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.

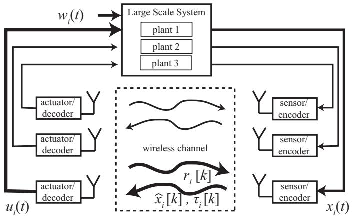
This project addresses the issue of resilience in WSANs.
A resilient system is one that maintains an active awareness of surrounding threats and reacts to those threats in a manner that returns the system to operational normalcy in finite time.
It has proven challenging to ensure resilience in large-scale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

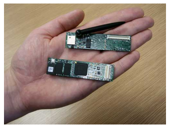
Project Objectives and Approach

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.

Modeling Channel Burstiness

Wireless communication channels are inherently bursty. This burstiness can result in channel outages of relatively long duration. Formally modeling such bursty channels is often done using a two state Markov chain which introduces an intrinsic statistical dependence in the probability of successful transmission.

This project makes use of an *exponentially bounded burstiness* (EBB) model for channel outages. In particular, let R_k denote the number of received bits for the *k*th consecutive packet. The channel is said to be EBB if there exists β such that

$$\Pr\{ R_k > \sigma \} < e^{-\beta\sigma}$$

for any σ>0 and all *k*>0. EBB channels bound the likelihood of long outages as an exponential function of the outage duration.
The EBB channel model is used because
- it is a more realistic model of the wireless channel's outages
- it can be related back to existing two-state Markov chain models
- and it has a close connection to stronger notions of control system stability (almost sure stability) that address safety issues.

Impact of Burstiness on Control Performance

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 that as time goes to infinity, the probability of a large state deviation goes to zero.

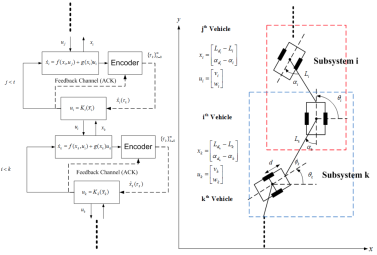
$$\Pr\{ \limsup_k \{|x(k)| > \varepsilon\} = 0$$

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.

Leader-Follower Formation Control

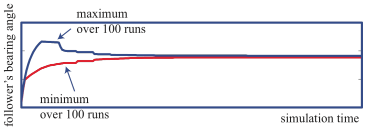
These concepts are being implemented on a multi-vehicle leader-follower application. The formation consists of a platoon of ground vehicles interacting over a communication tree in which each node's leaf is a "follower".

System structure



The system shown above is viewed as a string of leader-follower pairs. Communication links are now realized using Xbee radios. Future plans will use M2M radio networking modules.

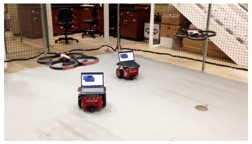
Formation control uses a novel switching control structure that switches to a less aggressive controller when the channel state is poor. This switching decision uses information regarding the relationship between channel state and vehicle state. As a result, it becomes possible to assure almost sure practical formation stability even when the channel exhibits deep fades.



Monte Carlo simulation of Leader-Follower system demonstrates almost sure convergence since the max and min of all simulation runs asymptotically converge to the desired fixed point.

Notre Dame Ground Robot Testbed

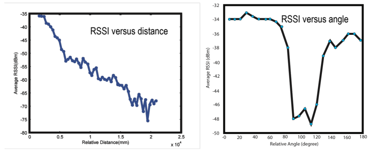
The resilient control architecture and wireless networking technologies will be evaluated on an indoor multi-robot testbed consisting of a heterogeneous mobile robots communicating over an M2M wireless communication network. The testbed consists of both autonomous unmanned ground (UGV) and aerial vehicles (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 component consists of ActivMedia Pioneer robots with acoustic proximity sensors and gyro-corrected wheel encoders for odometry.

Low-level robot motion control is programmed using a set of C++ classes developed by ActivMedia. On-board PC has been added to each robot to implement coordination algorithms among robots that communicate to each other over either an Xbee or M2M radio.

Leader-follower formation controls have been realized using these robots. Experiments involve leader-follower formation control have been conducted to investigate the impact wireless channel burstiness on performance. These experiments help calibrate channel models relating RSSI and dropout rates back to the formation's physical states.



Notre Dame Aerial Quadrotor Testbed

For the UAV component of the testbed, there are three quadrotors from Unmanned Dynamics. Each quadrotor is equipped with microcontroller, IMU, pressure sensor and onboard GPS module. The quadrotor offers Xbee or Bluetooth communication to the ground station running on PC. 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 Xbee. Our current efforts include equipping these UAVs with M2M wireless networking components to enable inter-vehicle communication and realizing the proposed resilient hierarchical controllers

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