Aerocoach

A technology innovation journey

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The Need For Cycling Sensors

Competitive cycling is highly data-driven, with accurate and accessible sensors widely used to optimize athlete performance. Power meters, speed sensors, and heart rate monitors are common tools cyclists use to support their training. Although a collection of these sensors can provide meaningful information regarding a rider's physical and physiological states, there is currently no commercial solution to measure and link aerodynamic factors to rider physiology in real-time.

Value Proposition

The original goal of the project was to develop a simple CdA sensor, called Cyclaero, telling users their coefficient of drag in real-time. As we progressed through the project and completed more testing we realized that just telling users their drag value was not the most valuable to improve rider performance. There is a trade off between how aerodynamic the rider is (bending towards the handle bars) and how much power they are able to put out. The fastest position is not always the most aerodynamically efficient position.

We set out to develop a full system, called Aerocoach, that would coach users into the optimal position to go the fastest for the least physical effort in real-time under changing road conditions. This optimal position is often counterintuitive, and over time this coaching would teach athletes to ride more efficiently.

The CdA measurement component of the device will be useful for teams and individuals who want to quickly understand the aerodynamic effects of position changes, on the rider's body, where 90% of drag incurred by a cyclist occurs. The ability to suggest position changes based on the real-time road conditions is a feature that does not exist in any product, and would be a new piece of information for cyclists.

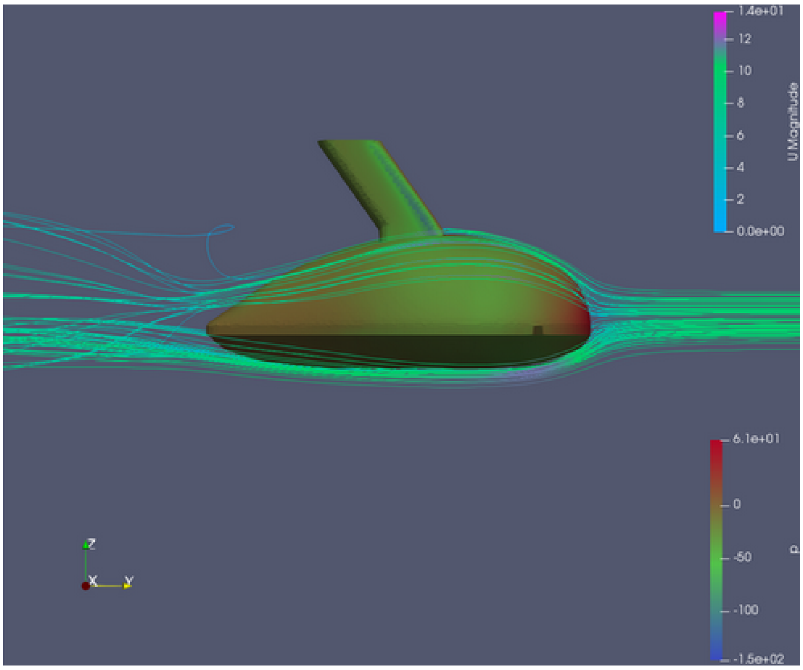
Our goal with Aerocoach from the outset was to create a device that demonstrated the value of real-time position coaching, and license the technology to interested industry leaders. Our industry partners would bring manufacturing, distribution, and marketing capabilities far beyond our reach.

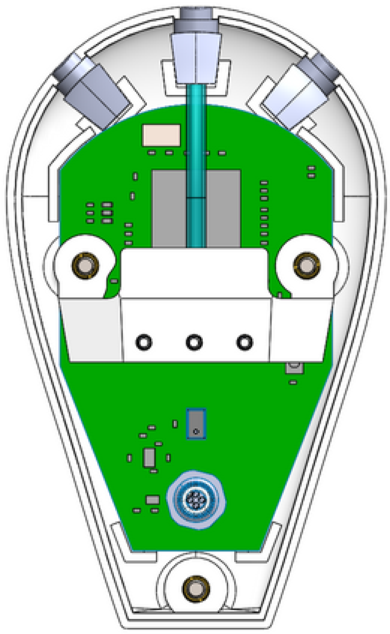
Early Prototyping

Nacelle Module

The Nacelle is a sensor module with the core function of measuring wind speed as accurately as possible, in conditions experienced while cycling. One breakthrough was the inclusion of a multiport design, which enables the sensor to measure airspeed at high degrees of yaw. CFD simulations were used extensively to predict the behavior of various designs in cycling wind conditions.

