Gear Up for Safety: Development and Evaluation of an Assisted Bicycle

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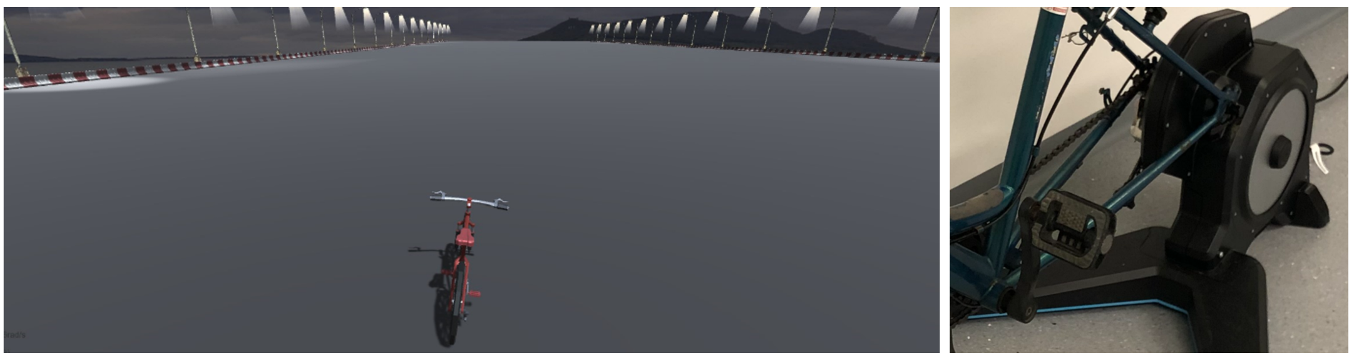

Figure 1: Current status of the work packages. Left: Training of the self-balancing function with reinforcement learning. At least in the virtual environment, the bicycle is able to self-balance also when providing (virtual) input and simulated weight shifts. Right: Tacx Flux 2 smart bicycle trainer used to build the motion bicycle simulator.

ABSTRACT

Although cycling is a promising transport modality for the future, cyclists could not substantially benefit from the safety gain in the last decades. To improve cycling safety and convenience, as well as extending the user base, we proposed to develop a self-balancing, assisted, and connected bicycle that transfers several assistance functions from the vehicle to the cycling domain. In this work-in-progress we sketch our vision of this bicycle, discuss some challenges for its development, and present early results. We present a self-balancing function using reinforcement learning and current progress in the development of a virtual reality motion bicycle simulator. If the progress in the projects continues as expected, we will report results from studies with human users soon.

CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile devices**; • **Applied computing → Transportation**.

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KEYWORDS

cycling, bicycle, assistance systems, human-machine cooperation, vulnerable road users, simulator development, machine learning

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1 INTRODUCTION

Although cycling shows many advantages compared to traditional automobiles (less emissions, better weight-to-power ratio, etc.), cyclists have not substantially benefited from the traffic safety gain in the last decades. Cyclists belong to the group of "vulnerable road users" (VRUs), a group which is increasingly involved in traffic accidents (representing roughly a third of all fatalities in 2014 [11]). This may intensify in the future given the rising number of electric bicycles, which can lead to even more severe injuries [14]. Thus, cyclist safety is becoming a prominent research topic. While modern vehicles utilize technology to improve safety and mitigate crashes (for example, advanced driver assistance systems or automated driving functions), cyclist are mainly protected with passive safety measures (like protective gear or helmets) or properly designed infrastructure (like designated and separated bike lanes). To "bring active safety, automated, and connected driving to the bike lane", we are developing an assisted bicycle that uses technological advances to improve cycling safety and convenience.

Recent projects have begun to address support systems for cyclists. Those include commercial products such as helmets with light strips [9], as well as research efforts focusing on navigation and safety [9, 10], or augmented reality support [15, 16]. We propose to build a bicycle with self-balancing, "automated driving", "steer-by-wire", and "bicycle to everything" communication to transfer various concepts from the automotive to the cycling domain. Kooijman et al. [7] have shown that balancing a bicycle means to continuously steer into the fall, and we acknowledge that this project is not the first attempting to build an automated self-balancing bike. For example, Yavin [17] have applied and inverse control strategy to added rotors, Sanchez [13] or Matsuzawa et al. [8] proposed to balance using adjustments of the steering to develop an unmanned bike.

