

Design and Development of a Modular Open-Source Platform for Two-Wheeled Self-Balancing Vehicles

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Abstract—This paper presents a modular, open-source robotic platform designed for the study and development of two-wheeled single-tracked autonomous vehicles. Unlike proprietary or rigid systems, this platform utilizes a tubular frame architecture and 3D-printable components, allowing for non-destructive modification and rapid hardware iteration. We demonstrate the platform’s utility through a reaction wheel-stabilized configuration, introducing a control methodology that actively modulates the system’s balance point in response to actuator torque. The integration of SLAM-based navigation with this decoupled stabilization approach provides a robust foundation for research in dynamically unstable systems.

I. INTRODUCTION

Two-wheeled robotic platforms, often modeled as inverted pendulums, provide a practical medium for testing nonlinear control and autonomous navigation. However, developing a reliable hardware base for these experiments often requires significant design and fabrication time, which can detract from the primary focus of control or software research. Our design takes inspiration from the Cubli [1] for its use of reaction wheel balancing and builds upon the work of the Xuan bike [2], which successfully demonstrated a reaction wheel-based autonomous bicycle. This work presents an open-source, modular platform designed to provide a ready-to-build solution for studying these systems using easily accessible components and 3D-printed parts.

The defining characteristic of this platform is its structural modularity. Built upon a tubular frame, the design allows for the integration of sensors and actuators without drilling or welding. This non-destructive philosophy ensures that all additions can be moved or edited to suit specific research needs, effectively lowering the barrier to entry for complex robotics experiments.

While the hardware is designed for general research, this paper validates the platform through the implementation of reaction wheel-based stabilization. While reaction wheel-driven balance is an established concept, our work contributes a unique control strategy: the implementation of a high-frequency PD loop coupled with an adaptive outer loop. Instead of utilizing a standard PID controller, the outer loop dynamically shifts the system’s balance point in response to reaction wheel torque. This mechanism effectively serves the role of an integral term by eliminating steady-state error and desaturating the reaction wheel motor, shifting the equilibrium to counter persistent wheel rotation.

To support the reproducibility of this work and lower the barrier for experimental research, the complete platform is open-sourced. This includes the mechanical design files, the control software, and a full Bill of Materials (BOM) for the

under \$1000 bare-vehicle assembly, all of which are hosted on this GitHub repository [3].

II. SYSTEM DESIGN AND MODULARITY



Fig. 1. Complete physical assembly of suggested platform

A. Mechanical Architecture

The vehicle is designed around a high-rigidity tubular frame that serves as the primary mounting rail for all subsystems. To maintain the integrity of the frame for future reuse, all components—including the drive motors, sensor housings, and the reaction wheel assembly—are secured via 3D-printed friction-fit and bolted clamps. The reaction wheel itself is engineered with a rim-weighted geometry to maximize the moment of inertia while minimizing total mass, ensuring high stabilizing torque capacity without an unnecessary weight penalty. Furthermore, the assembly is designed to maintain structural integrity by withstanding the significant centrifugal stresses generated during high-speed rotation. This modular approach allows researchers to rapidly shift the center of mass of the vehicle or reconfigure the sensor layout without permanent structural changes.

B. Actuation and Internal Stabilization

For stabilization, the system incorporates a custom high-inertia reaction wheel driven by a 100KV high-torque brushless DC outrunner motor. Control is managed via an ODrive-based servo controller, enabling high-frequency torque modulation. This setup enables internal stabilization, which decouples the robot’s balance from its forward locomotion, providing stability even when stationary or at low speeds.

C. Sensing and Computation

The platform employs a distributed architecture to manage the competing needs of real-time stability and high-level autonomy. An STM32 microcontroller executes low-level control loops using filtered IMU data to maintain balance. For perception and navigation, a Jetson Orin Nano processes data from a 2D LiDAR and a stereo depth camera. Importantly, the stabilization computing for the reaction wheel is kept entirely separate from the navigation and autonomy stack, with each subsystem powered by separate batteries. This provides electrical isolation between the Jetson and STM32 and serves as a critical safety fail-safe; by decoupling balance control from the high-level system, the vehicle maintains upright stability even in the event of a software crash or high computational latency within the navigation layer. This separation also improves the modularity of the platform, making each subsystem easier to develop, test, and replace independently.

