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New Approach for an Easily Detachable Electric Drive Unit for Off-the-shelf Bicycles

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Summary

While an increasing number of electric bicycles are sold, the majority is still conventional, i.e. pedal powered. But electric bicycles could raise the share of people using them instead of more inefficient modes of transportation. This paper proposes a new approach for an electric drive unit that can easily be attached and detached to a large majority of existing off-the-shelf bicycles to convert them into legal electric assisted bicycles (pedelecs). This is achieved with a single unit that incorporates batteries, electronics, motors and sensors. It is mounted on the seat stay tube with a simple clamp mechanism and powers the bicycle over a friction roller at the rear wheel. The legally required pedal detection is done with an integrated proximity sensor. A prototype is built to prove a simple and unspecific installation and convenient usage.

Keywords: bicycle, electric drive, light vehicles, mobility concepts

1 Introduction

With the ongoing problems of urbanization, which is resulting in increased traffic congestions, bicycles form a more efficient mode of transportation compared to cars and others – not only in terms of energy consumption, but also from space occupation perspective [1]. The electrification of bicycles can improve their usable radius and acceptance, therefore enabling this transportation mode for more commuters. The main motivation of this concept is that most bicycles being sold are still conventional despite a strong trend towards electrically assisted bikes, especially in Europe [2]. Reasons for that are mainly because of the higher initial purchase costs, but also in arguments like the effort for charging in an urban environment and the insecure parking situation of an expensive vehicle outside [3]. In addition, many people still own a conventional bicycle, which is still suitable for them and they would therefore not intent to replace it despite having an interest in e-bikes [3]. A solution for this is to equip existing bicycles with a drive unit, which converts the bike into an electric one. Such a conversion must be achieved as easy and simple as possible. Otherwise, commuters might not accept it as many cyclists might not have the required skills and tools for installation. Besides, it must be easily removable, so that it can be brought indoor for charging while the value of the bicycle remains unchanged. However, these requirements can be challenging to achieve, since bicycles frames are produced in a huge variety and therefore a wide compatibility is difficult to accomplish.

2 State of the Art

There are already a few existing solutions that convert conventional bicycles into electrically assisted bikes. These solutions are at different stages of development: some are readily available on the market, for some the inventors are still seeking for funding, while others are just concepts. Since every bicycle frame is different, the number of models, which they are applicable, can be limited. Different solutions have different conversion mechanisms and ways how the assisting force is engaged. First of all, it is possible to buy conversion kits that can be permanently installed on a frame [4, 5]. Here an extended effort is required for the installation including the use of special tools. Very often, these kits consist of many different components and sometimes even require permanent and destructive alteration of the bicycle. Due to the complicated installation, many users would want to involve a professional mechanic. However, they have to be careful with the liability, since they then by law become the producer of the final e-bike and therefore can be prosecuted in case of malfunctions. Some other solutions are easier to install, but have fixed requirements towards specific frame geometries or rim sizes [6, 7, 8]. For example, mudguards and luggage carriers may not be compatible anymore or the user has to order a very specific kit with the correct rim sizes/brake type/sprocket etc. Another interesting solution is the idea with all required components integrated in either the front or rear wheel hub [9, 10, 11]. While on the first view these look like the most suitable solution, the problem remains that the unit has to be bought matching a specific bike (rim size, tires, brakes, etc.). Furthermore, if mounted on the front wheel, there will be additional weight at the front, which adversely affects the driving dynamics. To remove the conversion kit a swap with the conventional tire is required, or otherwise, the bicycle becomes dysfunctional.

What always has to be considered, are the legislative requirements. While some countries like the United States of America have less strict rules on electric bikes [12], many countries follow the EN15194 standard [13] to decide if an electric bicycle is still accounted as such or is considered as a small motorbike. As an e-bike, most of the time a driving licence is not required, nor is a helmet or a registration (number plate) of the vehicle. To follow this standard, the main elements are a power limitation (250 W max.), an assisting speed limitation (25 km/h max.) and some kind of sensing of the pedal movement, so that the electric assistance is only available while the pedals are moving and not with the signal from a throttle or similar other manual input. While the first two rules can be easily implemented in the motor control, the last one is mostly done with a cadence sensor installed at the bottom bracket. This results in additional efforts in installing and wiring it up. It also will leave remaining parts on the bike after detachment.

