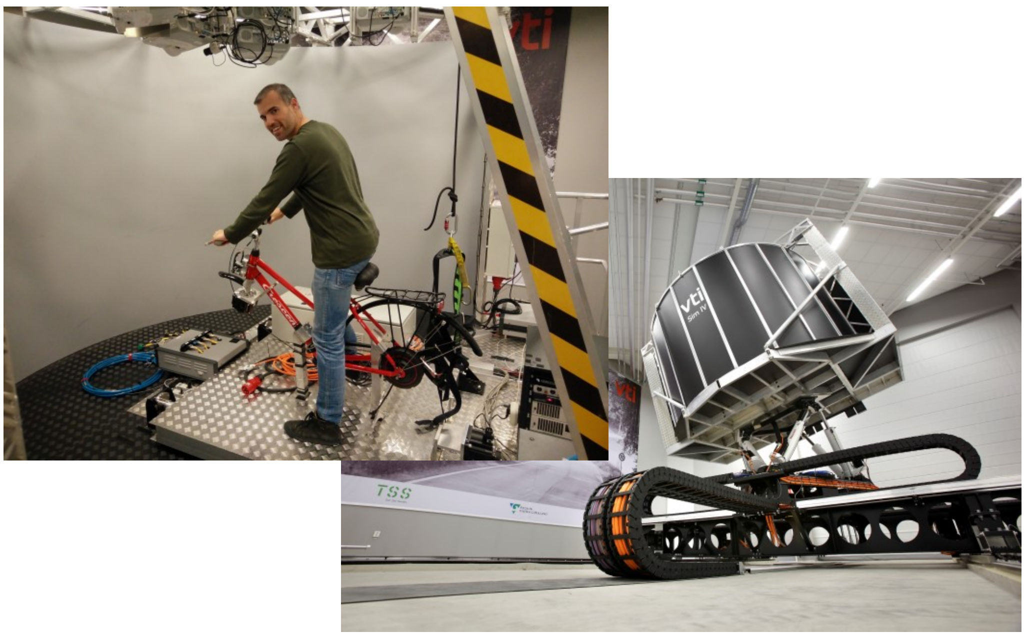
CykelSim

Development and demonstration of an advanced bicycle simulator

Public report



Project within Cyklar & andra fordon i säker och smart samverkan för en hållbar framtid

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Content

1. Summary

A bicyclist's ability to maneuver is a combination of factors such as the bicycle geometry, speed, tire to road surface friction, and cyclist movement. Fully understanding what affects and limits the maneuverability of cyclists can be very helpful for designing bicycles and tires as well roads and infrastructure. The aim of this project was to enable studies of these maneuvering properties, by developing a driving simulator as a complement to real tests which are often impossible to conduct in practice.

A bicyclist's mass, inertia and motion play a central role in the maneuvering of a bicycle and influence the trajectory to an extent not seen in any other road vehicle. A bicycle simulator with the aim to replicate real environments and behavior of cyclists, needs to consider these complex interactions between the cyclist and the bicycle. This is not the case for bicycle simulators seen in the literature, where the typical setup is a stationary bicycle with a visual system utilizing either computer screens or head mounted displays.

In this project, the bicycle simulator was developed to integrate with an existing facility at the Swedish National Road and Transport Research Institute (VTI). This facility, Simulator IV (SimIV), consists of a motion platform with 8 degrees of freedom and a 180-degree projection screen. The motion platform enables motion feedback capable of representing what a bicyclist would experience in a real bicycle ride, with frequencies up to 6-8 Hz.

The cyclist's steering commands and balancing act are directly coupled to the lateral control of the bicycle. The project studied three ways to implement the cyclist's interaction for steering and balancing. The first step was to allow the cyclist to balance the simulated bicycle with a mechanical roll degree of freedom and steering input, while presenting lateral accelerations with the motion platform. This approach mimics the steer-to-the-fall principal of riding a real bicycle and it was shown that this is possible. However, due to the latencies and dynamics in systems involved (communication between computers, motion platform, projectors, etc.) said technique requires substantial training time for riders and would be impractical if the aim is to conduct simulator studies with naïve test subjects.