Other design considerations early in the Nacelle life cycle included finding a stable reference static pressure measurement and resolving turbulence caused by case features. A notable challenge during early prototyping was simulation validation and device calibration. In order to overcome these issues, Motus built their own in-house wind tunnel to validate design choices.



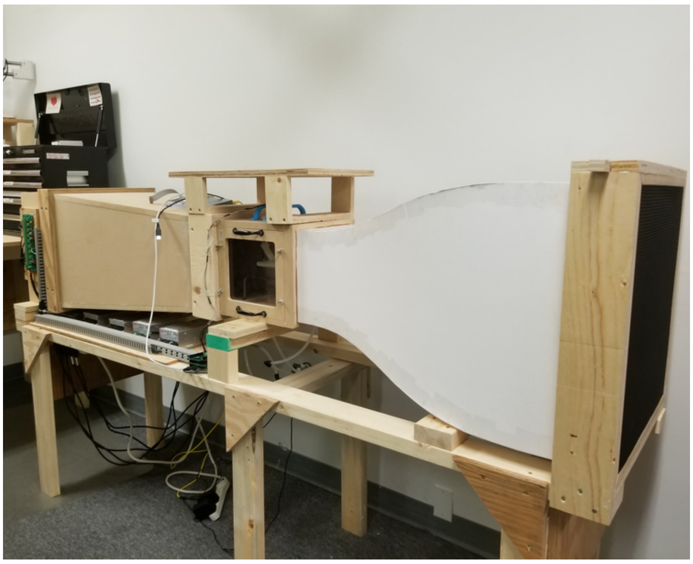


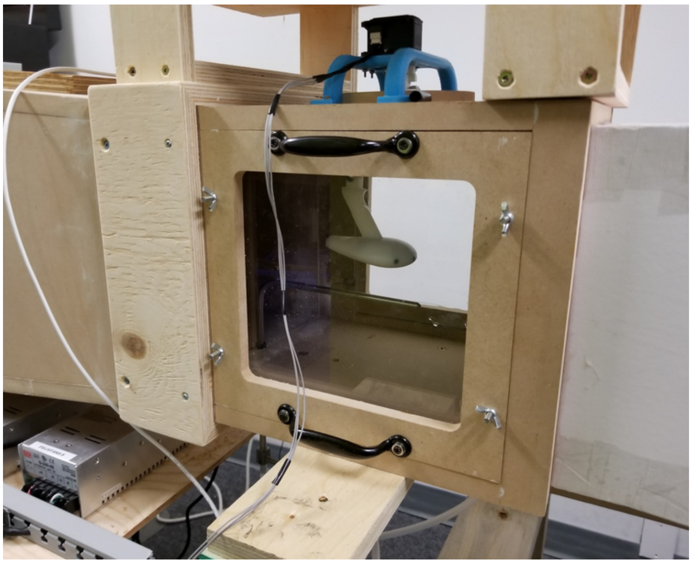
Wind Tunnel

Commercially available wind tunnels are not designed to operate in the range of cycling air speeds (15-60 km/h). In order to get high quality air speed testing in that speed range, a custom built wind tunnel was rapidly designed and fabricated in the Motus lab.

The wind tunnel captures reference wind tunnel airspeed, as well as measurements from the device, with synchronized time across all data output. The build consists of nine variable speed fans, an air intake channel, testing section with a variable angle mount, pitot tube, static pressure sensors, and a diffuser. The physical specifications of the apparatus are designed to simulate real-world conditions for the cycling aero-sensor (wind speeds 15-60km/h and ±30° Yaw).

The final product provides a flexible system that allows Motus to characterize air pressure sensors and verify wind speed measurements on the device.





