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Smart e-bike monitoring system: real-time open source and open hardware GPS assistance and sensor data for electrically-assisted bicycles

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Abstract: The smart e-bike monitoring system (SEMS) is a platform for the real-time acquisition of usage data from electrically-assisted bikes (also called pedelecs or e-bikes). It is autonomous (runs off the bike battery), replicable (open source and open hardware), scalable (different fleet sizes) and modular (sensors can be added), so it can be used for further research and development. The system monitors location (global positioning system), rider control data (level of assistance) and other custom sensor input in real time. The SEMS data feeds an online interface for data analysis, for riders to view their own data and for sharing on social media. The basic system can be replicated by other researchers and can be extended with modules to explore various issues in e-bike research. The source code and hardware design are publicly available, under the General Public License, for non-commercial use. SEMS was implemented on 30 bikes and collected data during 10 months of real-word trials in the UK. This study details the design and implementation of the hardware and software, discusses the system use and explores features for future design iterations. The SEMS turns singular e-bikes into a networked fleet and is an example of the internet of things in the cycling context.

1 Introduction

E-bikes are equipped with a power source and therefore offer unique opportunities to monitor and understand usage and their interaction with the urban environment with potential benefits for both e-cyclists and conventional cyclists. A detailed understanding of the usage of e-bikes in specific geographical and cultural contexts can help to understand and communicate their potential benefits for sustainable transport and beyond.

The term ‘e-bike’ in this paper refers to bicycles equipped with a small motor and battery where riders always have to pedal, but can switch on electric assistance (usually with a choice of low, medium or high settings) if they wish. The assistance cuts out when pedalling ceases or the speed of 15 m/h (25 km/h) is exceeded. These e-bikes are often referred to as pedelecs and are popular in many European counties. Other types of e-bikes exist, for example, those where assistance can be used without pedalling – these are especially popular in many Asian countries (see e.g. [1]) but are not within the remit of this research. Many configurations of motor and battery are possible on e-bikes [2, p5] with the models used on this study representing two of the most popular designs: (i) crank-driven motor with central battery and (ii) a front-hub motor with a rack-mounted battery (see Fig. 1).

E-bikes are rapidly becoming mainstream in European countries with developed cycling cultures, appealing to both existing and new cyclists [3]. For example, in the Netherlands, sales of e-bikes equal or exceed those of conventional bikes in value; in Germany, one in ten bikes sold is an e-bike; and there are estimated to be over a million e-bikes in use across Europe [3]. However, they are still not well-known in England. A better understanding of how people in the UK engage with e-bikes could help to identify issues for policy, design and research that could lead to a higher uptake of e-bikes. The 2011–2014 ‘Smart e-bikes’ research project [4] works on this and the smart e-bike monitoring system (SEMS) has been developed as part of this work. The monitoring system is implemented on a fleet of 35 e-bikes in Brighton (UK) (see Fig. 2).

This paper discusses related work, outlines the design framework for the monitoring system, before presenting, in detail, the workings of the hardware and software. It then shows how the monitoring system has been used successfully by 93 participants, including four 8-week public user trials with 20 participants each, and explores features for future design iterations. The system has been designed for and tested with two types of e-bikes, and could be adapted to work with other models. The source code and hardware design are publicly available [5] under General Public License, for non-commercial use.

2 Related work

The tracking of moving objects requires battery power, and therefore this has been largely implemented on those moving objects that already have a battery – typically vehicles with motors such as cars, lorries, boats or trains. Conventional bicycles are an example of a moving object without battery, where tracking is more challenging, as devices cannot feed off an existing power source. Therefore many ways of tracking bike use have focused on devices used by the rider (e.g. their mobile phone) or on attaching devices with a long battery life to bikes [e.g. global positioning system (GPS) trackers]. Whilst valuable in the absence of other solutions, both strategies have limitations, since they require compromise in terms of reliability and/or quality of data – the former because it relies on people taking their phone on each trip made (with the relevant application running), the latter because it relies on an extra device being charged, switched on and attached to the bike (plus, choosing a setting that extends the device’s battery life results in less data being recorded). E-bikes have an on-board battery that can be connected to a monitoring system that tracks the bike (rather than the rider via their phone) while not compromising data quality for battery life (as is often the case in cycling research).