A second alternative was to lock the mechanical roll degree of freedom of the bicycle and represent the roll angle visually on the screen as well as dynamically by the motion platform. This method requires simulation of the roll dynamics through a dynamic model, effectively removing the coupling between the cyclist and bicycle through motion of the cyclists. However, the steer-to-the-fall principal is still present as the cyclist needs to balance the simulated roll angle. Simple trails suggest that it is relatively easy to balance this simulated bicycle. However, the lack of coupling between the moving of the cyclist body and bicycle control makes steering counter intuitive. It is now necessary to initially steer in the opposite direction to create a fall and then balance the required angle to maintain the desired curvature in the trajectory. Even though this technique is commonly used among motor bicyclists, it is believed that it this is not the case for most bicyclists.

The third and final step was to remove the instability of the simulated roll dynamics to make the bicycle stable on its own. Real bicycles are self-stable through the aligning torque of the handlebar above a certain speed. This characteristic is captured in the simulator through the torque applied on the handlebar.

The project has successfully developed a bicycle simulator that utilize an advanced motion platform. It can be used in various studies of bicyclists behavior, their interaction with the bicycle as well as the simulated environment with a high level of realism compared to existing facilities of bicycle simulators.

2. Sammanfattning på svenska

En cyklists förmåga att manövrera en cykel är en kombination av faktorer som cykelgeometri, hastighet, däck till vägytans friktion och cyklisträrelsen. Att förstå vad som påverkar och begränsar cyklisternas manövrerbarhet kan vara till stor hjälp för att utforma cyklar och däck, liksom vägar och infrastruktur. Syftet med detta projekt var att möjliggöra studier av dessa manövrerande egenskaper genom att utveckla en körsimulator som ett komplement till verkliga tester, som ofta är omöjliga att genomföra i praktiken.

En cyklistens massa, tröghet och rörelse spelar en central roll i manövreringen av en cykel och påverkar banan i en utsträckning som man inte kan se i något annat vägfordon. En cykelsimulator med syfte att replikera riktiga miljöer och beteenden hos cyklister, måste ta in denna komplexa interaktion mellan cyklisten och cykeln. Det här är inte fallet för cykelsimulatorer som förekommer i litteraturen, där den typiska uppställningen är en stationär cykel med ett visuellt system som använder antingen dataskärmar eller huvudmonterade bildskärmar.

I detta projekt utvecklades cykelsimulatorn för att integrera med en befintlig anläggning vid VTI. Denna anläggning, Simulator IV (SimIV), består av en rörelsesplattform med 8 frihetsgrader och en 180 graders projektionsskärm. Rörelseplattformen möjliggör rörelseåterkoppling som kan representera vad en cyklist skulle uppleva i en riktig cykeltur med frekvenser upp till 6-8 Hz.

Cyklistens styrkommandon och balansering är direkt kopplade till cykelns sidokontroll. Projektet studerade tre sätt att implementera cyklistens interaktion för styrning och balansering. Ett första steg var att låta cyklisten balansera den simulerade cykeln med en mekanisk roll-frihetsgrad mot rörelsesplattformen genom sidoförflyttning av rörelseplattformen enligt cyklisternas påverkan av styrvinkeln. Detta liknar det riktiga tillvägagångssätt som en cyklist gör genom att styra mot fallet på en riktig cykel. Preliminära tester visade att detta var möjligt. På grund av latenser och dynamik i de involverade systemen (kommunikation mellan datorer, rörelsesplattform, projektorer, etc.) behövs dock betydande träningstid för cyklister i simulatorn och skulle vara opraktiskt om syftet är att genomföra simulatorstudier med naiva testpersoner.

Ett andra steg var att låsa den mekaniska rullningsgraden av cykelns frihet gentemot rörelseplattformen och representera roll-vinkeln visuellt på de projicerade skärmarna såväl som dynamiskt av rörelsesplattformen. Denna metod kräver simulering av rolldynamiken genom en dynamisk modell. Samspelet mellan cyklisten och cykeln genom rörelse av cyklistens kropp är nu borttappad. Dock är styr-mot-fallet principen fortfarande närvarande eftersom cyklisten behöver balansera den simulerade rollvinkeln. Enkla försök föreslår att det är relativt enkelt att balansera den här simulerade cykeln. Bristen på koppling mellan cyklistens hållning gör emellertid styrning av cykeln icke-intuitiv. Därav är det nödvändigt att först styra i motsatt riktning för att skapa ett fall och en rollvinkel för att sedan balansera den önskade vinkeln för att upprätthålla den önskade krökningen i banan. Denna teknik används bland motorcyklister, men känns inte naturlig i detta cyklistsammanhang.