Early Prototyping

AC Module

The AC module is an attachment designed to detect the body position of the rider. A requirement for the module is the ability to reliably measure the profile of the rider's torso while riding in all weather conditions, from bright sun to rain. Recent development in time-of-flight (TOF) sensor technology allowed us to use these light-based sensors to capture a small array of distance measurements along a rider's torso.

To ensure the field of depth measurements would work for cycling our application, we went through a range of tests on a development unit we designed and built. The development unit allowed us to experiment with locations, angles, materials, and lighting conditions to ensure we were getting the best measurements possible.

All of the information we gathered went into the design of the final AC module. Much sleeker than the development unit, it is intended to hold a bike computer and the Nacelle on an out-front handlebar mount. Three TOF sensors are arranged to capture the full torso and head of any rider up to 6’6” in height.

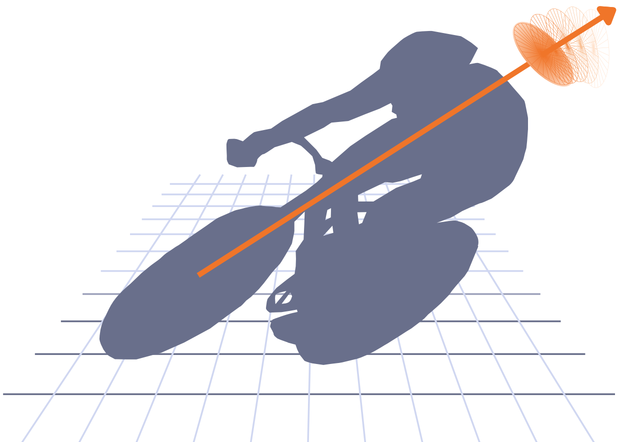
Cornering Orientation

When a cyclist rides through a corner at speed, the full bike and rider system experiences centripetal acceleration and the orientation of the cyclist changes as they bank into the corner. This presents a number of challenges for measuring active acceleration and the air speed that the cyclist experiences at their center of drag, as compared to at the wind sensor. The key challenges are identifying the orientation of the cyclist moving through the corner, and isolating for forward acceleration.

Classical orientation algorithms use a 6 or 9 axis Inertial Measurement Unit (IMU) coupled with a quaternion based gradient descent algorithm to solve for orientation. This method is highly reliable only if there are minimal active accelerations. These algorithms use the net acceleration as the gravity vector to adjust for any gyro bias that may exist. When the cyclist is actively cornering, the resolved acceleration direction gets skewed in the direction of the centripetal acceleration.

To account for these unique challenges, we developed our own quaternion based orientation algorithm. This method relies on the same gradient descent approach, but is adaptive to the current road conditions. When the magnitude of the gravity vector increases above 9.8 m/s2 we conclude that the cyclist is actively cornering, and our adaptive filter weights adjustments based on the gravity vector much less heavily. In that time when cornering was occurring, we relied more heavily on gyroscope and magnetometer readings.

