CPS: Synergy: Resilient Wireless Sensor-Actuator Networks

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Project Objectives

Wireless sensor-actuator networks (WSAN) are systems consisting of numerous sensing and actuation devices that interact with the environment and coordinate their activities over a wireless communication network. WSANs represent an important class of cyber-physical system (CPS) found in our national civil infrastructure.

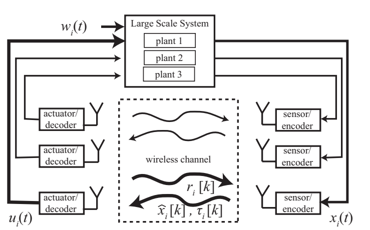
This project addresses the issue of resilience in WSANs.
A resilient system is one that maintains an active awareness of surrounding threats and reacts to those threats in a manner that returns the system to operational normalcy in finite time.
It has proven challenging to ensure resilience in large-scale WSANs because of the complexity such scale brings.

- The objective of this project is to develop WSANs that are resilient to faults in the underlying communication network. This will be done through the coordinated management of the WSANs control and communication functions. The methods will be evaluated on a multi-robotic testbed consisting of unmanned ground and aerial vehicles using machine-to-machine (M2M) communication technologies.

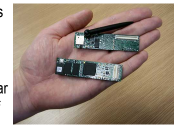
Project Objectives and Approach

The primary objectives of this project are to develop
• methods that optimally control the channel's physical layer in a manner that enforces probabilistic bounds on the channel's burstiness,
• methods that optimally "switch" the control application's structure in response to abrupt fades in the channel state.
• methods for distributed task coordination between multiple agents in the presence of unexpected faults.
•an autonomous multi-robot testbed consisting of ground and aerial vehicles, for the testing and evaluation of the resilient control and coordination algorithms,
• and M2M hardware and middleware to support the control algorithms and project testbed.

The project's approach rests on two fundamental trends. One trend concerns the revolution in machine-to-machine (M2M) communication networks that promise wireless networking with greater peak bit-rates and reliability than previously possible. Another trend concerns recent results that greatly reduce the bit-rates required to achieve control functions through dynamic quantization and event-triggered feedback.



What is M2M Communication?



Machine-to-machine (M2M) technologies build upon the significant advances and economies of scale of the commercial wireless industry surrounding the 3GPP Long Term Evolution (LTE) mobile cellular and IEEE 802.11 wireless LAN family of standards.

Chipsets for both standards can achieve *maximum data rates of 10-100 Mbps* through the coordinated use of *orthogonal frequency division multiplexing (OFDM)* and *adaptive modulation and coding schemes*.
This CPS project will develop middleware algorithms that provide the control application with neighbor discovery, QoS control, multiple access, and routing/dissemination on top of these advanced physical layers. Development is based upon the Gumstix platform shown in the photo above incorporating the latest IEEE 802.11 interfaces available from industry.

Almost Sure Stability of Networked Control Sytems

Wireless communication channels are inherently bursty. This burstiness can result in channel outages of relatively long duration. This project makes use of an exponentially bounded burstiness (EBB) model for channel outages. EBB channels bound the likelihood of long outages as an exponential function of the outage duration.

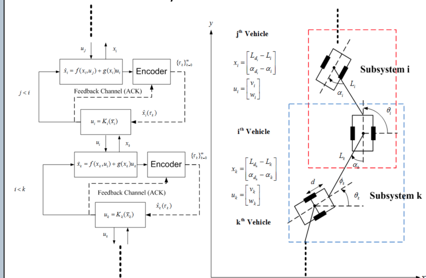
Traditional mean-square stability (MSS) is insufficient for safety-critical systems with bursty channels. This is because an MSSS system may still exhibit extremely large deviations away from equilibrium.

Safety critical systems require the stronger notion of *almost-sure* stability. This means that as time goes to infinity, the probability of a large state deviation goes to zero.

$$\Pr \{ \limsup_k \{|x(k)| > \varepsilon\} = 0$$

This formal definition has much in common with the EBB model for the channel and it suggests that if one can guarantee the model is EBB, it should be possible to establish almost sure stability of the controlled system.
These concepts are being implemented on a multi-vehicle leader-follower application. The formation consists of a platoon of ground vehicles interacting over a communication tree in which each node's leaf is a "follower".