Det tredje och sista steget var att avlägsna instabiliteten hos den simulerade rolldynamiken för att göra cykeln stabil på egen hand. Detta är också fallet för en riktig cykel genom styrets vridmoment över en viss hastighet. Denna egenskap är också fångad i simulatorn genom det vridmoment som är applicerat på styret.

Projektet har framgångsrikt utvecklat en cykelsimulator som utnyttjar en avancerad rörelsesplattform. Den kan användas i olika studier av cyklisters beteende, deras interaktion med cykeln såväl som den simulerade miljön med en hög realism jämfört med befintliga anläggningar av cykelsimulatorer.

3. Background

The accident rate for cyclists speaks for extra research efforts, concerning this group in a road safety context, [11]. The interaction between bicyclists and motor vehicle drivers' is of particular interest here as this is the most common scenario of accidents with lethal outcome [11]. Independent of how vehicles and bicycles are equipped with auxiliary safety systems, etc., it is ultimately the cyclist's and driver's behavior that lead to critical situations. In this context, driving simulators are an established tool to study human machine interaction, which could be used to bolter our understanding of these situations.

Cyclists' ability to maneuver depends on a combination of different factors such as the cycle geometry, speed, tire to road surface friction, the cyclist ability change posture etc. All these factors are likely a central parameter in all accidents involving cyclists, and the most frequent type of accidents, the ones involving only the cyclist [11]. Understanding in more detail what influences and limits the cyclist, could be of great help in designing bicycles and tires as well as roads and infrastructure. Furthermore, the knowledge can be used to understand crash events in a more systematic way than before.

A bike typically has two wheels in line with the direction of travel. When riding a bike, a key component is balance, in order not to fall over. Another aspect of a bicycle maneuverability is that the cyclist constitutes a large part of the vehicle's total mass and that the angle to the ground plane is entirely controlled by the cyclist through balancing. These aspects are fundamental properties of bicycle riding thus making bicycles unique and quite unlike four wheeled vehicles. Furthermore, they not only affect the actual behavior associated with balancing but are also shape a cyclist's behavior, either consciously or subconsciously.

A motion simulator environment can facilitate repeatable and reproducible conditions that isolate parameters of interest. Bicycle driving simulators are no exception to this thus enabling studies of e.g. cyclist's ability to avoid hazards (cars, other cyclists, pedestrians). The credibility or validity of such studies is strongly linked to the ability to recreate a cyclist's behavior in real traffic.

Today's bicycle simulators consist to a large extent of a bicycle frame that is fixed in an upright position. An example is the Viktoria Institute's bike simulator, see [1]. A computer-generated environment is presented to the rider in the form of screens that face the latter or, alternatively, head mounted displays. The bike's movements are simulated around the world using a dynamic model that takes the driver's pedal movements and handle bar angle as input. In these cycling simulators, the roll dynamics are usually not simulated at all. Consequently, this invokes a sensation that resembles more driving a four wheeled vehicle. A noticeable mismatch between expected and simulated behavior on the bike can cause discomfort and nausea. Furthermore, the missing or misrepresented cues potentially undermine the case for driving behavior, which is representative of its real-world counterpart.

Trials with simulated roll angle and balancing in a fix base simulator, without mechanical possibility of rolling, have been performed at The Technical University of Delft's bicycle dynamics group, see [2]. One conclusion is that it is difficult to keep the balance of the simulated cycle without the feedback from the physical cycle's roll angle. Balancing, however, is greatly improved by an appropriate torque feedback through the handlebar, see [3].

A natural follow up step to the concepts hereby introduced is to allow the cyclist to balance itself, i.e., have influence over its roll angle relatively to the road. To achieve such a goal, the latter will have to be exposed to dynamic cues, in line with what is expected from cycling. This can be achieved using motion base driving simulators, which are ubiquitous in research concerning driver behavior coupled to motor vehicles. A moving platform would be used to create motions that resemble those the cyclist is exposed to during cycling. Given the inherent limitations on the dynamic range of any motion system, the goal is not so much to represent the exact motions of the simulated vehicle, but rather to recreate those which yield an adequate experience, from the driver's perspective.

Already in the literature, [4-8], solutions emerge where a bicycle is integrated in a motion simulator, however, none take in consideration the driver's balancing, and consequently, control of the roll degree of freedom. This project studies the possibility to integrate cyclist balancing in a bicycling simulator via feedback of motion cues. This implies a degree of freedom from the bicycle frame relatively to the simulated ground, over which the driver has full control, just like in a real bicycle. In principle, this would shrink the gap between simulated and real bicycling experiences by supplementing the interaction with the simulated environment.

