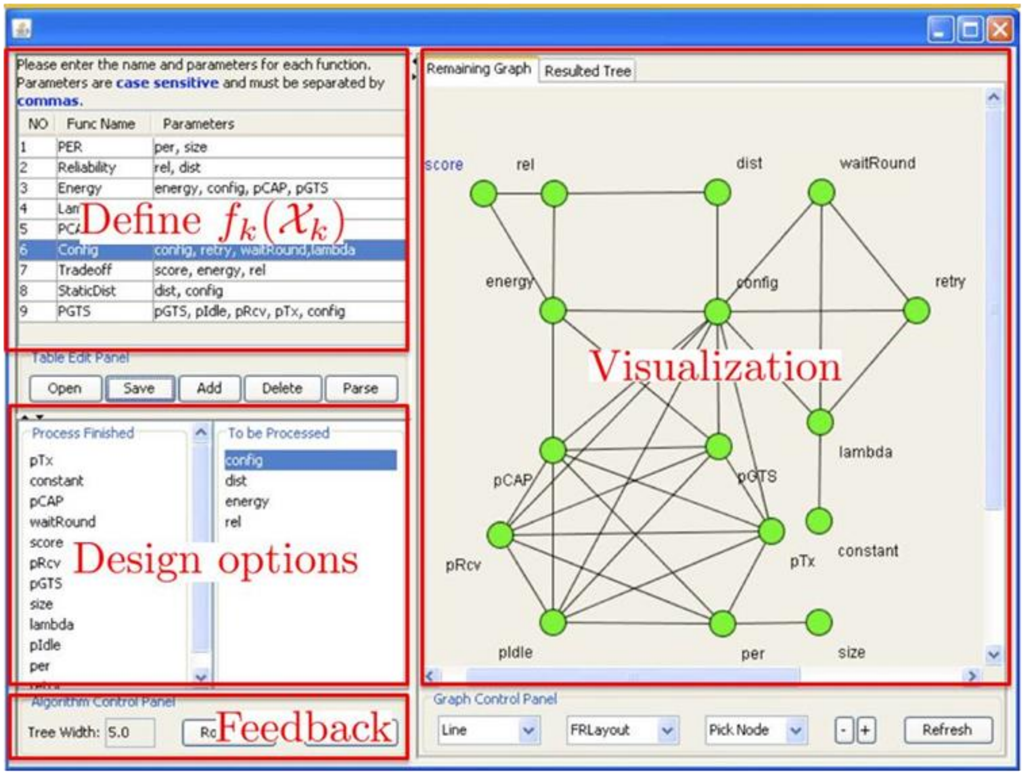
An important problem in the synthesis of large and complex networked CPS is the development of methods and tools to manage the enormous complexity of these systems throughout their design and operations cycle. During the reporting period we continued our investigations on this critical problem.

Dynamic Bayesian networks (DBNs) can be effectively used to model various problems in CPS. In [130] we performed an empirical investigation on compositional analysis of DBNs using abstraction. In static systems and hidden Markov models, computation of a metric called treewidth induces a tree decomposition that can be used to perform logical or probabilistic inference and {max, +} optimizations in time exponential in treewidth and linear in overall system size. Intuitively, the linear scaling means that very large systems can be analyzed as long as they are sufficiently sparse and well structured. In these simple cases, summary propagation, which uses two operations, summation (projection) and product (composition), suffices to perform the inference or optimization. In this part of our research work, we extended this result to structured networks of communicating dynamic systems. We [130] defined generalizations of projection and composition operators that treat labeled Markov chains as primitive objects. The projection operation, corresponding to summation, is implemented as label deletion followed by exact state reduction for Markov chains, similar to Hopcroft's DFA minimization algorithm, with

$O(n \log m)$ complexity. The composition operation is the product of state machines. We used canonical MDDs, similar to BDDs, to capture logical dependencies symbolically. The composition operation is the product of state machines. We used canonical MDDs, similar to BDDs, to capture logical dependencies symbolically. Combining symbolic representations with Markov chain lumping algorithms is a novel contribution. Using this approach, we have created a tool leveraging model based systems engineering technologies. The communicating Markov chains are specified using UML Statecharts via Papyrus extended using an ANTLR parsed domain specific language (DSL).