Several projects demonstrate methods for gathering sensor data from cyclists. Dill and Gliebe [6] required cyclists to switch on a

Fig. 1 *SEMS was implemented on the two types of e-bike used in user trials, the Raleigh Dover (left) and the Velo-cité (right); both are used in low-step and cross-bar versions*

GPS device for each trip (and mount it on the bike) and the data was downloaded from the device after a period (of at least 7 days). Their 2007 study used GPS devices on normal bicycles, with 164 participants carrying a GPS device for (at least) 7 days each. The research aimed to map where cyclists were riding their bikes in Portland Oregon to assess the effect of different types of infrastructure, such as bicycle lanes or paths, on bicycling [6]. The team used the Garmin iQue, a GPS personal digital assistant that was programmed to collect additional information from trial participants about the trip and the related weather that had to be put in manually for each trip. The device had to be attached to the bike (unique mounting for each bike type) for each trip taken by trial participants. The data was collected on the device's memory card. After collection of the device, the researchers analysed and visualised the data and subsequently, trial participants accessed maps of all their trips via an online interface where they were asked to add more information for each trip. This required quite a high level of involvement from trial participants (remembering to take the device for each trip and attaching it to the bike, putting in additional information about each trip, charging the device, reviewing and annotating all trips via an online interface).

The Biketastic [7] and UbiActive [8] projects both used Android applications that were installed to run on the participants' own phones and used only the inbuilt sensors on the phone. The Copenhagen Wheel [9, 10] took this further, by connecting the riders' phones with Bluetooth sensors mounted on the bike. Paefgen and Michahelles [11] used the Telex Picotrack GPS monitor to track e-bikes, transmitting data via general packet radio service. The BikeNet project [12] monitored a variety of sensors, including video and pollution monitors, via a mobile phone, and sent data via mobile network and WIFI. Paefgen's Picotrack monitor shows how a monitor can run independently using power from the e-bike battery, however, these modules are limited to GPS sensing only. The BikeNet project shows a good example of using the mobile phone as the central part of a monitoring system. Finally, the Campus Mobility project monitored e-bikes on a university campus [2]. They used a small Android touchscreen computer and GPS module mounted on the bike.

There are several public bike schemes that collect real-time data about their usage but they rely on parking/charging stations. E-bike hire schemes include those in Germany [13] and the Netherlands [14], a forthcoming pilot integrating with a car sharing company in the San Francisco Bay Area [15] and institution-based system such as the one at the University of Tennessee-Knoxville [16–18]. Many hire schemes log data when bikes move in and out of parking stations, but most do not collect data about the actual journey between stations. When analysing the movement of bikes in public hire schemes, the trip data uses the location and time of the station at the beginning and end of each trip rather than a GPS data of the actual route taken, for

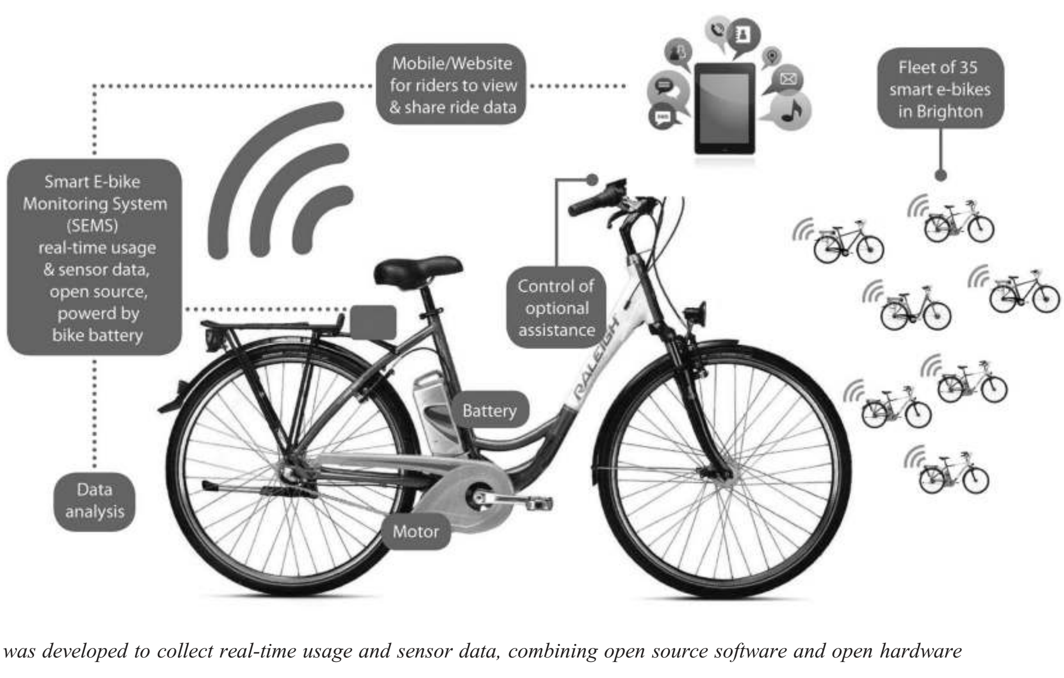

Fig. 2 *SEMS was developed to collect real-time usage and sensor data, combining open source software and open hardware*