4. Purpose and Objective

It is seen in traffic accidents statistics that bicyclists are a group of road users with constant or even increasing rate of accidents. At the same time their is desired that the use of bicycles should increase as a mean of transportation due to its health and environmental advantages over other means. There is a need to study bicyclists and their behavior in order to create a traffic system that can be shared with more users, in a safe manner. In many situations, an ecologically valid, controlled and safe test environment is needed. This could be provided by a bicycle simulator.

This project upholds the premise that balancing is a critical component of bicycling and that it should be taken in consideration in motion simulation of bicycle riding, for the sake of increased fidelity and/or immersion. Therefore, the project purpose is to investigate the feasibility of integrating the balancing act in a motion simulator, as well as to design and construct such simulator.

The bicycle simulator will not be built purely from scratch and is intended to use the existing VTI facilities, namely SimIV, as much as reasonably possible. By integrating it in existing facilities, whose applications are quite well disseminated in the research community, we can not only expand the potential of an existing national research resource, but also encourage future bicycle related research.

5. Implementation

Implementation encompasses all steps from the initial design and its motivations, to the state of the bicycle simulator at the end of the project.

5.1 Hardware design

The developed bike simulator was designed to use as much of the existing infrastructure at VTI SimIV as possible. At SimIV a motion platform with a total of 8 degrees of freedom is available by default, together with a 180deg field of view screen and plentiful digital/analog interfaces. Given these properties, it was specified at early stages that the development of the bike simulator would not focus on visual representation of the world and that all types of dynamic cues should be generated by the available motion system. Furthermore, given the nature of the project, sound cues or any other cues other than visual and motion, were down prioritized as the main goal was to study the cyclist balancing act.

1.1.1. Cabin Design at SimIV

Given that SimIV is used for several types of simulation, the bicycle specific infrastructure must be mounted/unmounted with no detriment to the existing system. To fit this purpose, a platform (dubbed **Bicycle Cabin**), was created to host the bicycle, actuators, and electronics necessary for integration in the VTI simulation environment. In more detail, the bicycle cabin consists of an aluminum platform, where all components are attached to, the control electronics for the actuators mounted on the bike frame, the computers managing the interface with the SimIV software, a bike frame with no wheels and no front fork, and all actuators/sensors needed to simulate the bicycling experience. Packaging all bicycle simulation elements in a single structure facilitates the exchange between simulator cabins, maintenance of the hardware, and any future development efforts.

FIGURE 1 Constriction of the platform, the entire system attached to a crane (left), the system mounted to the simulator (middle) and the aluminum construction of the base with the bicycle on top (right).

1.1.2. Actuators and Sensors

It was intended that the cyclist would be able to adjust the bicycle frame roll angle to allow natural balancing motions. This meant that a roll degree of freedom was required between the frame and its mounting to the simulator dome. Said mounting consisted of a free rolling axel to which the frame was attached. An electric motor was coupled to one of the axel's ends with the purpose of generating torque that could assist the driver in the balancing act. This actuator was intended to mitigate the shortcomings of the simulator dynamics capabilities to represent the frequency ranges needed by the driver, for the purpose of balancing.

The bicycle simulator was further complemented with two additional actuators. First, a wheel hub motor was added to simulate dissipative forces as well as to represent the inertia of the bicycle plus cyclist, while accelerating. Second, to actuate the torque at the handle bar, an electric motor was mounted on the steering axle.

All motors provide estimations of their respective states in terms of angles and angular speeds, meaning that there was little need for additional sensors in the initial development phase. Later tests showed that the encoder on the wheel hub motor had insufficient resolution and had to be replaced by and external one. Additionally, a potentiometer was coupled to brake handle, thus allowing the driver to have control over the bicycle deceleration.

1.1.3. Safety

Bicyclists at SimIV are exposed to dynamic cues like what is experienced in actual bicycle riding. This includes situations which can induce loss of control and, consequently, accidents. It is therefore important to account for such situations in the bicycle simulator.

A harness has been mounted above the bicycle which allows for comfortable motion all the while safeguarding the cyclist from extreme simulator displacements. In addition, emergency stops have been mounted on the bicycle frame to give the rider possibility to initiate a safe stop of the simulation.