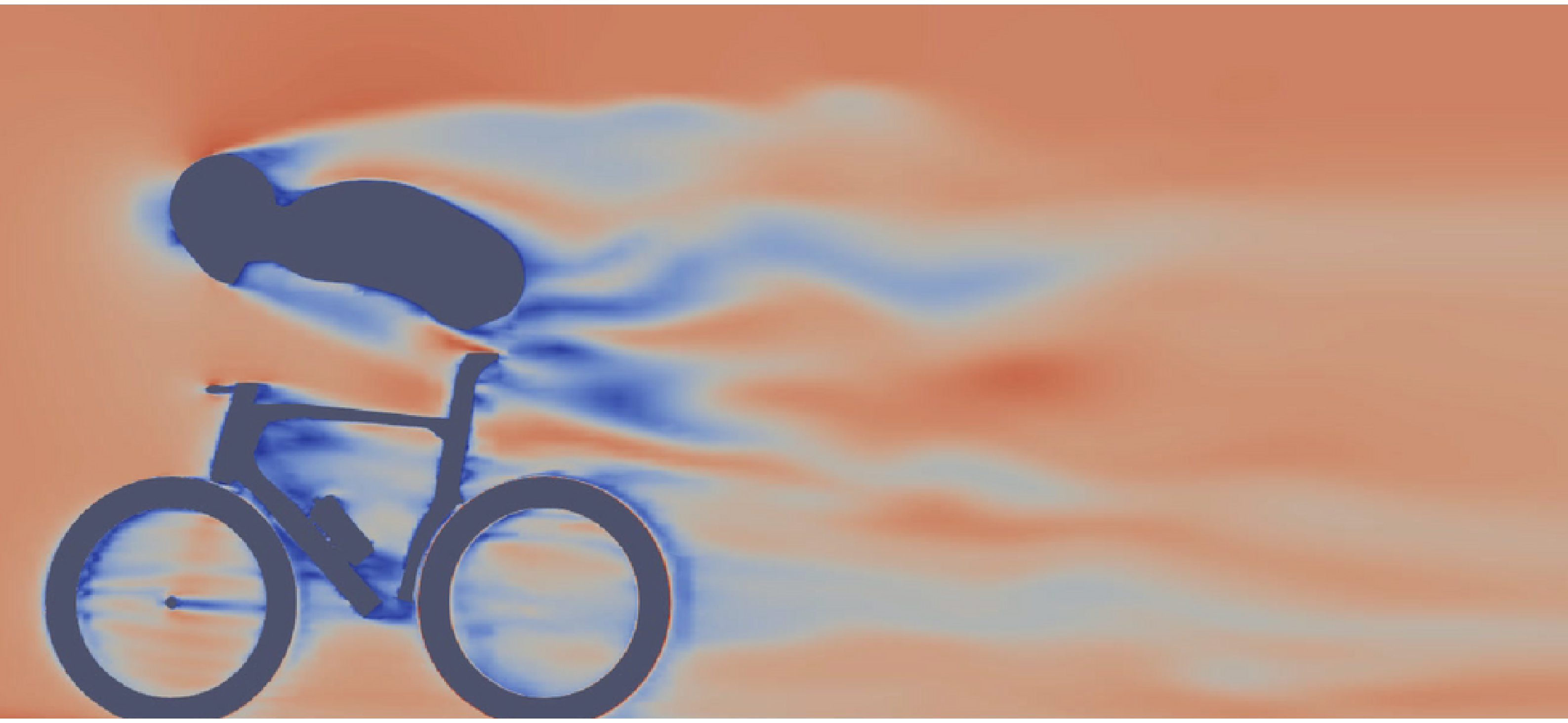
The result is a significantly improved orientation measurement through corners. After implementing the algorithm on the device firmware, we are able to identify the angle at which the cyclist is cornering and adjust our drag and wind speed formula in real-time.



Calculating CDA

The best approach to calculating CdA is not immediately obvious. The first assumption is to take the simple approach, take all of your state variables at each time step and solve the balance of energy equation for CdA. There are two issues with this approach. First is that there are two unknown variables in the balance of energy equation: CdA and Crr. Explicitly solving for both of these variables results in a very unstable system of equations. The second issue is that we are also measuring state variables through multiple sensors that operate on different fundamental frequencies; this means that we need to determine the best estimates to use at any given moment.

After experimentation, we found the Extended Kalman Filter (EKF) to be the best approach. The EKF can accept an arbitrary number of state measurements and produces an optimal estimate for both the CdA and Crr in real-time. The EKF is designed to work on non-linear systems and is highly tunable, which allows us to adjust the response of the filter to best fit our application. We have implemented our custom EKF in firmware on the device so that both CdA and Crr can be computed and sent to the head unit in real-time.