III. CONTROL MATHEMATICS AND DYNAMIC SETPOINT MODULATION

A. Inner Loop Control

The primary stabilization is managed by a high-frequency PD controller that regulates the reaction wheel torque based on the error between the current tilt angle and a reference setpoint. In this architecture, the setpoint is not a fixed constant; rather, it is a discrete-time variable updated by an adaptive outer loop. This design allows the platform to dynamically adjust its balance point, leveraging the average control torque to desaturate the reaction wheel during persistent disturbances.

B. Adaptive Setpoint Model

To handle systematic offsets and motor saturation, we use a three-stage adaptive update. First, compute the mean torque command $\bar{\tau}_n$ over N control ticks to filter high-frequency oscillations and capture persistent bias. Next, map this to a bounded correction using gain K_{outer} and slew-rate limit \dot{s}_{max} :

$$\delta_n = \max(-\dot{s}_{max}, \min(\dot{s}_{max}, K_{outer} \cdot \bar{\tau}_n)) \quad (1)$$

Finally, update the setpoint with saturation $\pm s_{max}$:

$$s_{n+1} = \max(-s_{max}, \min(s_{max}, s_n + \delta_n)) \quad (2)$$

This acts as a physical integrator driven by control effort, giving a clean estimate of persistent disturbances without the noise sensitivity or windup of traditional integral action.

IV. EXPERIMENTAL VALIDATION AND PERFORMANCE ANALYSIS

To evaluate the effectiveness of the modular hardware platform and the proposed dynamic setpoint control strategy, the vehicle was subjected to a series of stationary and dynamic balancing tests. The following data validates the system's ability to maintain stability while managing the internal energy states of the reaction wheel.

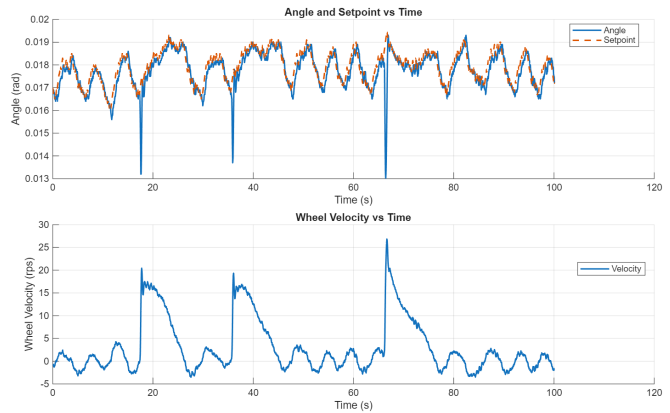


Fig. 2. Vehicle tilt θ and setpoint s_n (top) vs. reaction wheel angular velocity ω_{wheel} (bottom) during a disturbance recovery event.

A. Dynamic Balance and Reaction Wheel Desaturation

The primary objective of the adaptive outer loop is to prevent the reaction wheel from reaching its maximum angular velocity (saturation) during sustained lean angles or disturbances. Fig. 2 illustrates the relationship between the vehicle's tilt angle θ , the reference balance point s_n , and the reaction wheel's angular velocity ω_{wheel} .

As shown in the data, when a persistent disturbance is introduced, the inner PD loop initially commands a high reaction wheel torque to maintain an upright position, causing a rapid increase in ω_{wheel} . Subsequently, the adaptive outer loop begins nudging s_n in the opposite direction of the lean of the bicycle. This shift provides the necessary counter-moment, resulting in a measurable decay of ω_{wheel} toward zero while the tilt angle θ converges to the new equilibrium. This confirms that the system effectively significantly reduces steady-state error and recovers acceleration headroom.

V. FUTURE WORK AND CONCLUSION

Future research will focus on the implementation of a SLAM-based autonomy stack to improve environmental awareness. We intend to provide an open-source ROS2 autonomy stack to enhance the platform's utility. Additionally, the platform serves as a testbed for Reinforcement Learning (RL) for steering control. We plan to investigate how RL-learned behaviors can be blended with the existing reaction wheel stabilization logic. To support this, we will release simulation-ready Universal Scene Description (USD) files for training RL agents in high-fidelity environments.

This work presented a modular, open-source platform designed to lower the barrier for research into two-wheeled autonomous vehicles. Experimental validation demonstrated that the proposed dynamic setpoint modulation effectively desaturates the reaction wheel, allowing the system to maintain stability under persistent disturbances. By providing the complete mechanical design, bill of materials, and control software to the research community, this platform serves as a robust and cost-effective foundation for future developments in nonlinear control and autonomous navigation.

REFERENCES

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