5.2 Simulator integration

Information exchange between the bicycle cabin and the existing simulator infrastructure is achieved with a single connection with the Controller Area Network (CAN) protocol. This connection reaches out to a real time computer and is used as a bridge between the control electronics for the bike motors and the simulator software. The same real-time computer hosts the bicycle model. The latter takes in the motion states of the actuators and the driver inputs, such as braking and steering, to simulate the bike dynamics which in turn are used to actuate the motion platform and regulate the motors in the bicycle cabin. Actuation of the motors and simulation of the bicycle dynamics is performed at a rate of 1kHz.

5.3 Lateral displacement and dynamics

The lateral displacement of a bicycle is central in the balancing act of the cyclist. The lateral displacement is one of two means to prevent a fall over where the other is a shift of posture of the cyclist. The lateral displacement is controlled by front wheels steered angle through the handlebar. The dynamics of in road plane motions is modelled by a simple single-track model, see e.g. [14], using a linear tyre model in slip and camber angle.

Introducing the speed vector (V_x, V_y) and the angular speed $(\omega_z)$of the frame, the effective steering angle (δ) and the speed vector of the front wheel as,

$$V_x^f = V_y \cos(\delta) - V_x \sin(\delta)$$
$$V_y^f = V_y \sin(\delta) + V_x \cos(\delta)$$

and the lateral slip on the front and rear wheel as,

$$\sigma_y^f = \frac{\left(V_y^f - \omega_z(b-a)\right)}{|V_x|}$$
$$\sigma_y^r = \frac{\left(V_y^r - \omega_z a\right)}{|V_x|}$$

where a and b are the distances from front axle contact point to center of gravity and distance between the wheels contact points. The forces on the front and rear wheels are given by the linear tyre model,

$$F_y^f = -g\frac{a}{b}(C_y\sigma_y^f - C_\psi\psi_r)$$

$$F_y^r = -g\frac{b-a}{b}(C_y\sigma_y^r - C_\psi\psi_r)$$

where ψ_r is the camber of the wheel (further assumed to be equal to the roll angle of the bicycle) and C_y and C_ψ are the load normalized stiffnesses of the linear tyre model. The magnitudes of the stiffness are taken from experimental results in [13].

The equations of motion are given by the lateral force balance and the yaw torque balance as,

$$\dot{V}_y = F_y^f\cos(\delta) + F_y^r - V_x\omega_z \tag{1a}$$

$$\dot{\omega}_z = \frac{(b-a)F_y^f\cos(\delta) - aF_y^r}{\frac{d^2}{2}} \tag{1b}$$

Where d is the radius of thought cylinder making the yaw inertia of the cyclist and the bicycle and $A_y = \dot{V}_y + V_x\,\omega_z$ is the lateral acceleration of the carriage.

Despite the simplicity of (1a-b), this gives a relatively correct motion in the plane. All geometry related effects and effects related to leaning and steering of the bicycle and the tyres have been neglected apart from the roll angle (ψ_r).

5.4 Handlebar feedback

The steering angle of the bicycle is controlled by the cyclist through the handlebar. This is the main interface of the cyclist to control the path of the bicycle and one of the main means to balance through steering into the fall. The angle of the handlebar (δ) is directly measured in the motor attached to the handlebar shaft and the feedback torque in the handlebar is given by the simulation. This torque is governed by the angle, simulated speed, roll angle among other things. A key characteristic of the torque is that it is self-aligning and steers into the fall above a certain speed of the bicycle. This is a central component that guides and supports the cyclist to balance and control the bicycle. Hence, it is of importance to simulate a correct torque feedback at the handlebar.

The handlebar feedback torque is given by the simple, yet complete model presented in [14] with the addition of a speed dependent damping according to the study in [15]. The expression for the torque is given by,

$$T_{HB} = \frac{2\left(\frac{\sin(\lambda)V_x^2 - bg\cos(\lambda)}{b}\delta + g\psi_r\right)acm\sin(\lambda)}{b} + D_{HB}\,\dot{\delta}V_x \tag{2}$$

where m is the mass, c is the caster trail, λ the head angle (i.e. the angle between the fork and the plane) and D_{HB} a damping constant.