example, in an overview and analysis of data from 38 public bike hire schemes across the world [19] and in more detailed studies of specific schemes such as the public cycle hire scheme in Lyon [20], Barcelona [21] and London [22]. Data analysis such as these tend to assume the shortest possible route is cycled between both stations, whereas other research shows that bike trips frequently do not use the most direct route [6]. Therefore it was important that SEMS records the entire e-bike journey in detail. Moreover, the research fleet used by us needed to operate independent of parking/charging stations because trial participants take ownership of an e-bike for 6–8 weeks and use, park and charge them as they please. Hire bike usage differs from personal bike usage, and our trials were designed to simulate e-bike ownership and highlight issues related to this, rather than those faced by a public hire scheme.

3 Design requirements

Scalability, replicability and modularity were overarching concerns for the system design. These make it possible to grow our own research fleet in the future or to replicate the SEMS for other e-bike fleets, for example, in different locations in the UK, or in other countries. This allows for the collection of comparative data and lowers development costs for monitoring of e-bike fleets. To allow for the scalability, replicability and modularity of the SEMS, it was implemented with open source software and open hardware. The additional design requirements for developing a system to collect e-bike use data fall into three categories: experimental, data and engineering. An overview of all design requirements in relation to the projects and systems reviewed in Section 2 is given in Fig. 3.

3.1 Experimental requirements

The key experimental requirement was that no user interaction was needed (e.g. switching the monitoring system on and off, charging it, transmitting data). This ensured that operating the monitoring system is not a factor that could discourage trial participants from using the e-bike or from logging its use. An autonomous monitoring system also improves data quality as the participant is not relied upon to charge batteries, or to remember to attach a device to the bike when they depart for a journey. Additionally, it minimises intervention from the researchers during the trial period which results in a more natural context for the e-bike use.

The SEMS was designed to work with off-the-shelf e-bikes in the low-to-medium price range so that the e-bikes used on trials reflect a typical e-bike experience. The on-bike part of the system needed to be weatherproof and robust to cope with vibrations and shocks from road surface and bike handling. Finally, but most importantly, the system needed to work safely and reliably.

3.2 Data requirements

The system needed to track each bike's location (longitude, latitude, altitude and time) so that each trip can be documented in detail (and visualised on online maps). The altitude data is of particular interest for analysing e-bike usage in relation to the terrain, to see if and how usage (and use of the assistance) might change in relation to the incline (steepness) of the route.

The SEMS needed to track how cyclists use the assistance on the e-bike, including whether the assistance is switched on or off, and, if switched on, reading which level of assistance has been selected (low, medium or high). This allowed us to see how users use the assistance in different ways, if specific types of usage emerge (e.g. a user group that always uses the same setting for all journeys, or another user group that switches the assistance on and off frequently), if these patterns change over time for trial participants (e.g. using less assistance over time), or how assistance use is related to trip length, terrain and other variables.

The system needed to give real-time information so participants can be given live online feedback. The real-time data also gives vital feedback to the researchers for checking on the health and status of the fleet. Additionally, this also allows us to make selected ride information available to the wider public while (and after) it is being collected by e-cyclists, for example, via social media.

3.3 Engineering requirements

Power was a fundamental issue. To fulfil the requirement of autonomy, SEMS needed to draw its power from the e-bike battery and this meant that a key engineering requirement was battery safety. The e-bikes in the fleet use lithium-ion batteries; these can be permanently damaged if too much charge is drawn, so a battery management system was needed to prevent the batteries being drained below 3 V (volt) per cell. In addition, SEMS should not draw so much power as to significantly affect the range of the e-bike, so the monitor had to be designed to conserve energy at every opportunity. The aim of autonomy also meant minimising maintenance; the system needed to be protected from the weather, in particular the corrosive sea air in Brighton, the location of our study. Another concern was theft and vandalism; to avoid undesired attention, the system needed to look as inconspicuous as possible.