3 Approach

To design a more suitable solution, a market analysis was conducted first. This was primarily done to estimate current and future bicycle sales numbers, but also on the other side to get an idea of what a "standard" bicycle looks like and what kind of attachments can be expected. It was found that there is a strong trend towards e-bikes, but a large share of conventional bikes sales would still remain in the near future [14]. Also, due to a rather long average service life, the existing and future bicycle population will still consist mainly of conventional bikes and it will take a long time to change that significantly [15]. Therefore, the availability of electrification kits has a relevance and could electrify additional parts of the bicycle population. For the frame variety, it was observed that unique frames, which are not following the standard diamond shape, only make up for a small percentage. Even small foldable bikes do not have a big market penetration yet [14]. Additionally, a target customer group was defined based on their requirements. It was concluded that an electrification solution is more suitable for commuters and entrance level leisure cyclists, as other users would be willing to spend higher amounts to get a solution that is more suitable for their individual applications.

With this data, different mechanisms of how the propulsive forces of a conversion kit can be engaged to accelerate a bicycle were thought of with a strong emphasis on integration with majority of bicycle frames. Initial ideas looked at tires, wheels, sprockets, chain, crank, pedals and the road itself to design a suitable propulsive mechanism. Several initial concepts were prototyped in a simple way to develop a better understanding, especially on the usability and driving dynamics behaviour, as these are otherwise hard to evaluate.

A design with a friction roller on the rear wheel behind the ending of a possible mudguard was found to be a suitable approach as this area is almost always accessible for most bike configurations. Other bicycle components and areas have a higher possibility of variation and therefore decrease the compatibility of the kit. A one sided application was adopted as it would make the mounting easier for a single person and requires less alignment. Mounting can be achieved on one of the seat stays as long as the bike is following the most common, “diamond” frame shape. For bikes with a luggage carrier there is an additional space requirement between the wheel and the unit to allow additional structural tubes from the luggage carrier. This is accommodated by a slight curve/bending of the unit (figure 1(b)). In this design configuration, the roller is pulling itself towards the tire surface and thus enhancing the contact pressure and friction. This mechanism therefore minimises the slip between the tire and the roller without the need of an additional higher weight of the unit (figure 2(b)).

The required sensing is implemented with a sensor, which measures the distance from a fixed point on the device to the cyclist’s leg over time. With the intended mounting position as shown in figure 1, this is made possible with a proximity sensor located at the very front of the device as seen in figure 2(a). With this configuration, a pedal movement including its frequency can be determined with high accuracy and used as an input signal for the motor controller and therefore the assisting motor power.

Through this design approach, a functional prototype proved to be easy to install, complying with the legal requirements and being able to be used on most of the existing off-the-shelve bicycles.

Figure 1(a): Side view of the prototype; Figure 1(b): Top view of the prototype

4 Implementation

The final prototype consists of a unit that is foldable in the middle to achieve a more compact design when detached. It is milled from aluminium with plastic inserts to house the electronics. The aluminium is coated to have a homogeneous, metallic appearance and the 3D printed plastic parts are spray-painted for a better surface in the right colour. In the front part, there are one battery pack with three Li-polymer pouch bag batteries in series, the mounting unit and the proximity sensor. Sensing is accomplished with an infrared LED and sensor, which outputs an analogue signal depending on how far an obstacle is placed in front of it. The range of the sensor is around 80 cm to cover the whole leg movement possibilities.