5.5 Pedal torque and longitudinal dynamics

The longitudinal motion of the bicycle is governed by the road slope, wind resistance, rolling resistance of the tyres and the cyclist torque applied at the pedals. The longitudinal acceleration is modelled as,

$$\dot{V}_x = -\frac{1}{m}(\sin(\phi_r)mg + C_{dA}\hat{V}_x^2 + F_{rr} + T_{bk}/r) + K(V_x - \hat{V}_x) \tag{3}$$

where ϕ_r is the road slop, C_{dA} is the air resistance, F_{RR} the constant rolling resistance and T_{bk} is the brake input of the cyclist. $T_{bk}$is a reading from the potentiometer attached to the brake handle on the handlebar and scaled to appropriate value to represent a braking torque of the cyclist. The modified speed is given by,

$$\hat{V}_x = \max(V_x, \omega_r r) \tag{4}$$

where ω_r is the measured angular speed of the rear wheel hub and r the simulated rolling radius. The last term in (4) is equal to zero if the cyclist is not pedaling faster than the simulated speed V_x. When the cyclist is pedaling faster than the simulated speed, the last term of (3) becomes active and forces the simulated speed V_x to be equal to the modified speed $\hat{V}_x$ at a rate determined by K. Hence, when the cyclist is pedaling faster than the simulation, the modified speed is given by pedaling speed. Consequently, giving the cyclist control of the longitudinal dynamics.

For close to zero speeds, the rolling resistance and the cyclist torque need to be scaled down to prevent numerical problems with scattering.

The pedal resistance that the cyclist experiences is given by the resistance that governs the longitudinal dynamics when the cyclist is pedaling faster than the simulated speed. Hence, the torque request to the rear wheel hub motor is given by,

$$T_w = \sin(\phi_r)\, mgr + rC_{dA}V_x^2 + rF_{rr} + K_r(T_{bk} + mA_x) \tag{5}$$

where K_r is used to scale the torque request of the most significant terms, due to limitations of the peak torque of the motor. A soft mechanism for the transition between zero torque and the torque given by (4), when the cyclist pedals faster than the simulated speed, was introduced as a gain acting on (4) as,

$$\min\left(\max\left(1, \left(\frac{\omega_r r}{V_x}\right)^2\right), 0\right)$$

5.6 The roll dynamics

The roll dynamics were approached with three different alternatives. In the first alternative, the roll is given by the real roll of the bicycle frame which is mounted in the simulator. Hence, there is no need to simulate the roll dynamics, since the driver was in control of the bike frame. Torque around the roll axis could still be regulated for non-bicycle dynamics porpuses such as effects of wind, gyroscopic effects of the wheels, etc. Furthermore, a weak self-stabilizing feedback was applied in the form of a proportional controller that actuated the roll motor, and it is worth noting that the latter was not strong enough to keep the bicycle in upright position without the rider.

In the second alternative, the mechanical roll degree of freedom in the simulator platform, between the base and the bicycle, was locked. The roll dynamics where were simplified and approximated using a simple inverted pendulum,

$$\ddot{\theta} = (g\sin(\theta) + A_y\cos(\theta))/h \tag{6}$$

where A_y is the lateral acceleration given by the single-track model above. The mass of the cart was assumed to be uninfluenced by the roll motion, i.e. the contact point does not move if the roll angle changes. The motion of the cart is instead given by the equations in (1a-b).

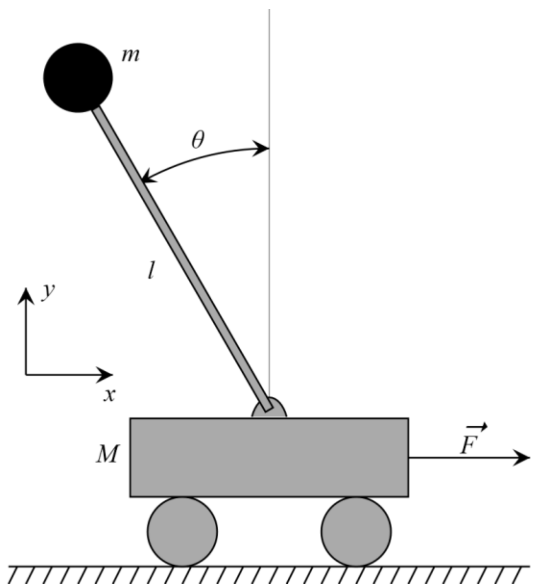

FIGURE 2 Schematic picture of the roll dynamics of the bicycle. Picture from Wikimedia.