The tool reduces the number of states in networks of Markov chains by several orders of magnitude. In one example, a network having a product state space of more than 600 million states is reduced to about 500 states. A feature of this technique is that the state space is examined incrementally, meaning that the full state space is never explicitly represented, even as an input to the reduction algorithm. The primary reduction appears to come from symmetry which is surprising because the technique includes no explicit symmetry handling. We note that composition is efficient at least for systems with high symmetry. We have applied these methods and algorithms and tools to two CPSs: a modern aircraft power generation and distribution network and its management system (VMS), and a hospital intensive care unit (ICU).

We also developed an *Interactive Tree Decomposition Tool* for Reducing System Analysis Complexity [129]. The overall tool is based on a graphical tool for the calculation of *treewidth*, a metric on the parametric structure of a system that is intimately tied to the complexity of system analysis. For many graphically describable systems, such as systems of parametric equations, as in a SysML Parametric Diagram, Bayesian networks, mind maps, writing term papers, analysis of the system is exponential in treewidth and linear in system size. A tool facilitating comprehensive analysis can serve to bring competitive advantage to a systems engineering workflow by reducing costly unanticipated behaviors. Furthermore, a byproduct of computing treewidth is a framework for enumerating computationally compatible distributed algorithms.



Please enter the name and parameters for each function. Parameters are **case sensitive** and must be separated by **commas.**

NO	Func Name	Parameters
1	PER	per, size
2	Reliability	rel, dist
3	Energy	energy, config, pCAP, pGTS
4	Lan	
5	PCA	
6	Config	config, retry, waitRound,lambda
7	Tradeoff	score, energy, rel
8	StaticDist	dist, config
9	PGTS	pGTS, pIdle, pRcv, pTx, config

Process Finished

pTx
constant
pCAP
waitRound
score
pRcv
pGTS
size
lambda
pIdle
per

To be Processed

config
dist
energy
rel

Tree Width: 5.0

Figure 14: An illustration of our complexity analysis and reduction tool for CPS

Though there are classes for which treewidth computation is tractable (*chordal graphs*), it is generally NP-complete. For this reason, we pose [129] the problem from the perspective of finding satisficing solutions, exposing choices that can influence the complexity of the resulting system to the designer. A designer can contribute two important things to the structure of the system: a visual intuition about the relationships between the underlying objects and the ability to *change* the relationships themselves at design time to reduce analysis complexity. Having a visual tool that provides instant feedback will help designers achieve an intuitive grasp of the relationship between design decisions and system complexity. As complexity is the root of almost every systems engineering problem, and also something not easily understood, incorporating complexity analysis into a design process should improve resulting system designs.

Our tool [129] uses a randomized, anytime algorithm for interactive optimization of treewidth. It presents a sequence of choices to a designer and incrementally lowers an upper bound on system treewidth over time. This algorithm is novel, as few algorithms are targeted at interactivity with a human user. We have investigated a number of CPS examples for using the tool. We showed how our tool helps to decompose some example systems, including a quadrotor design optimization, a wireless sensor network design optimization, a Bayesian network, and a mind map. An instance of using the tool is illustrated in Figure 14.

2.6. Component-Based Synthesis of Wireless Sensor Networks

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.

During the reporting period we continued our focused efforts for creating such a synthesis environment for heterogeneous wireless sensor networks (WSN). In our work heterogeneous wireless sensor networks (WSN), are viewed as large heterogeneous 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. Existing ad hoc system design methods for Wireless Sensor Networks (WSNs) suffer from lack of reusability. In addition, the interactions between the continuous-time physical environments and WSNs have not been well studied.

