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Poster Abstract: Toward Fast Closed-loop Control over Multi-hop Low-power Wireless Networks

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ABSTRACT

We sketch our ongoing work toward the first design, implementation, and evaluation of a low-power embedded system providing reliable wireless feedback control of several distributed processes over multiple hops with update rates of 10 Hz or higher.

1 MOTIVATION

Distributed control and coordination are key to present and future cyber-physical systems (CPS), including smart materials, industrial automation, and swarming drones. To enable these applications, sensor readings and control signals must be exchanged using low-power wireless technology across dynamic multi-hop topologies. Closed-loop stability, however, often requires end-to-end communication delays below 100 ms and sub-percent packet drop rates. Moreover, non-trivial control logic must run on constrained embedded devices, and the entire system must quickly adapt to dynamically changing application demands and operating conditions.

Prior work on closing both the forward and feedback direction over a wireless network has targeted different design points. Low-power wireless solutions exist for processes with slow dynamics requiring end-to-end delays of tens of seconds [2, 6]. Solutions for fast dynamics requiring delays of tens of milliseconds have also been demonstrated, but only in a single-hop low-power wireless network [3] or using power-hungry technologies offering higher data rates, such as Wi-Fi [10]. This, however, leaves open a significant need for a wireless closed-loop control solution that can truly support emerging CPS that require short end-to-end delays and energy efficiency in the face of application and network dynamics.

Our work thus seeks to answer the following research question: Can we design a low-power embedded system for reliable wireless feedback control of several distributed processes over multiple hops with update rates of 10 Hz or higher? A positive answer would enable a number of novel application scenarios. How to design such system is, however, a non-trivial task and requires addressing at least the following three key challenges:

(1) efficient, adaptive, and reliable wireless many-to-many communication with small, predictable delay and jitter;
(2) controller design robust to network imperfections (packet drops, etc.), adaptive to system dynamics, and amenable to an implementation on constrained embedded devices;
(3) stability and performance guarantees for the entire CPS, including physical process, communication, and control.

In this poster abstract, we report on our work toward the first design, implementation, and evaluation of a wireless closed-loop control system that addresses all the above challenges.

2 SYSTEM OVERVIEW

Our design targets distributed CPS, where application tasks execute on a multi-hop network of wireless embedded devices and exchange messages with one another. A CPS with periodic feedback control executes a sequence of three application tasks that repeats indefinitely: sensing, control, actuation, etc. These tasks exchange sensor readings and control signals. There may be multiple control loops running in the network, and different tasks may execute on the same device or on different devices.

We solve challenge (1) with a time-triggered approach; that is, all system components are time-synchronized, and all task executions and message transfers are globally co-scheduled to minimize end-to-end delay [9]. Specifically, every device is a dual-processor platform, where an application processor (AP) executes tasks, and a communication processor (CP) executes a modified version of the Low-Power Wireless Bus (LWB) [7]. LWB maps every message transfer onto a Glossy flood [8], which disseminates the message to all other CPs in the network with a high reliability above 99.9 % and within a bounded time of a few milliseconds. LWB also synchronizes all CPs with sub-microsecond accuracy, and every AP locally synchronizes to the attached CP. Using the Bolt interconnect [11], AP and CP can also exchange messages within a bounded time.

To solve challenge (2), we design a feedback controller that respects the characteristics of the above wireless networking solution. The basis forms a linear quadratic regulator (LQR), which yields optimal control for linear process dynamics [1]. We augment this LQR to account for communication imperfections. In particular, the approximately constant end-to-end delay is compensated for by predictions based on a mathematical model of the physical process. Similarly, the effect of packet drops, which can be considered approximately i.i.d. in Glossy [14], is attenuated through such predictions. Moreover, the inherent capability of many-to-many communication using LWB enables effective and efficient distributed control similar to other solutions relying on a shared bus [12, 13].

The properties of the communication system and the dedicated control design allow for a formal stability proof for the overall CPS using well-known techniques [5], thus solving challenge (3).

3 PRELIMINARY EXPERIMENTS

We run experiments using the setup illustrated in Fig. 1. It consists of a cart-pole system as an example physical process, which is remotely controlled over a multi-hop low-power wireless network.