Finally, SEMS needed to be compatible with the two models of bike in our e-bike fleet, the Raleigh Dover, and the Raleigh Velo-cité, which we have in low-step and cross-bar versions, and which are all from the 2011 collection (see Fig. 1). The Velo-cité is designed to fit into the GBP1000 (Pound Sterling) price limit of the UK's *Cycle To Work Scheme* that allows employees to get tax and other benefits when purchasing a bike (to fit into this price

Systems & projects (as referenced in the text) / Design requirements for SEMS	Dill & Gliebe	Bike-tastic	Ubi-Active	Copen-hagen Wheel	Paefgen & Micha-helles	Bike-Net project	Campus Mo-bility project	SEMS
Open source software	no	yes	yes	yes	no	no	yes	yes
Open hardware	no	no	no	no	no	no	n/a	yes
No user interaction needed	no	no	no	yes	yes	yes	yes	yes
Weatherproof and robust	yes	no	no	yes	yes	yes	no	yes
Safe and reliable	yes	no	no	yes	yes	yes	yes	yes
Track bike location (GPS)	yes	yes	yes	yes	yes	yes	yes	yes
Track use of assistance	no	no	no	no	no	no	no	yes
Give real-time information	no	yes	yes	yes	yes	yes	yes	yes
Power from e-bike battery	no	no	no	yes	no	no	no	yes
Compatible with our two e-bike models	yes	yes	yes	no	yes	no	yes	yes

Fig. 3 *Overview of SEMS design requirements (rows) in relation to the projects and systems reviewed in Section 2 (columns)*

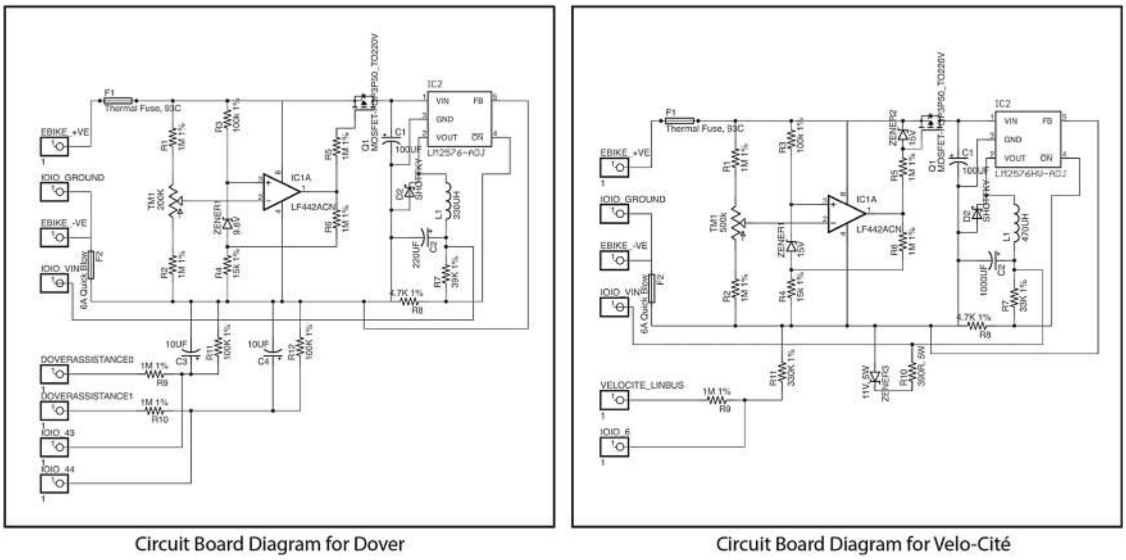

Fig. 4 *Circuit board diagrams for the custom power boards for the Dover (left) and Velo-cité bike type (right)*

bracket, the battery needs to be bought as a bike accessory). This e-bike model has a front wheel mounted motor, and a rack-mounted battery. The Dover e-bike is a medium range model, with a more advanced centrally mounted hub motor and battery. The key differences affecting the design of SEMS were the different drive systems and batteries. The Velo-cité uses a higher voltage ten cell battery with a drive system made by ID-Bike, and the Dover uses a lighter seven cell battery with a Panasonic drive system. This meant that SEMS needed to run in two different voltage ranges, and interface with two different designs of motor control system.

4 Hardware design

The SEMS hardware consists of three main components: an Android phone, an open hardware interface board and a custom power board to connect the system to the e-bike battery. Fig. 4 shows the circuit diagrams for the custom power board for the Dover bike and the Velo-cité. All components are housed in a small water and dust proof box behind the bike rack (under the saddle) as shown in Figs. 5 and 6.

