Demo: Closed-Loop Control over Wireless – Remotely Balancing an Inverted Pendulum on Wheels

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ABSTRACT

Achieving closed-loop control over wireless is crucial in realizing the vision of Industry 4.0 and beyond. This demonstration shows the viability of closed-loop control over wireless through a high-performance wireless solution. The closed-loop control problem involves remote balancing of a two-wheeled robot that represents an inverted pendulum on wheels.

KEYWORDS

Balancing robot, closed-loop, inverted pendulum, wireless control.

1 INTRODUCTION

Closed-loop control or feedback control is one of the most prominent industrial control applications [2]. Typically, closed-loop control takes place between a controller and a spatially distributed system of sensors and actuators. Closed-loop control represents a networked control system wherein control and information packets are exchanged over a shared medium thereby closing a global control loop.

Closed-loop control poses significant challenges to the underlying communication network. First, it demands real-time connectivity with very low latency and very high reliability. Second, it involves bi-directional information exchange with cyclic traffic patterns which requires highly deterministic connectivity, i.e., communication latency between cycles must have very low variance. Third, the presence of a large number of sensors and actuators creates the requirement of highly scalable connectivity.

In legacy industrial applications like factory automation, closed-loop control is realized through wired connectivity technologies like fieldbus systems or industrial Ethernet. However, wired connectivity incurs high installation and maintenance costs. Moreover, it is not suitable for many new industrial closed-loop control applications like formation control of automated guided vehicles, highway platooning and collaborative remote operation which are characterized by the requirements of mobility and flexibility.

To this end, the main objective of this demonstration is to show the viability of real-time closed-loop control over wireless. We consider the case of remotely balancing a two-wheeled robot that represents an inverted pendulum on wheels. We leverage a high-performance wireless technology, known as GALLOP [3], [1], developed in our previous works and specifically designed for meeting the stringent requirements of closed-loop control.

2 DEMONSTRATION OVERVIEW

The inverted pendulum is a classic closed-loop control problem in control theory and widely used in benchmarking control strategies. The inverted pendulum is naturally unstable without active control. A two-wheeled robot actually depicts an inverted pendulum on wheels. Conventionally, such a robot balances itself through an onboard closed-loop control algorithm based on wired connectivity between a controller and one or more sensors/actuators. Our objective is to realize such closed-loop control over wireless. The demonstration scenario is illustrated in Fig. 1. We decouple part of the overall balancing functionality from the robot such that the balancing algorithm runs in a remote controller which communicates with the robot over wireless.

3 DESIGN AND IMPLEMENTATION

3.1 Balancing Robot

We use the Balboa 32U4 balancing robot by Pololu[1] that is both programmable and customizable. Its control board is built around an Atmel ATmega32U4 AVR microcontroller. The control board features two H-bridge motor drivers, quadrature encoders and a complete inertial measurement unit (IMU) comprising a 3D accelerometer, a 3D gyro and a 3-axis magnetometer that allows it to determine its orientation. The robot uses two micro metal gearmotors to drive external 2-gear gearboxes. Our robot uses 80 x 10 mm wheels.

3.2 Balancing Algorithm

The balancing functionality is achieved through a proportional-integral-derivative (PID)-like feedback control algorithm. The key to remotely balancing the Balboa robot is the nine sensors pertaining to the IMU that provide a sense of its orientation in 3D. On the forward channel, the robot sends the orientation information along with the encoder values to the wireless controller. The balancing algorithm computes robot's rate of rotation and sends updated motor speed on the feedback channel. The remote balancing operation is illustrated in Fig. 2.

[1]https://www.pololu.com/

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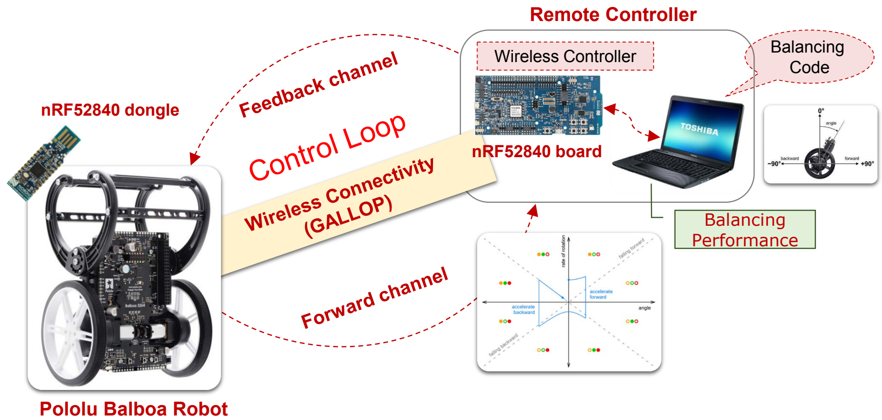

Figure 1: Closed-loop control scenario and configuration.