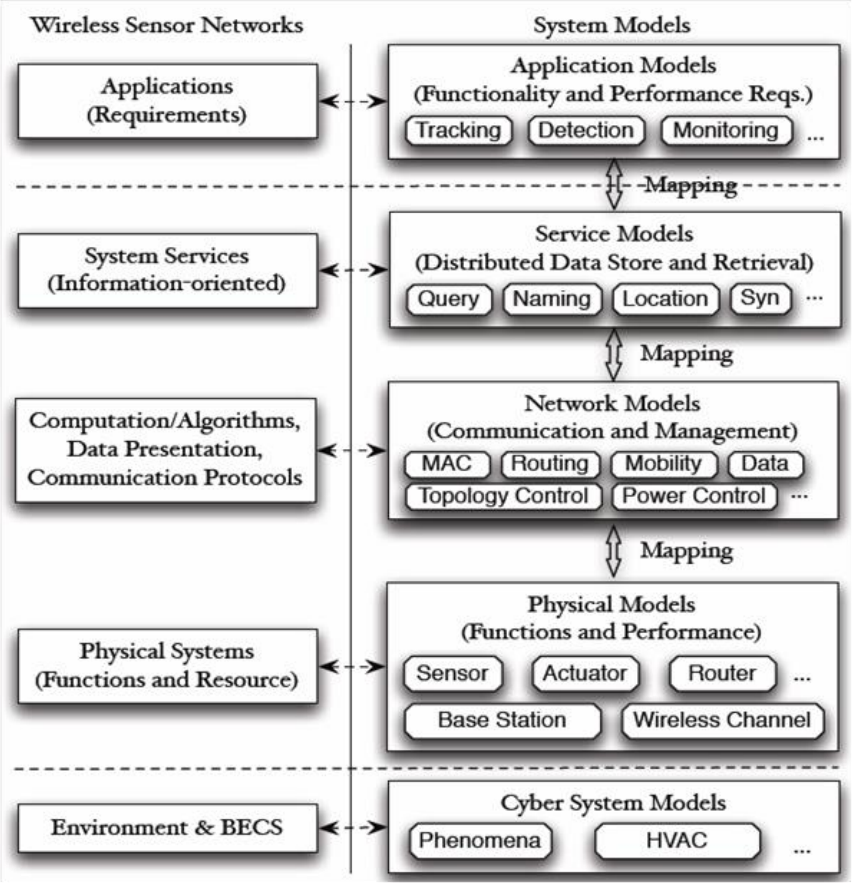


Figure 15: WSNDesign model libraries

In our work [131][139], we developed a model-based systems design (MBSD) framework for WSNs, called WSNDesign, which is a systematic methodology applying systems engineering principles to enhance model reusability and collaborations among multiple modeling domains. Firstly, WSNDesign provides model libraries to model various behaviors and structures of WSNs in the context of Smart Buildings. Event-triggered components are either modeled in SysML Statechart Diagrams, or imported from existing TinyOS libraries. Continuous-time components are modeled in Modelica and their behaviors are described by differential equations, which are then transformed and imported to WSNDesign. Therefore, with the help of WSNDesign, system engineers can take advantage of many existing TinyOS and Modelica libraries, rather than design everything from scratch. Secondly, WSNDesign can estimate the performance of designed systems, providing instant feedback to sysstem engineers to quickly explore the performance trade-offs space. In WSNDesign, each component has a performance model described using SysML Parametric Diagrams. System overall performance can be calculated by traversing the system structure tree. Thirdly, WSNDesign can generate simulation codes and configuration scripts directly from system models. Although theoretical analysis provides immediate performance results, accuracy is often sacrificed due to oversimplifications, especially for large complex systems. With code generation, WSNDesign can save system engineers the trouble of writing simulation codes manually. WSNDesign integrates the existing widely accepted simulators to increase the confidence of the simulation results. Finally, WSNDesign provides an interactive tool to reduce the complexity of system analysis using summary propagation on factor graphs transformed from SysML Parametric Diagrams, and expose a sequence of design choices to system designers to provide instant feedback about the influence of a design decision on the complexity of system analysis. Figure 15 illustrates the model libraries of WSNDesign. Figure 16 shows the design flow of WSNDesign.