System structure



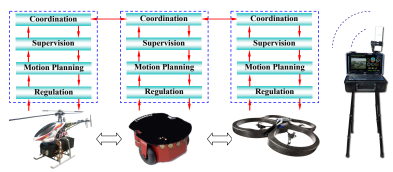
Resilient Cooperative Tasking

Besides leader-follower formation control, we also studied the resilient cooperative tasking for a group robots in uncertain and dynamic environments.

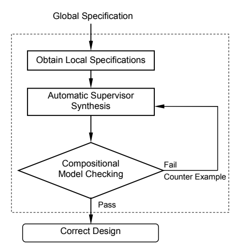
In particular, we aim to develop a scalable and provably correct design method that can guarantee the accomplishment of high-level team missions through automatic synthesis of local coordination mechanisms and control laws.

The basic idea is to decompose the team mission into individual subtasks such that the design can be reduced to local synthesis problems for individual robots. Multidisciplinary approaches combining hybrid systems, supervisory control, regular inference and model checking are utilized to achieve this goal. The developed theory will enable robots in the team to cooperatively learn their individual roles in a mission, and then automatically synthesize local supervisors to fulfill their subtasks.

This is different from most of existing approaches, such as swarming robotics, behavior based robotics, multi-agent system etc., which are bottom-up.



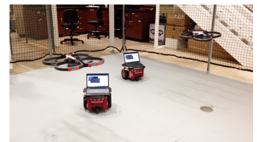
We adopt a hybrid hierarchical control architecture that helps to manage the complexity of controlling heterogenous robots, and to meet the requirements on flexibility and reconfigurability. Compared with existing architectures, the architecture proposed here is different due to its emphasis on distributed automatic synthesis for guaranteed multi-robot cooperative tasking based on a unified hybrid system theoretic framework.



Initially, the global specification is used to guide the local synthesis, and then the assume-guarantee reasoning is employed to check whether the current design satisfies the global specification. If not, the model checker will generate counterexamples that can be used to redefine individual tasks and re-synthesize supervisors accordingly. After supervisor re-synthesis, the assume-guarantee reasoning is performed again and the co-design process repeats until no further counterexamples are found. The co-design process can also be triggered by new counterexamples on-the-fly due to the change of environments or occurrence of failures. Hence, the proposed design approach can adapt to changing environments and dynamic tasking as the design is distributed, automated and reactive.

Notre Dame Multi-Robot Testbed

The resilient control architecture and wireless networking technologies will be evaluated on an indoor multi-robot testbed consisting of a heterogeneous mobile robots communicating over an M2M wireless communication network. The testbed consists of both autonomous unmanned ground (UGV) and aerial vehicles (UAVs) together with a 24-camera OptiTrak motion capture system that provides indoor localization information. The novelty in Notre Dame's UAV/UGV testbed rests in its focus on multi-robot swarm resilience and its use of novel M2M communication technologies.



The UGV components consists of six ActivMedia Pioneer robots that use acoustic proximity sensors for collision avoidance, and a combination of gyro-corrected wheel encoders and laser rangefinder for localization and environment map building. The robots are equipped with a 2-DOF gripper with grasping pressure sensor, and are controll ed through an on-board PC that communicates to each other over an 802.11 wireless LAN card or M2M radio.

The UAV component consists of three quadrotors from Unmanned Dynamics, which are equipped with micro controllers, an analog 9-degree IMU, a pressure sensor and an onboard GPS module. To make these UAVs suitable for our research tasks, significant upgrades on their on-board sensing and processing capabilities have been carried out in my lab with the addition of wireless communication modules, upper-level processing board, on-board camera and vision processing. The quadrotor can both fly outdoor and indoor. We already tested outdoor autonomous flight using GPS modules to get position data. For indoor flight, we integrated the indoor localization module (Optitrack) into the ground station who sends the position data to UAVs via 802.11 wireless LAN.

Our current efforts include equipping these UAVs with M2M wireless networking components to enable inter-vehicle communication and realizing the proposed resilient hybrid hierarchical controllers and top-down design theory.

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