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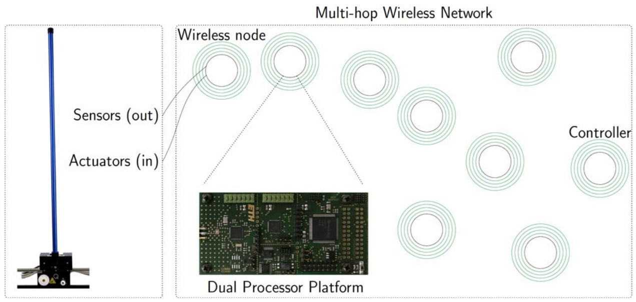

Figure 1: Setup for our preliminary experiments. A cart-pole is stabilized across a three-hop low-power wireless network consisting of nine embedded devices.

Remote controllers can be found in many real-world scenarios; for example, in factory automation the control logic for the process plants often runs on a remote computer. Using horizontal movements of the cart, the pendulum can be stabilized in the upright position ($\theta = 0°$), which represents an inherently unstable equilibrium. The cart-pole system is a challenging benchmark problem with fast and nonlinear dynamics [4].

For our experiments, we use nine devices forming a three-hop network. Each device has as CP a TI CC430 running at 13 MHz and transmitting with a sub-GHz 250 kpbs radio, and as AP a TI MSP432 ARM Cortex-M4F running at 48 MHz. One node is attached to the pendulum and one remote node acts as controller. The controller receives sensor readings of the process over the multi-hop network, computes control signals based on this input, and sends the control signals back to the process over the network. The end-to-end communication delay is 80 ms, and the sampling interval is 40 ms.

The results are shown in Fig. 2. We see that the pendulum deviates most of the time no more than $\theta = 3°$ from its desired position, while the cart also stays in its allowable range of ±25 cm. Moreover, the control input u is well within its limits of ±10 V, meaning that it operates in a safe regime. We thus conclude that the controller is able to stabilize the pendulum despite occasional packet drops and an end-to-end delay of 80 ms. All control computations (including model-based predictions) are executed on the AP in about 1 ms.

4 CONCLUSIONS AND FUTURE WORK

Many emerging CPS rely on fast, distributed control and coordination over multi-hop low-power wireless networks. We have presented our initial design and evaluation of the first low-power embedded system that can reliably control several processes over multiple hops with update rates of 10 Hz or higher. Our design allows for a formal stability proof, and preliminary results show that it is applicable to a challenging control problem while smoothly handling packet drops and delays. Future work includes experiments with several processes and multiple control loops with different requirements in terms of packet drops and end-to-end delay.

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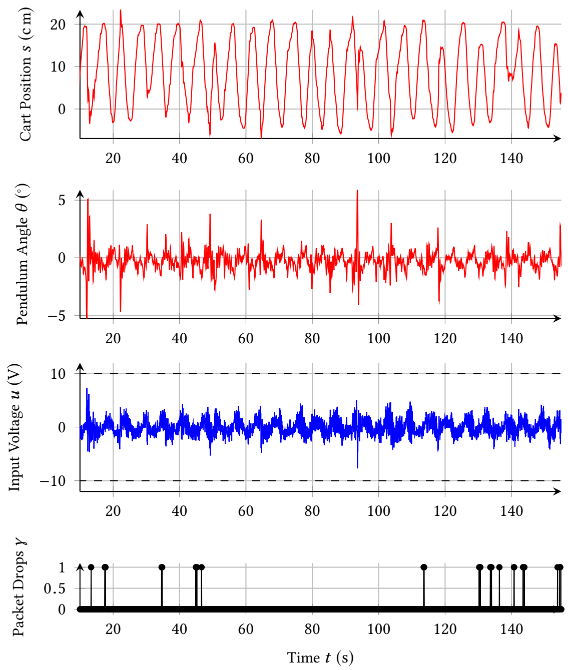

Figure 2: Results from a multi-hop experiment showing over time, from top to bottom, the cart position s, the pendulum angle θ, the control input u with its maximum and minimum values of ±10 V (dashed lines), and the packet drops over wireless γ ($\gamma = 1$ indicates a lost packet). Our design stabilizes the pendulum despite network imperfections.

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