Fig. 7 shows an overview of the monitor system hardware. SEMS is based around an Android phone, coupled with an IOIO board. The IOIO is a low-cost interface board that connects to the phone via universal serial bus. It allows connection with a large range of sensors using analogue inputs and a selection of digital input/output

Fig. 5 *SEMS electronics are housed in a water-proof box that is mounted under the saddle and fixed to the bike rack. No user interaction such as charging or switching on is required*

protocols. An Android software library allows communication between board and phone. This combination gives the benefits of the Android application programming interface (API) and phone sensors (including GPS and accelerometer) along with allowing very flexible hardware customisation with the IOIO. Crucially, the IOIO can be powered by the bike battery, which can in turn charge the phone, allowing the system to run continually without intervention.

4.1 Powering the system

The two bike batteries have different working voltage ranges: the Dover from 21 to 30 V and the Velo-cité from 30 to 42 V. The higher level represents the voltage level after a full charge. The voltage must not drain below the minimum level or it will damage the battery. SEMS connects to the e-bike battery in parallel, at a place in the circuit before the e-bike's drive system; this means it can run when the bike is not switched on, but also means that it needs to provide its own battery management system to prevent over-draining. This management is provided by an under-voltage lockout circuit, which cuts off power to the system below a preset threshold, and restores it when the input voltage rises again. The circuit is designed with a low-power LF442 op-amp to minimise current drain. Both e-bike battery voltages are too high to power the IOIO board which runs at a maximum of 15 V, so the voltage is stepped down using an efficient LM2576 regulator. There are two versions of SEMS, one for each model of bike. The two versions are very similar, with small differences due to working voltage ranges and assistance monitoring methods (see Section 4.4).

4.2 Phone selection

To choose a phone that would act as the hub of each monitoring system, several Android phones were tested. Principal requirements were low cost, boot-on-charge capability, GPS signal quality, third generation (3G) connectivity and good battery life. Boot-on-charge capability was fundamental to achieve the design goal of autonomous operation for SEMS; a phone was required that would boot up automatically (without human intervention) in a situation where it had run out of battery (for any period of time). Restoring the power supply (i.e. attaching a charged bike battery to the e-bike) needed to automatically initiate the recharging of the mobile phone, but also to reboot the phone and launch the SEMS app. This was to cover situations where the participant may run down the bike battery or remove it from the bike, causing the phone to run out of battery. An initial design using mobile phones that do not reboot created problems in real-world use, for example,

Fig. 6 *SEMS electronics, the IOIO board and the Android phone are housed in a water-proof box and are wired into the e-bike battery*

when trial participants were not using the e-bike for longer periods of time, for example, due to holidays or sick leave. Therefore, this feature became the prime requirement for selecting a device. It was challenging to find a low-cost Android phone with boot-on-charge capability, and after some experimentation a phone was found that, after rooting and alterations to low-level operating system functionality, would do this reliably. This phone was the Samsung Galaxy Ace 2 S6500. Further testing of this device showed that the GPS quality, battery life and connectivity were satisfactory for use in the project.

4.3 Deploying the hardware

SEMS was a rolling prototype, so rather than printing a printed circuit board for the power board, the circuits were put together on strip board. This would allow the addition of new sensors and modifications over the project lifetime. The electronic components, consisting of a phone, the IOIO board and the power board, were placed in a environmentally sealed polycarbonate box, mounted using custom brackets in the area behind the saddle. Durable Teflon wiring was used to connect the components in the box.