For alternative three, the unstable dynamics of (6) were removed from the simulation. The linearized dynamics of (6) have poles on $s = \pm\sqrt{g/h}$ and steady state at $\theta^0 = -A_y/g$. The instable pole was removed, and the resulting dynamics is given by,

$$\dot{\theta} = -\sqrt{\frac{g}{h}}\theta - \sqrt{\frac{1}{hg}}A_y \tag{7}$$

5.7 Motion cueing

Each roll dynamic modelling strategy warranted its own motion cueing approach. In the first alternative, when the roll degree of freedom was present in the bicycle simulator, the motion feedback is the only means of balance for the rider. For a left turn of the handle bar the simulator needs to steer to the left and move the corresponding contact point in the ground. This gives the rider the possibility to counter steer his fall and balance. The lateral motion of the contact patch in the road surface is described by the equations in (*1a-b*). The translation actuators of the motion platform were used to actuate this displacement. The motion feedback was only present for the lateral direction and was performed as unfiltered and raw as possible, so as to not introduce additional discrepancies between the simulated and actuated lateral position of the bicycle.

The second alternative was never tried with motion feedback because the drivers were no capable of basic balancing, even without motion.

The third roll dynamics alternative had a locked mechanical roll angle and simulated (stable) roll dynamics. The roll angle is now displayed to the rider in the screens. The lateral displacement still needs to be actuated according to the lateral displacement described by the single-track model in (*1a-b*). A clean lateral displacement (acceleration) of the platform would apply a lateral force on the rider, which corresponds to the roll aligning force during balancing in the first alternative. Since the roll dynamics was modified to be stable, the force is not needed to balance the bicycle and the rider. In these circumstances, the rider would experience a push in an unexpected direction, which would feel erroneous and possibly warrant a counter action. To reduce this effect, an artificial roll is added of the motion platform to counter the experienced push. Observe that this roll is only perceived by the vestibular system of the rider as the screen follows the roll of the platform, i.e. it is only added to the motion cues, and not the virtual bike model.

The longitudinal motion feedback was performed through standard motion feedback principals of motion cueing in driving simulator with pre-filtering of the acceleration given by (*3*), and washout filters, bring the simulator resting position in the center of the motion envelop, as described in e.g. [16].

6. Results and Discussion

The results of the project can in fact be divided into two parts; the actual hardware and software that forms the bicycle simulator and, more formally, the outcomes/insights collected under the initial trial tests performed during the development of the simulator. This chapter focuses on the latter. The three alternative approaches devised to emulate balance and roll dynamics were tested separately. Unfortunately, given the development-like nature of the project, the tests could not be performed in an ideal way. Instead of naïve test subjects and proper experimental designs and hypothesis, simpler evaluation tests were performed by the authors and a small sample of colleagues, whose impressions were noted.

For the first roll dynamics alternative, the roll angle of the bicycle was mechanical, and the balancing was achieved by the rider through steering into the fall. From all the test subjects, only one was able to balance the bicycle for indefinite periods of time. It was evident that balancing did not come naturally, and the rider needed to learn how to counter steer the fall. It is believed that the latencies between the steering action and the actual motion were the main contributor to the non-natural sensation. From previous measurements this could be up to 60 milliseconds, which could is far more than acceptable for an untrained rider compared to real bicycle riding. Attempts to make the balancing easier by introducing a small reference torque on the roll motor had little to no effect. From classical control theory it is well understood that a latency (delay) in the control loop will have a destabilizing effect and may even be used as a measure of robustness of the control loop. For some individuals, the latency is too large to cope with and will likely never learn how to balance under these conditions. It should be noticed also that the latency between simulated motion and motion represented in the visual system also act destabilizing. Previous measurements suggest that this latency can be up to 100 milliseconds. However, it is relatively less clear how this latency is acting on the rider when trying to balance as the actual roll is real and not simulated in the visual system.

The second roll dynamics alternative locked the mechanical roll degree of freedom, and simulated roll with an inverted pendulum model (unstable dynamics). Here, only tests without motion feedback were performed. For this phase the latency of the visualization system is central as the information about the roll angle is only presented visually. With some additionally simulated aligning torque of gyroscopic effects, among others, it was not a major challenge to balance the bicycle. However, taking a turn and achieving a controlled trajectory was non-trivial. To initiate a steering maneuver, one needs to have an initial roll angle of the frame. For real bicycle riding this can be initiated by counter steering, i.e. steering in the opposite direction initially. This will create a roll angle that can be maintained by balancing in a similar fashion as when balancing and riding straight. Another approach to initiate steering on a real bicycle is to move the body such that the bicycle starts to lean and wait with the steering until an angle is reached that corresponds to the desired turning radius and start the balance around this angle. In the bicycle simulator it is only possible to use the first approach, counter steering, as the simulation is unaware of the rider's posture. Counter steering is non-intuitive, and it is believed that this fact explains why it was almost impossible to keep the bike upright during these tests.

