A first step towards an autonomously driving E-Scooter ⋆

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Abstract:
The electric scooters appearing in the modern mobility mix of larger cities face several problems. To tackle some of them, we develop an autonomously driving e-scooter. In this paper we introduce a balancing mechanism that allows driverless locomotion as a first step towards fully autonomous driving. The self-balancing mechanism is implemented in a prototype based on a regular e-scooter. It works with a reaction wheel that is used to generate a torque to prevent the scooter from tipping over. The combined system of the e-scooter and the flywheel is modeled and a controller is designed. Tests at the prototype show that it is able to balance, drive and withstand pushes to the handle bar.

Keywords: Autonomous Vehicles, Mechanical design of autonomous vehicles, Motion control, Positioning Systems

1. INTRODUCTION

Electric scooters (e-scooters) become increasingly popular as means of transportation for mostly short distances (Degele et al., 2018). In the last few years, their popularity and the number of vehicles increased and especially as part of dockless sharing systems they shape the image of many larger cities (Gössling, 2020). As Gössling (2020) mentions, the dockless systems come with several drawbacks, from which at least some could be solved by introducing autonomously driving electric scooters. Cluttering, meaning that the e-scooters are not parked properly after being used and block sideways such that pedestrians have difficulties passing by, and environmental issues resulting from the need to pick up electric scooters with an empty battery with a car in order to bring them to a charging station, can be overcome. An autonomous e-scooter does not need to be parked properly, it can simply drive to an appropriate parking space on its own or directly approach the next customer. Similarly, an e-scooter with low battery can drive to a charging station saving the necessity of persons gathering empty e-scooters and bringing them to charging stations. Since the electric scooters are usually collected by cars with combustion engine, this reduces the carbon footprint of the e-scooters. By those two benefits compared with regular e-scooters, also the social acceptance will potentially increase, reducing vandalism and mitigate the conflict between proponents and opponents, which are further concerns on e-scooters mentioned by Gössling (2020). An additional benefit of autonomously driving e-scooter is that they can be called by a customer of a dockless sharing system. The scooter can then drive to the location where the customer wants to pick it up saving time and effort for the customer and improving the service of the sharing system. In some scenarios as for example on the Campus of the University of Stuttgart in Vaihingen, for which the presented prototype is developed in the course of the "MobiLab" [1] Project, an additional advantage comes into play. There, the regular commutes are mainly in the same direction. In the morning they start at the central train station or the parking lot and lead to the lecture halls and offices. In the evening they are reversed. Approximately 40% of the ways are longer than 400 m and thus are the perfect use case for an e-scooter. However, since most of the routes are in the same direction, a very large number of regular scooters would be necessary to meet all requests. To have a lower number of e-scooters and nevertheless cover all requests autonomous electric scooter, which can be commanded to drive wherever they are needed, can be employed.

In order to implement autonomously driving e-scooters, a first challenge is to stabilize it, which is the objective of the presented prototype. The balancing of a scooter with two wheels in a row is equivalent to the balancing of an inverted pendulum, which is a nonlinear and unstable system. As described in Lam (2011), there are several possibilities to stabilize such a vehicle as for example gyroscopic stabilization, moving the center of mass, or turning the handle bar which only works for a driving scooter. For our prototype of a self-balancing e-scooter, we decided to employ a reaction wheel as used in the "Murata Boy" [2], which is accelerated in order to generate a torque that stabilizes the e-scooter. The presented prototype serves as a proof of concept that the stabilization of an e-scooter without a driver on it by means of a reaction wheel is a viable approach.

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[1] www.uni-stuttgart.de/en/university/news/showcase/mobilab
[2] https://corporate.murata.com/en-global/about/mboymgirl/mboy

Fig. 1. The first prototype of the self-balancing e-scooter driving without a person. The reaction wheel used to balance the scooter is mounted in the blue cylinder.

2. SYSTEM DESCRIPTION

For the control of the self-balancing e-scooter which is described in Section 3, only the tilting dynamics is considered. It is modeled in Section 2.2 and the hardware used to build the prototype is described in the sequel.