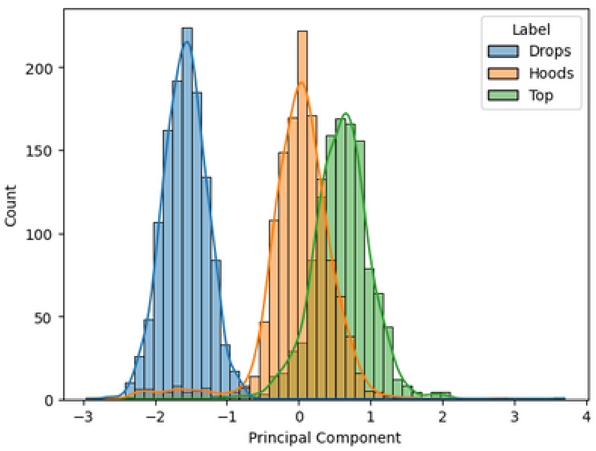


Sensing Body Position

Ability to identify body position is critical for determining a rider's optimal position. Labeling discrete positions allows us to group CdA and power measurements in order to determine how aerodynamically efficient and how much power an athlete can sustain over varying time durations. This forms the fundamental basis for body position recommendations to an athlete, given current cycling conditions.

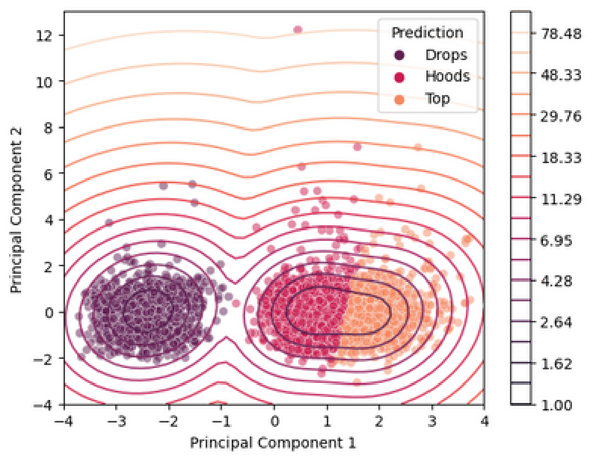
The Aerocoach system uses machine learning algorithms to estimate the rider's body position from input TOF sensor data. Datasets were collected from controlled lab settings and on local cycling roads. Body position models were trained based on discrete riding positions, where TOF values were interpreted using principal component analysis. Labels were applied to the dataset based on the location of the rider's hands: drops of handlebar, shifter hoods, and top of handlebar. A machine learning model was trained to predict the rider's position, based on Gaussian distributions of the principal components. The outputs of the model each have an associated CdA and power duration curve. Given the collection of these values, the Aerocoach system is able to use an optimization algorithm to make a coaching recommendation in real-time.

Principal Component Analysis



Principal component analysis of TOF data in different body positions

Gaussian Mixture Model



Negative log-likelihood predicted by machine learning model

"Drops" position

"Hoods" position

"Top" position

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Nacelle Module

The Nacelle module is the first module that was built and tested. It provides the wind speed measurement that is critical for the drag calculation, as well as acceleration, vertical velocity, temperature, and humidity. The Nacelle acts as the hub for communications between the various 3rd party devices and Motus Design modules. Low Energy Bluetooth (BLE) sensors communicate to the Nacelle, which uses a time synchronization protocol to ensure all the collected data is time aligned.

The Nacelle uses a three port design to accurately measure wind speed regardless of cross winds or gusting conditions. The profile of the case is designed to minimize drag, while also holding the battery, PCB, and internal tubing in place. The case can be removed from the bike with a sliding-lock mechanism to allow for easy charging of the battery between rides.

AC Module

The AC module uses three multi-directional TOF sensors to accurately measure the position of the cyclist's torso in 2D space. The angle and position of a cyclist's upper body is the largest factor in the total drag of the cyclist+bike system, and is also the variable that is most easily adjustable. The AC module allows us to learn and group rider positions as well as adjust EKF parameters to get a better CdA response if the rider changes positions.

Garmin UI

To allow for testing with a broader audience, we had to migrate the Aerocoach system from an internal data collection and display platform to something more widely available. Garmin head units are the standard in cycling, so we created a custom application on the Garmin IQ platform that would display and record data from the Aerocoach. This allows us to use the Aerocoach system with athletes' existing bike and computer configuration.

Usability of a test platform is critical when delivering to external testers, particularly athletes. If a system is not streamlined and usable, the athletes will simply not use the device. A custom layout was implemented on the Garmin application that gives a simple representation of wind speed and target body position for the athlete.