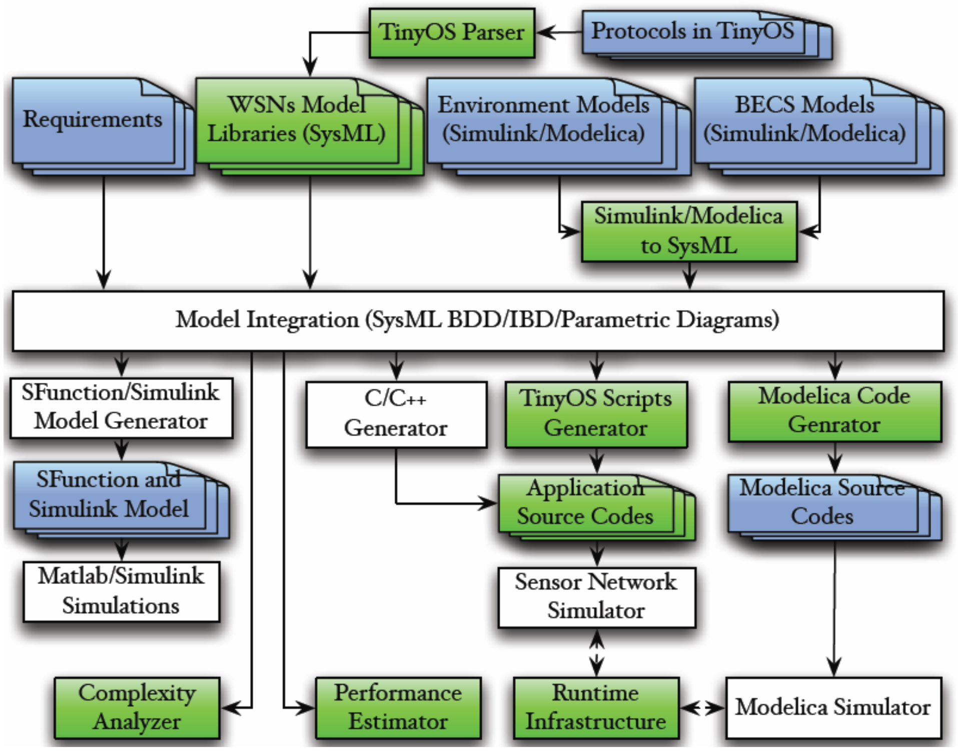


Figure 16: WSNDesign design flow

On top of WSNDesign we designed and implemented HybridDB [145], an efficient distributed database system for flash-based storage-centricWSNs. HybridDB exploits a novel resource-aware data storage system, called HybridStore [126], to store and query sensor data in situ on each sensor mote. HybridStore can process typical joint queries involving both time windows and key value ranges as filter conditions extremely efficiently. Based on HybridStore, HybridDB provides the support for incremental ε-approximate querying that enables clients to retrieve a just-sufficient set of readings by issuing sub-queries with decreasing error-bounds. HybridDB will return an approximate dataset with arbitrary L^1-norm error bound, after applying temporal approximate locally on each sensor, and spatial approximate in the neighborhood on the proxy. In addition, HybridDB exploits an adaptive error distribution mechanism between temporal and spatial approximate for trade-offs of energy consumption between sensors and the proxy, and response times between the current subquery and following subqueries. Our implementation of HybridDB in TinyOS 2.1 can be transformed and imported to WSNDesign as a part of the model libraries.

3. Systems/experimental research

3.1. Model-Based Design and Integration of Automotive Cyber-Physical Systems

Automotive systems have recently been gaining increased attention due to the increased pressure to integrate as much functionality on as few ECUs as possible, in addition to the persistent effort for low production costs and tight time-to-market. These economic factors have fueled various emerging challenges in the design of automotive application. Due to these economic drivers, automotive control applications are typically developed independently. Afterwards, global system objectives, such as autonomous driving, are achieved through the integration of the independently designed control applications with each application performing a specific sub-objective towards the global goal.

During the integration of these applications, various interactions from cyber and physical domains manifest. These complex interactions, which result from the complex interactions within and between the cyber and physical domains of CPS, can potentially lead to unforeseen and undesirable overall system behaviors if not properly handled. In [95][96], in an effort towards achieving autonomous driving, we integrate two independently designed controllers, a lane keeping controller (LKC) and an adaptive cruise controller. While the LKC controls the lateral dynamics of the vehicle in order to keep the vehicle within the lane markings, the ACC on the other hand controls the longitudinal dynamics of the vehicle in order to maintain a specified velocity or distance based on a presence of a leading vehicle.

Although, the two controllers control seeming different dynamics of the vehicle, there exist physical interactions that couple the behavior of the two controllers, such as geometry of the road or road curvature. For example, the ACC during its typical operation, when a leading vehicle is detected, adjusts it speed to maintain a specified distance while following the lead vehicle. On a curved road, the ACC in an effort to track the leading can attain a vehicle speed that might be too fast such that it can potentially obstruct the LKC's ability to maintain the desired lateral distance. These types of conflicts can often lead to catastrophic consequences. In order to address these types of conflicts, we integrate a supervisory controller whose main objective is to restrict the regions of operation of the integrated system in a safe desirable manner.

The Figure 17 depicts the overall integrated system.