2.1 Hardware setup

The self-balancing e-scooter shown in Figure 1 is based on an early prototype of the Yorks S1-elite scooter, which has the same functionality as many other e-scooters on the market. For the balancing mechanism, a reaction wheel is added to the scooter to exploit the same principles as for example used in Meyer et al. (2009); Gajamohan et al. (2012); Lin et al. (2015) to balance an inverted pendulum. The reaction wheel is propelled by a "T-Motor U8 II KV85" brushless DC motor. It is controlled by a "VESC 6 Plus" (VESC) motor controller which has an internal measurement unit (IMU) that is used to sense the tilt angle of the e-scooter and its angular velocity. The rotational velocity of the reaction wheel is measured by means of an additional motor encoder connected to the VESC. The reaction wheel can be mounted vertically in order to have the maximum input power, or tilted by an angle of 15° to have a more elegant appearance. For the modeling, the reaction wheel is assumed to be vertical.

2.2 System Model

The dynamics of the e-scooter can be modeled as an inverted pendulum which is actuated by accelerating a reaction wheel. Similar to Lin et al. (2015), the system model can be derived with the Lagrange-Formalism resulting in the equations of motion

$$\begin{aligned} \ddot{\phi} &= \frac{mgz}{I}\sin(\phi) - \frac{1}{I}u \\ \dot{\omega} &= -\frac{mgz}{I}\sin(\phi) + \left(\frac{1}{I} + \frac{1}{I_D}\right)u \end{aligned} \tag{1}$$

where ϕ is the tilt angle of the e-scooter measured from the vertical position, m is its total mass with the center of mass located at a height z above the contact points of the wheels and the ground. The gravitational constant is denoted by g. I is the moment of inertia of the e-scooter and I_D the moment of inertia of the reaction wheel. The rotational velocity of the reaction wheel measured relative to the scooter is denoted by ω. The input to the system is the torque u, whereas the control input given by the VESC is the motor current $\bar{u}$. For simplicity we neglect the motor dynamics meaning that we approximate the current $\bar{u}$ to be proportional to the torque u generated by the DC motor, i.e. $u \approx k_T\bar{u}$ with the torque constant k_T of the motor.

Since we are only interested in stabilizing the e-scooter in its upright position and since the power of the motor is not sufficient to achieve a swing-up, a local consideration of the system is sufficient. For that, the system is linearized around the upright, instable equilibrium point. By introducing the state $x = \begin{bmatrix}\phi & \dot{\phi} & \omega\end{bmatrix}^\top$ the linearization around $x^* = [0\ 0\ 0]^\top$ can be expressed as

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 \\ \frac{mgz}{I} & 0 & 0 \\ -\frac{mgz}{I} & 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ -\frac{1}{I} \\ \frac{1}{I} + \frac{1}{I_D} \end{bmatrix} u. \tag{2}$$

The linearized system is controllable and the complete state x is measurable as described in section 2.1. All system parameters except the moment of inertia of the reaction wheel are calculated from simple geometrical shapes with the respective masses. Since the reaction wheel has the biggest influence on the control, its moment of inertia is measured directly.

Since the moment of inertia of the reaction wheel I_D is three orders of magnitude smaller than the moment of inertia of the e-scooter I, its rotation speed ω is significantly higher than the rotation speed of the scooter $\dot{\phi}$ for the same input torque u. The dynamics can be approximated by

$$\dot{x} \approx \begin{bmatrix} 0 & 1 & 0 \\ \frac{mgz}{I} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ -\frac{1}{I} \\ \frac{1}{I_D} \end{bmatrix} u. \tag{3}$$

since the terms $\frac{1}{I}$ and $\frac{mgz}{I}$ are minor compared with $\frac{1}{I_D}$. This approximation, shows that the dynamics of the e-scooter and the reaction wheel can be considered to be only coupled by the input.

3. CONTROLLER DESIGN

For the given hardware setup, a first stabilizing controller is designed. The implementation has the prerequisite to be easy to program and easy to tune. It is implemented as a "custom user App" on the VESC in order to have the highest possible sampling rate and the shortest possible delay. Before starting the controller design, a very brief test with the built in "balance App" of the VESC shows that a major challenge is the limitation of the rotation speed of the reaction wheel, which is implemented in software in order to prevent damage of the motor.