Our approach is novel in a way that we want to translate various automotive-related concepts to the bike in order to increase cycling safety, reduce emissions, and expand the user base to currently excluded target groups. Beside reducing riders' risk to fall over, this includes **(1) Active Safety Features**, such as automated emergency braking, cruise control, or lane keeping; **(2) Device Integration** to allow cyclists (at least for a short time) to use digital services (utilizing, for example, augmented reality or "earables" [12]); **(3) Connected Driving Features**, such as platooning with bikes or better integration into cooperative, intelligent transport systems.

In this work-in-progress, we report about major challenges of this project and present early results, which focus on the realization of the self-balancing function with Reinforcement Learning (RL), as well as the development of a potentially realistic virtual reality (VR) bicycle simulator for user studies.

2 RESEARCH AND DEVELOPMENT CHALLENGES

Several issues have to be resolved to develop the assisted bicycle. Most importantly, there is the issue of the bike rider having to cooperate with the system. Due to the "steer by wire" concept, control input is provided from the system and the rider simultaneously, which satisfies the "shared control" [2] paradigm.

A relevant question in such a setting is: would users accept and trust such a system. Since cycling is a well-trained motor task for most humans, deviations from expected behavior (i.e., the system correcting steering input of the handle bar) could be perceived as strange. In addition, the system must be able to correctly determine the intent of the rider and deal with individual differences (for example, a strong tilt could indicate a fall but also intended behavior by a sporty rider), making the situation an interesting use case for human-automation interaction research.

Still, also technical issues must be resolved to develop the assisted bicycle. First, we opted against a flywheel due to weight and disturbing placement on the bicycle. Second, we chose reinforcement learning (RL) over the alternative of mathematically modeling the complex physical forces involved. Consequently, we aim at self-balancing the bike only with regular lateral/longitudinal controls using RL (i.e., the bike can only self-balance while moving). The technical challenges include finding the appropriate set of sensors (such as an accelerometers and/or gyroscopes) to describe the system state (i.e., tilt, momentum, etc.) sufficiently for the RL-agent, as well as including edge-computing devices to perform the necessary calculations. In addition, complex assistance systems will require more sophisticated sensor setups (for example, LIDAR sensors), which pose additional requirements to the power supply and space constraints.

To succeed in these challenges, we have planned the following work packages:

(1) **RL-controlled balancing/driving function:** We are setting up a VR simulation in Unity with a reasonably accurate physical bicycle model. Then, we train an RL-agent (actuating the handle bar, speed control) in this environment to determine the minimal set of sensors and parameters for balancing and navigation. This requires to correctly deal with simultaneous input (on the handle bar) and weight shifts by the rider. Simultaneously, we develop a working prototype with real sensors and an on-board Raspberry PI computer to control the steering interference motor (i.e., the "steer-by-wire" function). First, the working prototype will be trained and tested in the lab on a roller trainer, which will then be exchanged with training wheels to operate on the test track. If all tests are successful, we will remove the training wheels and test with real users.

(2) **Assisted Bicycle Simulator:** To conduct user tests and evaluate the advanced safety and connected driving features, we are building up a VR motion bicycle simulator. The simulator will have all the features of the real bike, including the "steer-by-wire" function (i.e., the fork can be controlled and is "virtually" disconnected from the handle bar), as well as tilting in both axes (tilting is necessary to realistically simulate curves and the self-balancing functions). The simulator will be connected to the same VR environment as the physical bike model above (i.e., a "digital twin"), so that the it performs similar movements and corrections as the trained RL agent. This setup will allow us to conduct first user tests early in the development, where we will include different test scenarios – for example, following predefined trajectories with/without the self-balancing function, where we will assess and compare psychological concepts like cognitive demand (using NASA TLX [3]), technology acceptance [1], user experience [4], or trust [5].

(3) **Real-life evaluations of assisted and connected cycling:** Provided the development phase and prior evaluations are successful, we will build a second working prototype in order to develop and evaluate cooperative driving with both bicycles. We will conduct different user studies to test features as described above (such as lane keeping, platooning, automated emergency braking, etc.) and investigate the applicability, effectiveness, and user acceptance in real driving tests on a test track.