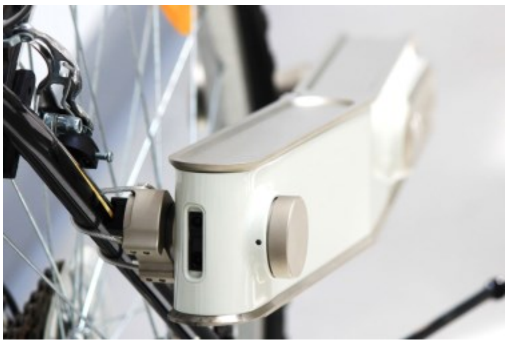

Figure 2(a): Mounting and proximity sensor; Figure 2(b): Friction roller engagement

The mounting unit consists of a sleeved cable loop that can be hooked around the seat stay. By turning a knob, the circumference of the cable loop can be adjusted to tighten the mounting, as shown in figure 2(a). This mechanism thereby allows the unit to be mounted on any kind of tube, independent of its cross section and shape. The mounting unit also has the ability to rotate to accommodate different seat stay tube angles and to ease the installation process. The rotation makes it easier for the user to install the unit as the friction roller can be dropped onto the tire after securely mounting the unit first. The rotation on the other hand could allow the unit to 'bounce' off the tire in certain situations such as driving down a curb. To minimise this effect, a rotational damper is included on the axis of the mounting unit.

The rear part holds a second, identical battery pack with another three cells, the motor including the friction wheel and the electronics. All six battery cells are connected in series to achieve a nominal voltage of 22.2 V and a total capacity of 10 Ah. A battery management system controls several battery functions and can switch off the energy supply in case of a safety-inflicting situation. Beside of that the integrated electronic hardware consists of a DC/DC converter to supply all auxiliaries and a microcontroller platform based on an *ATmega328* created by *Atmel.* External communication is either possible with an integrated USB port or over an integrated Bluetooth module. Two buttons and a 10 LED bar graph as a battery indicator keep the user interface as simple as possible. A rear light, which also functions as a brake light if certain deceleration value is reached, is located at the very rear of the housing. An inertial measurement unit (IMU) is used to recognise on which side of the bicycle the unit is mounted. As the housing is designed symmetrical and the unit can detect its orientation, it can react accordingly and alter the spinning direction of the motor. This enables an even higher bike coverage as on some bikes one seat stay might be impracticable due to some Bowden cables or similar.

The motor is a standard brushless DC (BLDC) electric motor in an "outrunner" configuration, where the rotor with the magnets is turning around the static coils. Its integrated cooling features are enabled with special openings in the housing, where fresh air can be drawn from the opening for the mounting unit when folded and hot air blown out through a gap next to the rear light. The power for the 3-phase motor comes from a microcontroller enabled three-phase full bridge MOSFET inverter. The power electronics are integrated behind a separated metal structure to ensure the waste heat is dissipated to the ambient without warming up the main housing and therefore the batteries. This ensures longer battery life.

The friction roller is mounted directly on the rotating case of the motor and is not coupled to any gears. Two additional bearings support the loads on the motor axle. The roller itself has a blank surface, as the friction is enabled through the forces that pull the roller on the tire. With the avoidance of a special surface, wear and tear can be neglected. The roller profile is designed to be of a concave cylinder shape, which allows the roller to self-centre on the round surface of the tire. As the chosen motor works more efficient at higher speeds, smaller diameters of the roller are preferred. In this case, a roller diameter of 30 mm is selected.

Figure 3: Installation of the unit on a bike with mudguards and luggage carrier

The normal operation pattern for this conversion kit would first be to mount it on the bicycle and then switching it on with one of the buttons as shown in figure 3. The second button can define the level of assistance. The device would then be ready and awaits the cyclist to start pedalling. A feedback from the motor would let the controller know, at which speed the bike is moving. Only if a certain threshold speed is reached, the controller would start to read the signal from the distance sensor to fully avoid false powering. The reading of the sensor is analysed over time to identify typical pedalling pattern in both frequency and amplitudes. If pedalling is detected, the motor is powered according to the current speed and level of assistance. If the speed is over 25 km/h or the pedalling stops, the motor is switched off immediately. With the measurement of current and voltage, it also can be ensured that the mean motor power is within the legally allowed 250 W.

