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# Low-power, modular, wireless dynamic measurement of bicycle motion

Dale L. Peterson[a,*], Jason K. Moore[a], Danique Fintelman[a,1], Mont Hubbard[a]

[a]*Sports Biomechanics Lab, University of California Davis, Davis, CA, 95616, USA*

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## Abstract

A low power, light-weight, and modular system of sensors and data acquisition hardware was developed to measure the configuration, velocities, and accelerations of a bicycle. Measurement of angular velocity of the bicycle frame, acceleration of three points fixed to the frame, steer angle, and wheel spin rates is implemented. Measurements will be compared with dynamic models of the bicycle and human rider in order to assess model fidelity. In this way, we hope to 1) better understand how humans control bicycles, and 2) pave the way for bicycle design improvements based on quantitative and relevant dynamic measurements.

*Keywords:*
bicycle dynamics, instrumentation, wireless data acquisition

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## 1. Introduction

Accurate measurement of the bicycle parameters and dynamic variables is crucial for experimental validation of dynamic models. They include two angles (lean and steer), six angular rates (3 body-fixed rates of the frame, steer rate, and the two wheel rates), and the time derivatives of these six angular rates. By measuring or estimating each of these quantities, direct comparison with the equations of motion is possible.

A significant challenge of this measurement task is to allow for a small, unobtrusive solution which doesn't interfere with normal cycling or affect the dynamics significantly, yet is still capable of accurate measurement. Various approaches for experimental validation of bicycle models have been taken. In a CALSPAN study by Rice and Roland [1], the design parameters associated with the bicycle motion in the longitudinal plane were studied by performing a variety of typical bicycle maneuvers. One of the main conclusions was that short wheelbases and front

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[*] Corresponding author
*Email address:* `dlpeterson@ucdavis.edu` (Dale L. Peterson)
[1] Visiting intern at Sports Biomechanics Laboratory, January - April 2010

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brakes can be hazardous. In another CALSPAN study by Roland and Lynch [2], extensive efforts were made to develop a rider control model, perform bicycle tire testing, develop a computer graphics simulation, and to perform measurements of the bicycle during common maneuvers. Steer angle, roll angle, lateral frame acceleration, and forward speed were measured. Kooijman et al. [3] compared weave modes estimated from time histories of measured roll rate to weave modes predicted by thoroughly verified linearized equations of motion [4], and found that the model eigenvalues matched experimental ones reasonably well for low speed maneuvers (0 – 6 m/s).

The bicycle used in our experiments serves two purposes: 1) to validate dynamic bicycle models with both rigidly attached rider (as in [4]) and permitted to lean their upper body (as in [5, 6]); 2) to develop and validate dynamic control models of the human rider. The former purpose requires experiments be conducted *without* a human rider, so some basic stabilization and tracking control capabilities are needed, but autonomous operation is not. Here, actuation will be provided by use of electric motors for steer, rider lean (mimicked by an inverted pendulum on bicycle frame), and the rear wheel. The latter purpose requires that the bicycle be humanly rideable.

With the advent of smaller dynamic measurement technologies, it is now possible for a much more detailed measurement of the dynamic bicycle state. For example, 3-axis accelerometers, weighing less than 2.0 grams, with built-in 12-bit analog-to-digital conversion, capable of measuring ±2.0g are now available for less than $10 US. The case is similar for rate gyroscopes and optical encoders to measure the angular velocities of the frame, fork, and wheels. These measurements will allow for detailed validation of mathematical models through *direct* comparison of measurement with simulation. For example, by accurately measuring the wheel spin rate of *both* wheels, the hypothesis that the wheels roll without slip can be quantitatively tested by determining to what degree the measurements satisfy the nonholonomic constraints associated with the no-slip rolling assumptions. These types of validations have yet to be performed in the bicycle research community.

## 2. Materials and Methods

### *2.1. Overview*

The measurement system is implemented with sensors connected to a two wire ($i^2C$) sensor network; each sensor can be considered a slave device which responds to the commands of the master. Analog to digital conversion is performed immediately adjacent to each analog sensor to minimize effects of noise, and the digital representation of the measured signal is then made available on the $i^2C$ network in the form of a 2-byte integer. An Arduino [7] electronics prototyping board with an AVR micro controller [8, 7] was used for as the master $i^2C$ device and requests measurement from each sensors. Each set of sensor measurements is sent via the Arduino serial port to an XBee-PRO®wireless module (Digi International®), which then sends the measurements wirelessly to a PC with a mating XBee-PRO wireless module. The $i^2C$ sensor network is capable of 400kbps, while the wireless module is capable of 250kbps. This is more than adequate for our system because even in the case of 32 sensors (we use 20) at 16 bits per sample, a 100Hz sampling frequency would result in a data rate of 51.2kbps, drastically less than the network bandwidth.

Once wirelessly transmitted to the PC, the measurements are read from the serial port into the GUI. This allows for real time visualization of every measurement, and for quick verification