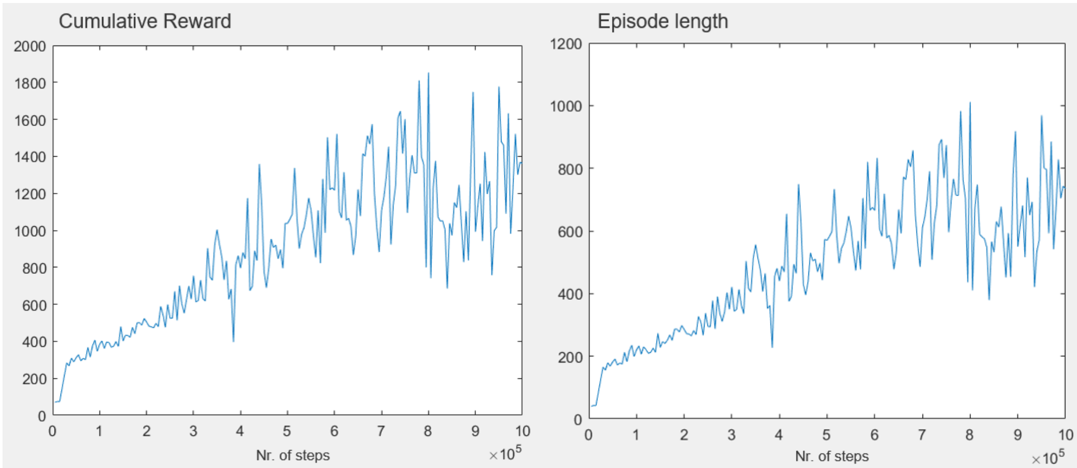

Figure 2: Initial results of the RL agent balancing the bike, showing the (average) cumulative reward (left) increasing and reaching the top at around 700 thousand steps while the length of the training run increases (right). As the performance also oscillates, we are looking for further improvements of the model and the used hyperparameters.

3 EARLY PROJECT RESULTS AND DEMONSTRATIONS

We have already begun to implement (1) the self-balancing function in VR and (2) the motion bike simulator, and we will demonstrate our progress in these two work packages.

3.1 RL-controlled Balancing/Driving Function

We have set up a bike simulation in Unity 3D (see Figure 1) using the "Wheel Controller 3D" asset, which provides a more realistic physical behavior (including wheel mass, spring, damper forces, or friction parameters) than Unity's built-in wheel collider. Then, we implemented an RL-agent using the ML-agents [6] library. Our initial environment model for the self-balancing function consists of 5 parameters: the velocity, the (longitudinal) tilt angle, the angular velocity of the tilt, the current steering angle (i.e., position of the handle bar), and the position of the center of mass. Based on these parameters, the agent trains to provide a single output, namely the desired rotation of the handle bar to balance the bike (from -1 to 1), where the minimum and maximum values represent the change possible within a single time step (i.e., in a real-life scenario it is not possible to fully flip the handle bar within the fraction of a second), using a frequency of 50 steps per second. We composed the reward function in a way to balance the bike with minimum effort based on the following formula:

$$R = \frac{1}{|t|+1} + \frac{1}{|c|+1}, \text{ where } t = TiltAngle, c = ControlSignal$$

Thus, the function returns a high reward when the bike is upright (i.e., low tilt) and the control needed to reach this state is minimal. Additionally, the episode is stopped when the bike falls over or when it leaves the environment (i.e., the plane where it is training, see Figure 1). During each training run, a (constant) speed is determined randomly so that the agent is able to balance the bicycle at different speeds. Using this formulation, the agent (trained with proximal policy optimization, $\lambda = .99, \gamma = .99, \beta = .0001$, buffer size = 1000, batch size = 100, two-layer neural network with 128 units per layer with a Sigmoid activation function) requires approximately 700 thousand steps until being able to balance successfully (i.e., completing the 400m long test track without a fall, see Figure 2). Currently, we are continuing these evaluations with randomly including steering actions and weight shifts (to simulate the behavior of a human driver), as well as variations of the agent's hyperparameters to identify the best parametrization.

