Inverted Pendulum Control over an IEEE 802.15.4 Wireless Sensor and Actuator Network

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***Abstract*—Recent research efforts are considering the problem of performing control of dynamical systems over wireless sensor and actuator networks. However, existing results lack an experimental evaluation in real platforms. In this demonstration an inverted pendulum system is controlled over an IEEE 802.15.4 wireless sensor and actuator network. This platform can evaluate several sensor networks and control algorithms and is currently used as an educational tool at KTH Royal Institute of Technology, Sweden.**

I. Introduction

Recently, control systems are operated over large-scale, networked infrastructures. The use of wireless communication technology provides major advantages in terms of increased flexibility, and reduced installation and maintenance costs. By considering these advantages, several vendors are considering merging sensor devices with low-power wireless sensor networks (WSNs) for industrial automation and process control. While WSNs have been widely analyzed and deployed to extract information from the physical world [1], actuation over wireless networks is still taking its first steps and demonstrations of its use in real-time control systems have not yet been considered.

When wireless communications are used to perform sensing and actuation tasks in a control system several issues arise which may not allow the controlled process to maintain a required level of performance or even remain stable. These issues are mainly given by the limited bandwidth, information loss and delays. In a control theory perspective, many solutions have been proposed to deal with a probabilistic communication behavior with losses and delays, when performing control but this is still the scope of current research under the topic of Networked Control Systems (NCSs) [2]. From a sensor network point of view we notice increasing research on the protocol design of Medium Access Control (MAC) to deal with losses and delays for control systems [3]. Few protocols, TSMP [4] and WirelessHART [5] have been devised, which design the MAC and routing layers for industrial automation. Most of these protocols achieve high reliability based on scheduling the network resources, but no latency guarantees can be made. All these approaches consider the IEEE 802.15.4 [6] as the physical layer.

In this demonstration, we show how sensing and actuation of a real-time system can be performed over low-power a wireless sensor and actuator network (WSANs). The experimental setup consists of an inverted pendulum system closed over a IEEE 802.15.4 WSAN as depicted in Fig. 1. In particular, a slotted mode of CSMA/CA algorithm of the IEEE 802.15.4 Standard is used and a Linear Quadratic Gaussian (LQG) is implemented at the microcontroller in order to perform a suitable sensor estimation and control of the inverted pendulum system. The Telosb platforms are used for sensing and actuation and a Zolertia mote is used for computation of the controller, both running the TinyOS operating system. The proposed demonstration system can be seen as a platform for validation of NCSs developments both from a pure control theory side but also from a sensor networks perspective. The inverted pendulum system is currently being applied in a large network where several other systems such as coupled water tanks and a 3 degree-of-freedom crane, are controlled over the same sensor and actuator network. In this network we investigate the performance of different MAC and routing protocols, but also how new control theory such as event-based control can be implemented in a WSAN context. This setup is also being used as an educational platform for two courses on Automatic Control and Hybrid and Embedded Control Systems, at KTH Royal Institute of Technology, Sweden.

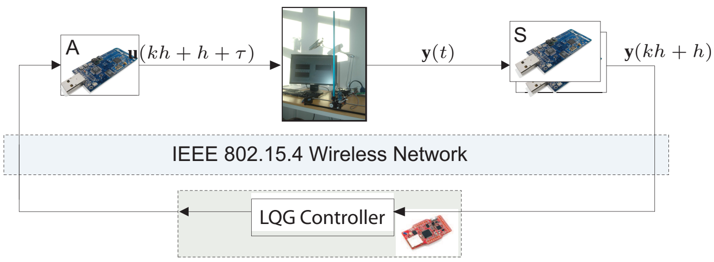
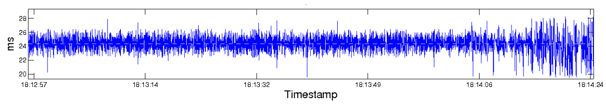


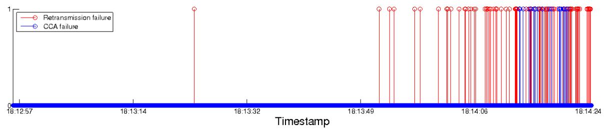
Fig. 1: Wireless Inverted Pendulum System