The unstable simulated roll dynamics of the second alternative were replaced with stable roll dynamics for alternative three. This made the riding and controlling of the bicycle simulator easy, with only a small effort required to learn. Full tests with motion feedback were performed with naïve subjects. In general, it was perceived as an OK experience, akin to riding a real bicycle. Comments from the riders were quite varied but almost all reported an unexpectedly responsive handlebar. Together with the latency of the motion and visual system, this is thought to have contributed to the few cases of unstable behavior witness in the cyclists. A mismatch of expectations and miscues, in addition to a stable bicycle model is believed to be the main source of this behavior. However, informing the riders about the response and the stable nature of the bicycle prior to the ride, seemed to improve the performance. The stable bike dynamics also contributed to false cues, particularly on the dynamic response of the roll angle for high frequencies, or when terminating a sustained curve and returning to an upright position. It is likely that these miscues are hard to mitigate and are inherited in the approach with a stable bicycle.

7. Dissemination and publications

7.1 Dissemination

The aim with the project was to deliver a platform that could be used for bicyclist studies of various questions and domains. An initial validation user study will take place on 2019, and plans exist for collaborations with Chalmers, where it concerns bicycle dynamics. An official inauguration of the platform is planned to take place during the annual Cykelmässan in Gothenburg, and additional simulator demonstrations to the public will disseminate the project and illustrate the usefulness of the platform.

7.2 Publications

The technical achievements of the project will be published in a journal paper that will be composed and submitted during 2019.

8. Conclusions

This project has developed a motion bicycle simulator. The simulator utilizes an existing facility consisting of a projector screen solution with a 180-degree view and 8 degree of freedom motion platform where the bicycle simulator is placed on. Focus has been given to the motions and the interaction between the cyclist and the cycle while riding the bicycle, and in particular the act of balancing. Three alternatives have been studied with a decreasing realism and complexity, for the simulation of the roll dynamics.

The first alternative comprised of a bicycle simulator with a mechanical degree of freedom between the motion platform and the bicycle. This enable a rider to make a real balance act by steering into the fall of the bicycle. Initial tests suggest that latencies of the platform, communications etc. makes this balance hard for the rider. For this to be a viable tool for research, significant improvements in the system must take place wr.t. to the latency, and possibly bandwidth of the existing actuators. This would imply investments of hardware and software of the platform in the facility.

In the second alternative, the mechanical roll degree of freedom locked, and the unstable roll dynamics is simulated and displayed visually. Trials suggest that balancing is feasible, while steering in general and maneuvering of the bicycle is hard. The main cause for this is believed to be the lack of information about the posture and center of gravity that the rider. By introducing load sensors, it would be possible to take the posture into account in the simulation and consequently make the maneuvering easier.

The third alternative replaces the unstable roll dynamics with a stable approximation. This made riding and maneuvering easier however miscues were added due to the synthetic stable roll dynamics.

In total, much of the conclusions presented here are based on preliminary trials. A substantial amount of testing remains to establish the conclusions more firmly and to evaluate the validity of the bicyclists behavior in the simulator compared to real bicycle riding. Future work should focus on validation for the tentative conclusions drawn in this work.

The developed simulator will be a useful asset in the investigation of bicyclist behavior and response to environment, traffic, infrastructure, and bicycle dynamics. The efforts of understanding bicyclists should go hand to hand with the political agenda to promote an increase use of bicycles without jeopardizing safety. The newly inaugurated competence center on bicycling at VTI and this simulator are evidence of such efforts. This simulator will be a national/international research resource that can be used for all sorts of research involving bicycle riding and any arising interactions with the cycling environment. The future development of the simulator will be shaped by our society's wishes for the future of cycling and its seamless admittance to the higher echelons of transportation.

9. Contact persons

While Cycleurope, Municipality of Gothenburg and Chalmers have been part of the project in an advising roll, VTI has performed all the work covered by this report. For future contact on the project and the bicycle simulator, please refer to the list below.

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