3.2 Motion Bicycle Simulator

To implement the bike simulator, we used a standard city bike and mounted it on a Garmin Tacx Flux 2 smart bicycle trainer. Via Bluetooth and the supported FTMS (Fitness Machine Service Protocol), this device allows us to both get the current speed and set the resistance, so that we can realistically simulate the forces of the assisted bike but also ascent and descent. Two other important features of the simulator are the tilting and the steer-by-wire function. For the tilting, we will use the Next Level Racing Motion Platform V3[1] with Unity integration. To simulate the steer-by-wire function, we have designed a simple system to assess the steering angle of the handlebar, where we utilize a potentiometer and some custom designed 3D-printed parts (see Figure 3) for mounting the components. In addition, a servo motor can apply forces in the rotational direction of the fork against the current steering angle (i.e., initiate a counter steer in order to avoid a fall). The system will also have sensors to measure the usage of the brakes whereby the intensity of the braking process is also taken into account. This setup allows to to fully have our "bicycle in the loop", meaning that we can get/set both in- and output for all relevant controls (tilting, speed profile, handlebar movement, braking). This is necessary to simulate sharing of control of the handlebar between the rider and the system.

The first question that we want to answer when we have realized the tilt function with the motion platform is: which tilt angle in VR

[1] https://nextlevelracing.com/products/next-level-racing-motion-platform-v3

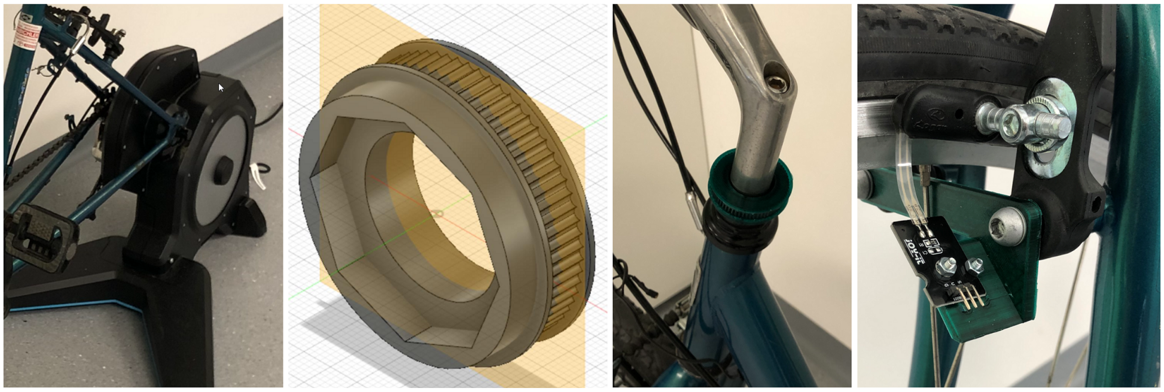

Figure 3: The FTMS protocol is used to control the smart bicycle trainer (left). To simulate the "steer-by-wire" function with the bike simulator, we will utilize 3D-printed components (middle) and a servo motor. The braking intensity is measured using a pressure sensor (right).

is appropriate to simulate driving a curve. As the simulator is not moving there is no centrifugal force, and we must expect that a one-to-one translation of the tilt is not appropriate. To systematically investigate this issue, we will mount sensors on a real bicycle and record the tilt of different curve radii at given speeds. Then, we will replicate this setting in VR and, in a user study, determine which tilt angle(s) are able to convey a realistic feeling (and, the influence of the tilt on participants' motion sickness). As soon as these questions are answered, we will begin to investigate users' perception of the assisted bicycle in VR user studies.

3.3 Conclusion

To improve cycling safety and convenience, provide access to bicycles for people with restricted mobility, and a more energy/space efficient alternative to self-driving cars, we propose to develop an self-balancing, assisted and connected bicycle that transfers a wide range of features from the automotive domain to the bike lane. In this work-in-progress paper, we have presented some challenges of this project, and discussed early results of our work, namely the development of a self-balancing function with reinforcement learning, and the setup of a motion bicycle simulator that we will use to investigate questions of user acceptance, experience, and trust in such a system. We are convinced that such technical developments are a promising area for future research while contributing to more sustainability, health, and safety in future traffic systems.

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