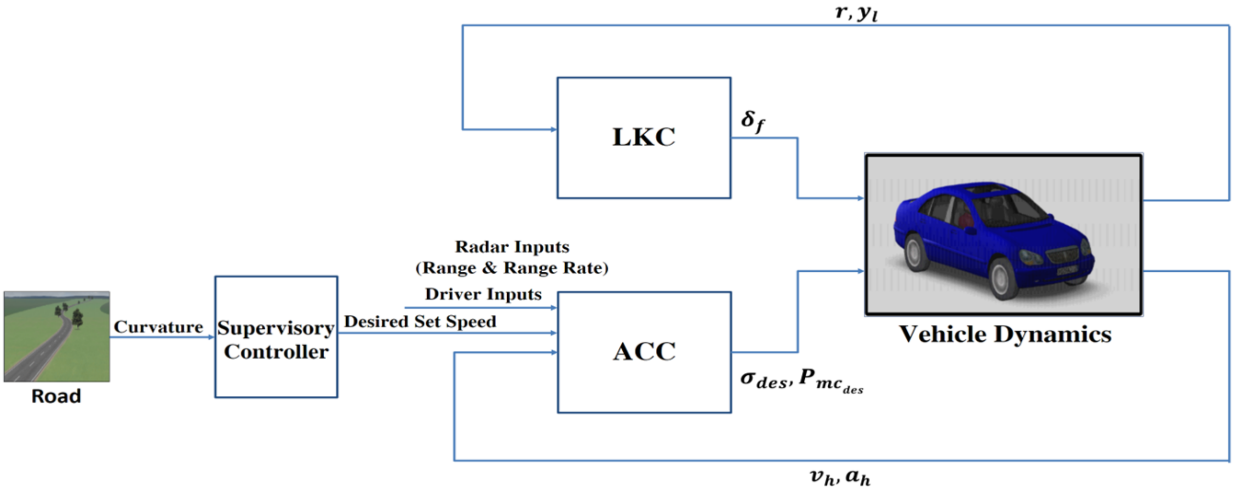


Figure 17: Simultaneous Simulation of LKC and ACC

Simulations, as well as experiments on the experimental platform are performed the evaluated the approach in addition to impact of cyber interactions due to platform effects.

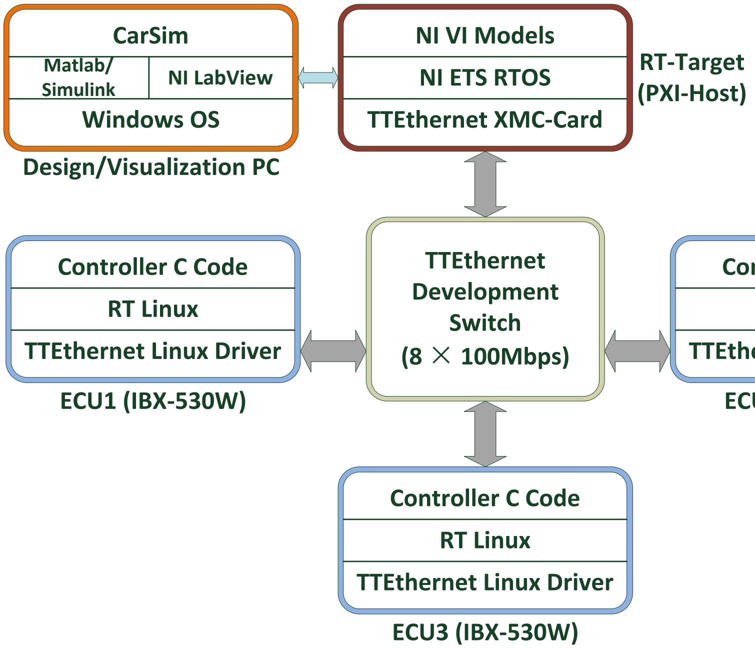


Figure 18: The automotive experimental platform

In the past year, GM R&D collaborated with the university partners to investigate the passivity for vehicle control composition. GM also assessed a vehicle control system robust testing tool and improved it for vehicle validation and verification. A multicore platform is under construction to evaluate the software architecture impact on physical performance and will be used to validate the results from virtual environment at VU and ND. The automotive experimental platform at VU is shown in Figure 18. The platform at ND is similar, except for the lack of the hardware-in-the loop simulation option. This enabled cooperation between ND and VU, e.g. in passivity analysis of the automotive controllers.

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