The control structure is chosen to be similar to a cascade controller with the reaction wheel in the outer control loop

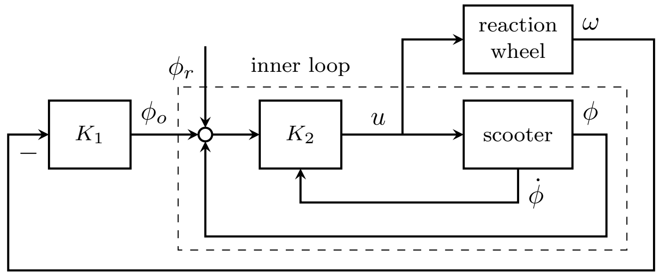

Fig. 2. Control structure.

and the balancing dynamics of the e-scooter in the inner control loop as shown in Figure 2. At first, it seems to be counter intuitive to have the actuator in the outer loop. However, since the velocity of the reaction wheel ω is proportional to the integrated control input u as described in the third line of equation (3) and since ω is bounded, the controller needs to assure that the velocity of the reaction wheel is always close to zero in order to preserve the possibility to apply positive and negative inputs equally. Due to the input-coupling of the systems, the deceleration of the reaction wheel can only be achieved while simultaneously accelerating the e-scooter. When the tilt angle ϕ is not stabilized before decelerating the reaction wheel, the tilt angle might increase to an extent from which the equilibrium $\phi^* = 0$ cannot be reached any more due to the limited torque of the motor. Thus, the control of the tilt angle is implemented in the faster inner loop and the control of the flywheel in the slower outer loop. The set-point ϕ_o for the tilt angle of the e-scooter is commanded according to the rotation speed of the reaction wheel ω by the controller K_1 such that the deceleration of the reaction wheel coincides with the acceleration of the e-scooter towards the equilibrium point ϕ^*. The controller K_1 is implemented as proportional controller and the controller K_2 is a PD-controller in order to quickly suppress to disturbances.

4. EXPERIMENTS

In order to test the self-balancing electric scooter, three tests are conducted. First, the scooter balances while standing on even ground without external disturbances. In the second experiment, it is slightly pushed at the handle bar and in the third test it drives on a parking lot.

The measurements in Figure 3 show that the e-scooter can balance upright and the tilt angle ϕ stays smaller than $0.25°$ when no external disturbances act on the system. The small oscillations are barely noticed with the naked eye. It can be observed that the tilt angle has a little positive offset $\phi^* = 0.045°$ which is the true equilibrium point of the system. That the equilibrium point ϕ^* is not at the measured angle $\phi = 0$ might be caused by sensor misalignment, asymmetric load, or an uneven ground. In the closed loop, the deviation of ϕ^* from $\phi = 0$ leads to an offset in the reaction wheel velocity $\omega^* = 10\frac{rad}{s}$ at equilibrium, which results in a set-point $\phi_o = \phi^* = k_1\omega^*$ commanded by the controller K_1.

When the scooter is slightly pushed at the handle bar, the balancing mechanism is able to recover the upright position as shown in Figure 4. Approximately $4s$ after the push, the desired tilt angle $\phi = 0$ is recovered. The

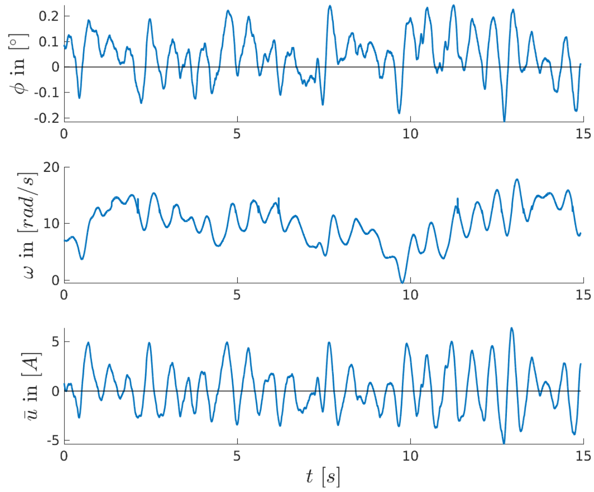

Fig. 3. Measurements of the tilt angle ϕ, the angular velocity of the reaction wheel ω, and input $\bar{u}$ of the balancing e-scooter. The signals are filtered with a first order filter.