5 Results

With the current implementation, it is possible to realize an electrification kit that is compatible to be mounted on most of conventional bicycles. The prototype was tested on many different bicycle types. The results showed that the prototype worked on majority of the bicycles, even including unconventional bikes like tandems. Problems were however faced with very small bikes like foldables. Firstly, here the length of the unit is too long and also very often the frame comes in very special shapes, not following the diamond shape. A solution for this could be to work with a different mounting mechanism, which can clamp around the seat post, but this is not implemented or tested. Also verified is the usage of different attachments like brakes, additional cables, mudguards, skirt protectors and bags. Only once a luggage carrier with special extension for a child seat was standing out too widely during the tests and therefore made the mounting not applicable. The friction roller was able to run with different tire surfaces. Even tires with rough profile for off-road usage worked, but made more noise. A slippage was not noticeable, even on wet tires.

The pedal detection was found to be working sufficiently well for a prototype. While the initial detection takes two to three rotations of the pedal before the activation of the motor, for stopping, the motor switches off within the required 288 ms. Due to the various requirements and verifications by the code it is not possible to falsely trigger the activation with hand movement or similar. Further improvement is possible with better algorithms on the detection to activate even faster. Additionally force/effort detection could provide increased electrical assist while cycling up steep hills, where currently the support uphill could be more and downhill reaches the speed limit very fast.

For such a solution to be successfully implemented on the market, costs would play an important role. A first complete prototype was built for less than 2,000 EUR in terms of material costs. This is still largely influenced by the expensive, individual 3D printed and milled housing parts along with the components that were sourced from expensive retail sellers. If the quantity for the same prototype with the same components is raised to a small series of 100 pieces, the price per piece can be reduced below 640 EUR. With an analysis of the current market in Germany as a reference, the average price for bicycles 2015 was 685 EUR [3] including the higher priced electric bicycles. This price region should be considered as a maximum target price, as the unit should not be more expensive than the average bicycle.

6 Conclusion

A fully functional prototype unit with the project name “ease” is built up so that it can be tested. It weights around 3.5 kg and is suitable for up to 50 km of range. A patent is applied for and currently in a pending status. It is proven that the system is working in a legal way without any additional attachment like sensors and can be attached/detached in a few seconds. Also it is possible to test it on a lot of bicycles to ensure compatibility. Friction losses in the form of slipping are minimal due to the special geometry of the attachment. Therefore, it could enable that more people equip existing bicycles with an electric support without purchasing a completely new bike. This could make more people to use bicycles instead of other modes of transportation for their daily commutes, which could have an impact on traffic congestion in bigger cities.

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Contributions

F. Roemer was mainly responsible for developing the concept and authoring the article. M. Mrosek and S. Schmalfuss were the executing force of the development and implementation of the concept and their work contributed to the article. M. Lienkamp supervised and evaluated the manuscript.

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Felix Roemer graduated from Technical University Munich as an Electrical Engineer in 2013 and since then is working for TUMCREATE in the team of "Individual Mobility Vehicle & Services" as a doctoral candidate. He was largely involved in the build-up of several, fully functional vehicle prototypes. His main work interests are in the area of fast implementing of electronic components for vehicle prototypes, micro mobility in general and batteries on a system level, where he investigates possibilities of new interconnections to increase overall efficiency.

Marius Mrosek laid out the methodology and multi prototype procedure paving the way for a new approach in bicycle electrification. On the technical side, he was responsible for the electric powertrain, sensing system and its software and analytics. His contribution is summarised in his master thesis about this concept.

Simon Schmalfuss oversaw the structural and thermal analyzations and optimizations. He was responsible for the overall packaging and construction as well as for the mounting system to enhance the usability of ease. His contribution is summarised in his semester thesis about this concept.

Prof. Dr.-Ing. Markus Lienkamp has been the director of the Institute of Automotive Technology at the Technical University of Munich since 2009. After his degree and Ph.D. at the University of Darmstadt he joined VW, where he held different posts, from vehicle dynamics to department manager of electronics and vehicle research.