PLT
COMPACT
X2-001


GARMIN
X2-001


GARMIN


12:18
WIND
km/h
SPEED
km/h
VAM
m/h
AEROSMART
AVG SCORE
LOSING TIME
s/h
"id_user1"
"id_user2"
Body Position
Target
GARMIN
COMPACT
PLT

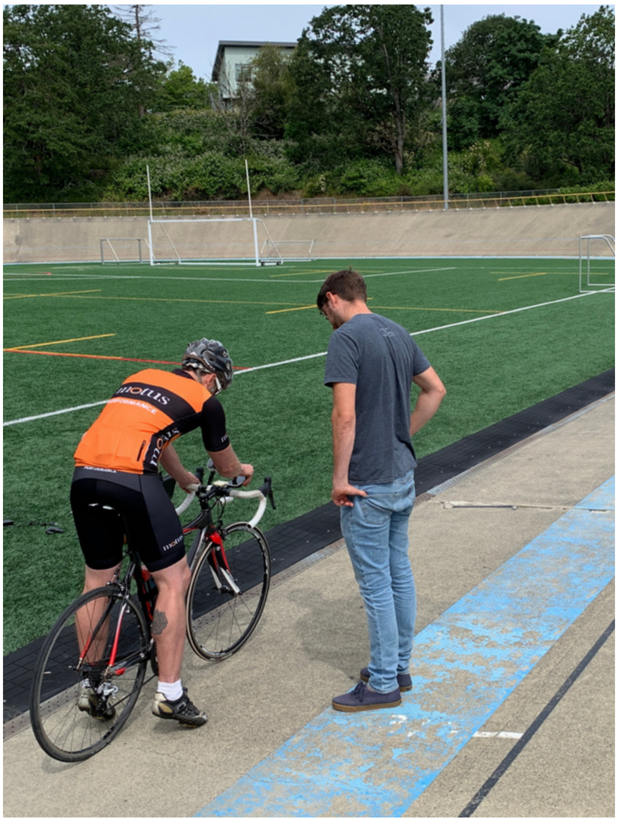
Velodrome Testing

The velodrome was chosen as the location for our first outdoor tests. The velodrome has no elevation changes, no obstacles that we need to brake for, and is sheltered from major winds. The repeatability of each loop makes it easy to see periodic errors or variations in measurements.

Through velodrome testing we were able to accurately evaluate the CdA of a rider for the first time. We were able to see variations in drag due to position changes, and could track the power losses due to drag in real time.

Velodrome testing allowed us to identify several areas for improvement and demonstrated difficulties we would face when moving to fully uncontrolled outdoor testing. The regular corners revealed the relative velocity differences between the rider's body and the wheels when going through a tight corner. Wind exposure revealed the static pressure variations that occur with differential wind speeds outdoors. Post analysis of results showed variable time delays coming in from the third party wheel speed sensor and power meter.

Velodrome Testing



Josh Erickson & Jeff Doyle performing field tests at Juan de Fuca Velodrome

On-Road Testing

A development Aerocoach unit was used with the Nacelle to gather data and run tests to inform algorithm development. We've logged over 50 test sessions, experimenting with how our device handles different road surfaces, weather conditions, cyclist body types and more. The result was a comprehensive dataset that we were able to use to develop a position grouping algorithm. We were also able to use the results to significantly improve our vertical velocity measurements and time alignment of all of our measured variables.

Completion

Ready for industry partners

The Aerocoach system is a completed, robust, preliminary product concept. The combined data from the Nacelle and AC modules, combined with 3rd party sensors allowed the Motus Design team to create a holistic cycling power model. The Aerocoach system can calculate drag in real time, evaluate and categorize body positions, collect power duration data, and give recommendations to riders based on the live conditions.

The future for the Aerocoach unit is in more testing. Collecting data on cyclists with a range of body sizes and athletic ability will allow us to improve the data models used for position classification and recommended position changes. Getting data over several months, by cyclists who are putting out a maximal effort over multiple training rides, will also ensure our models are flexible enough to account for physiology changes over time.

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Thank you.

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