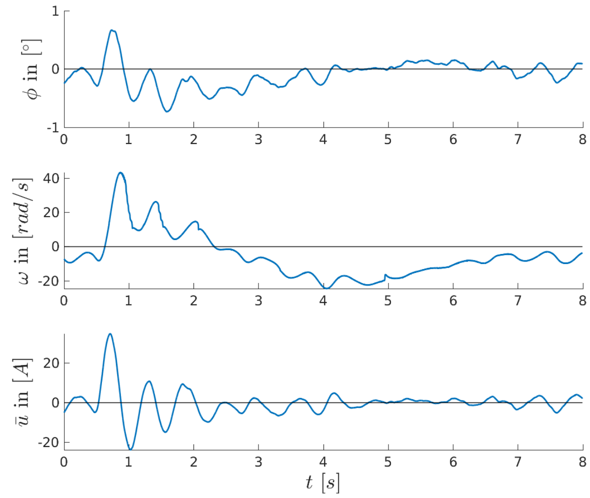

Fig. 4. Measurements of the tilt angle ϕ, the angular velocity of the reaction wheel ω, and input $\bar{u}$ of the e-scooter when being pushed at the handle bar at $t = 0.5s$. The signals are filtered with a first order filter.

angular velocity of the reaction wheel ω, however, is at its minimum of $-20\frac{rad}{s}$ at that time. Only when the scooter itself is in a neighborhood of the balancing position, the speed of the reaction wheel is slowly reduced through the influence of the controller K_1 without destabilizing the scooter. This observation supports the reasoning behind the implementation of the cascade-like controller.

Driving tests with the e-scooter show that it is robust enough to drive on rough terrains and withstand small potholes. Also cornering is possible even though the balancing controller neither gets any information on the speed of the scooter nor on the turning radius. It counteracts the centrifugal forces and disturbances through its robustness.

5. SUMMARY AND OUTLOOK

The presented prototype shows that a reaction wheel is suited to balance a self-stabilizing e-scooter. For this proof of concept, a regular e-scooter was used and augmented with a reaction wheel which is actuated by a brushless DC motor and controlled with a digital motor controller. The implemented controller has a structure similar to a cascade controller and manages to stabilize the scooter in its upright position and to reject small disturbances as for example slight pushes to the handle bar or potholes while driving.

The reference signal ϕ_r shown in Figure 2 is not yet used. When the e-scooter drives autonomously, the reference signal can be utilized in order to lean a bit while cornering. The lean angle ϕ_r can be computed according to the velocity of the scooter and the radius of the curve. By this, more dynamic maneuvers with tighter curves and higher velocities become possible, and the cornering is more robust against disturbances like uneven terrain.
In order to save energy, the controller K_1 can be changed to a PI-controller. The integral part can adapt to constant disturbances which might be caused by sensor misalignment or by the scooter standing on a slope and which result in a shift of the equilibrium point to a tilt angel $\phi^* \neq 0$. Due to the adaption to the real equilibrium point ϕ^*, the offset of the rotational velocity ω as observed in Figure 3 asymptotically decays to zero, which saves energy.

To increase the angle from which the e-scooter can jump up to its upright position, breaking of the reaction wheel can be used as done by Gajamohan et al. (2012). This doubles the total amount of energy that can be transferred from the reaction wheel to the scooter. For standing up, the reaction wheel will be accelerated to its maximum velocity, then stopped and immediately accelerated in the opposite direction. The total amount of energy necessary to move the scooter from an angle ϕ_0 to the upright position can be computed according to its geometry. Those considerations can be used to adjust the size of the flywheel and the length of the kickstand to one another such that it is possible to start the stabilization of the e-scooter from its kickstand.

In order to arrive at a fully autonomous e-scooter, further challenges have to be tackled. First of all, it needs to be able to detect its environment for avoiding collisions with obstacles, for which existing methods can be used (Hoy et al., 2015; Kanellakis and Nikolakopoulos, 2017). Depending on the use case, the sensors used for obstacle detection need to be robust with respect to different weather conditions and lighting.
A requirement for finding its way to a desired position is that the scooter can localize in its environment. Knowing the own position with an adequate accuracy and the capability to detect and avoid obstacles is the precondition for safely finding and following a path.

When considering a fleet of autonomous electric scooters, each individual scooter has to be sent to a desired location. The best possible locations can be determined according to various criteria and also needs to take the state of charge of every e-scooter into account. In the case of a fleet of autonomous electric scooters in a dockless sharing system on the campus of the University of Stuttgart, the criteria can be the time of the day or even the specific schedules for every lecture hall. For a general coverage of a given area, existing deployment algorithms can be used (Breitenmoser et al., 2010; Mahfoudh et al., 2012). In order to incorporate different goals and the state of charge in a meaningful way, the existing algorithms need to be adjusted and enhanced.

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