II. System Design

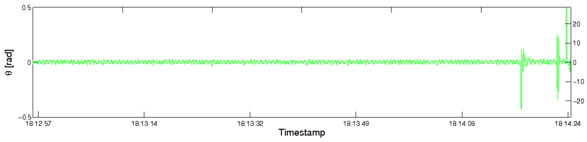
The inverted pendulum system is composed of a cart that can moved by a 6V DC motor in a track and carries a pendulum that freely rotates over the cart's axis of motion. The cart position and pendulum angle of rotation is measured by two incremental encoders which are interfaced with a Telosb mote through a digital counter using serial port interface (SPI) communication. The actuation of the cart is made by another Telosb mote connected to an amplification circuit which controls the DC motor and makes the cart move in the track in order to keep the pendulum in an upright position and not allow it to fall. A Zolertia Z1 mote is used to compute the control input to be sent to the actuation mote.



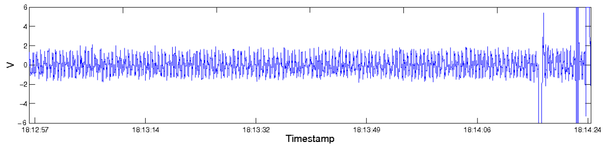
(a) Time between packets for pendulum angle



(b) Packet loss: Retransmission and CCA failures



(c) Angle θ of the pendulum



(d) Control voltage applied to the cart motor

Fig. 2: Network and Inverted Pendulum system analysis.

The MAC layer implementation of the IEEE 802.15.4 standard is made in TinyOS and follows the TKN15.4 [7] beacon-enabled design. The Zolertia Z1 motes are equipped with the new MSP430f2617 microcontroller (MCU) running at 16MHz which is twice as fast as the Telosb nodes. Since an LQG controller needs to be implemented at the controller node and several mathematical operations are required, a faster MCU is an advantage and so we chose to use the Zolertia Z1 for that purpose. For more details on the characteristics of the Telosb and Zolertia Z1 motes see [8], [9].

A separate circuit board is developed to interface the incremental encoders to the motes, where a digital counter LS7366R stores the number of encoder rotations and upon request, sends the data over SPI to the wireless node.

The rotation value for the cart position is translated into centimeters and the pendulum angle into degrees and sent over the wireless link to the controller mote where the control input $\mathbf{u}$ is calculated. The control input is then sent to another mote connected to the inverted pendulum. The sensed values $\mathbf{y}$ are transmitted periodically at every h ms. From the sampling instant until actuation in the actuator side there is a delay τ due to communication and computation time. The influence of the delay in the dynamical system can be compensated by suitably designing the LQG controller. Due to space limitations, the details on the controller can be found in [10].

Furthermore, we consider an interference node which induces stochastic packet losses and delays in the network transmissions. This node will periodically send messages in the same channel as the sensor nodes causing the channel to be busy and possibly generate packet collisions.

III. Evaluation

Fig. 2 presents the performance evaluation of the wireless network and the control system. In order to monitor all these parameters we deploy a special sensor node which is responsible for acquiring all the transmitted packets and log their data. Fig. 2b shows a snapshot of the packet loss on the wireless network. Furthermore, the inter-arrival time for each sensor packet is also measured which greatly influences the control of the inverted pendulum and is depicted in Fig. 2a, for the pendulum angle sensor. In the control side we evaluate the sensed pendulum angle, shown in Fig. 2c, and the cart position. Moreover, Fig. 2d shows the evolution of the control input as given by the LQG controller for the measured cart position and pendulum angle.

The sensors sampling period is selected as $h = 32$ms and the delay $\tau = 50$ms.

In Fig. 2, we consider three different scenarios of the network setup during 1min and 30sec of evaluation of the inverted pendulum system, which starts at 18:12:57. Up to 18:13:49 no interference is present in the network and a high control performance is achieved. After 18:13:49 an interference node is placed in the same network which transmits packets in the same channel as the sensor nodes with an inter-transmission period of 100ms which induces losses in the cart position sensor mote. However, the effect of these losses are negligible to the control performance of the inverted pendulum. At 18:13:55 the interference node is set to transmit a packet at every 10ms, which significantly increases the packet losses of the network. As a result of the losses in the pendulum angle sensor, the control performance degrades and at 18:14:22 the pendulum falls.

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