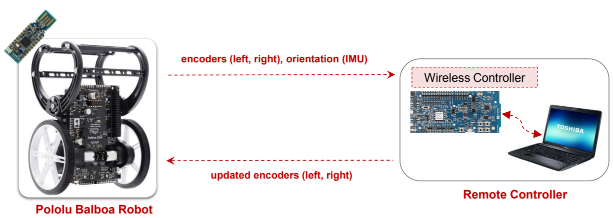

Figure 2: Illustration of remote balancing operation.

3.3 Wireless Design

The demonstration employs GALLOP as the underlying wireless technology for communication between the robot and the remote controller. GALLOP has been specifically designed to account for the peculiarities of closed-loop control. The medium access control (MAC) layer of GALLOP is based on time division multiple access (TDMA), frequency division duplexing (FDD) and frequency hopping. GALLOP provides very low and deterministic latency which is required for closed-loop control. GALLOP also implements a number of techniques for achieving very high reliability. GALLOP implements a flooding-based protocol for time synchronization [4]. Our GALLOP implementation is based on the 2 Mbps Physical (PHY) layer of the latest Bluetooth 5.0 standard. We have implemented GALLOP on the Nordic nRF52840[2] platform. The robot is equipped with an nRF52840 dongle.

3.4 Performance Evaluation

We quantify the balancing performance in terms of robot's forward/backward rate of rotation in degrees. As shown in Fig. 3, balancing performance over GALLOP shows a deterministic behavior with minimal rate of rotation. To achieve accurate balancing performance, the cyclic latency of the control loop should be less than 10 ms. With GALLOP, the communication latency is approximately 2 ms which provides sufficient margin for processing overheads and software delays. The competitor depicts a standard Bluetooth 5.0 protocol with minimal possible communication latency of 7.5 ms. As shown in the results, this leads to non-deterministic behavior with larger rate of rotation. A video of the demonstration is available at https://www.dropbox.com/s/le1r851dl1gzpvl/Balancing_Robot.mp4?dl=0

[2]https://www.nordicsemi.com/Products/Low-power-short-range-wireless/nRF52840

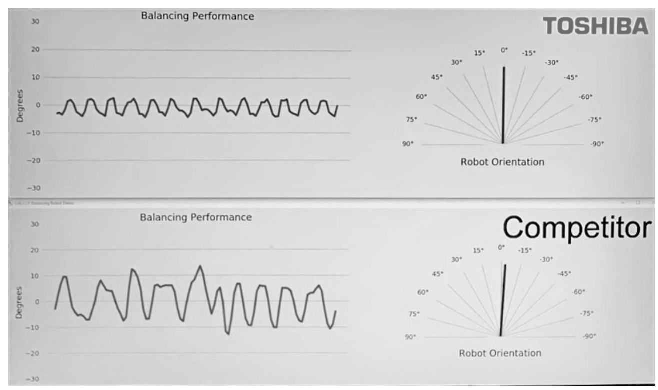

Figure 3: A snapshot from the demonstration showing balancing performance.

4 REMARKS

Achieving closed-loop control over wireless is crucial in realizing the envisioned transformation of industrial systems. This demonstration reveals that the stability of closed-loop control over wireless is heavily dependent on deterministic as well as low latency of the underlying communication technology.

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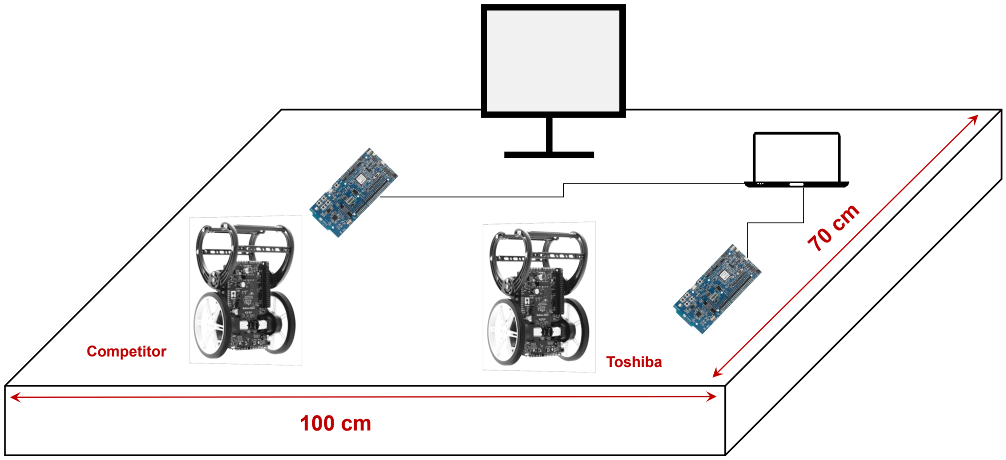

Figure 4: Layout of the demonstration.

APPENDIX

The demonstration requirements are highlighted in Fig. 4. A desk with approximate dimensions of 100 cm x 70 cm is required to display the following hardware components.

- 2 Pololu Balboa 32U4 balancing robots.
- 2 Nordic nRF52840 wireless modules.
- 1 monitor/display (to be provided by demo chairs).
- 1 laptop.