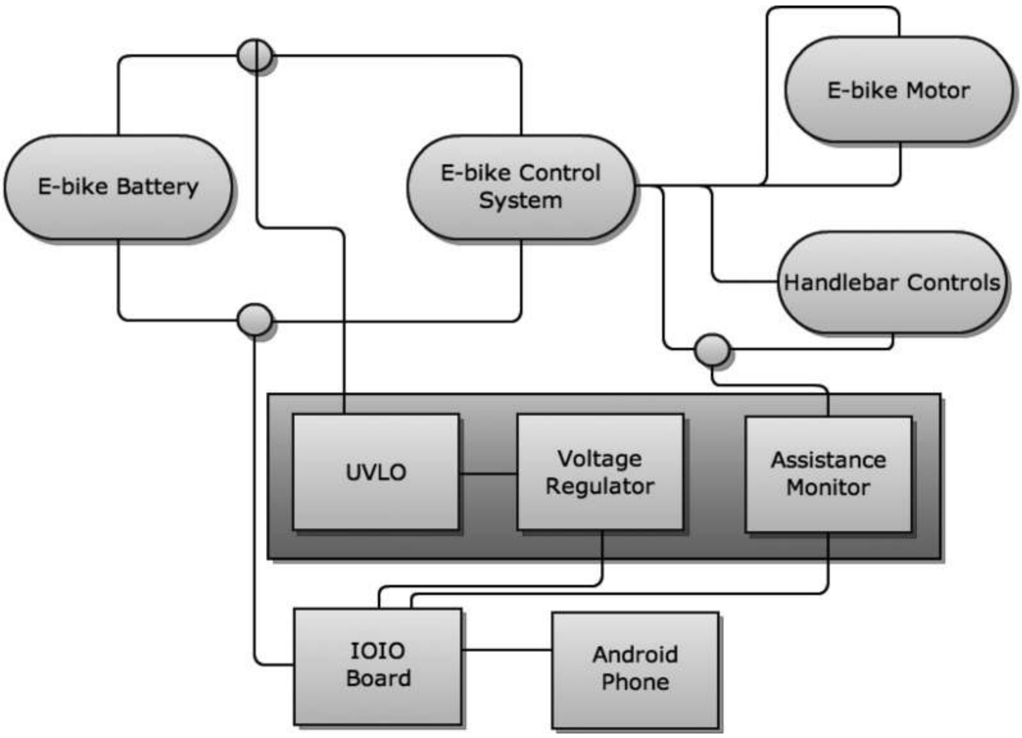

Fig. 7 *Hardware design of SEMS*

Cabling from the bike is secured to the bike frame and enters the box through a gland which is sealed with silicone. The box was grey, and was chosen for its unobtrusive look. To draw power from the bike battery, the positive and ground wires were cut immediately following the battery connector, and rejoined with a three pole connector, allowing SEMS to join the circuit at these points, drawing power even if the bike was switched off.

4.4 Assistance monitoring

A key feature of the electrically assisted bike is that the rider can choose to have assistance with pedalling. On both bikes, riders can switch the pedalling assistance on and off, and are able to change the assistance level that the motor will provide. This level of assistance (low, medium or high) is chosen with a button interface attached to the handlebars.

The two e-bike models feature very different designs for the controller system, so different methods were used to monitor assistance on each bike. The Velo-cité used the local interconnect network bus serial protocol [23] to communicate between interface and motor controller. The bus was connected to a UART port on the IOIO, and software on the phone monitored commands from the handlebar interface to detect assistance level changes.

Monitoring assistance on the Dover was less straightforward as we had no prior information about how the interface communicated with the controller. An experiment was conducted to explore the voltages on the eight wires that run between interface and controller, and two wires were found whose reading were indicative of assistance levels. The voltages on these wires are monitored using analogue inputs on the IOIO.

5 Software design

The software for the monitor system comprises two parts: the phone software (Fig. 8) and the server software (a standard Linux system). The client and server communicate over the internet using HTTP protocol, connecting through a standard mobile data network. Data from the e-bike monitors is received by PHP scripts running in an Apache 2 server, and stored in a MySQL database. There is a web interface for exploring the data, discussed in more detail in Section 6. The code is available from a public online repository [5].

The design requirements in Section 3 stipulate that the phone software needed to run using as little power as possible, and send sensor data back to the project server. To preserve the battery life, the software runs as a background service, which keeps the phone in a low-power sleep state for the majority of the time, with the screen and communications services switched off. Every 25 s, the phone wakes up and polls the accelerometer for 1.5 s. If motion is detected, then the bike is likely being ridden, so GPS and assistance monitoring services are switched on and the data is logged. When motion is no longer detected, all monitoring services are switched off and the programme returns to a sleep state. To preserve power further, GPS data is stored locally, and sent each 25 s in compressed form. The phone records longitude, latitude, altitude and GPS accuracy, approximately once a second. Assistance data is sent to the server every time there is a change. Every 3 h, the phone checks in with the server to indicate that it is still functioning, and sends information about the phone battery level and whether the phone is currently powered from the bike battery. This data is used to monitor the health of the bike fleet and track any problems. A phone battery will last for around 4 days once the e-bike battery has been drained, with the software continuing to send status messages to the server.

6 Online and social media reporting

The online system is used to analyse the sensor data and provide a reporting framework. There are two facets of the system: one private site for researchers where all data is accessible, and a private site for participants to view their own data as they progress through a trial (with secure log-in). Fig. 9 shows an example (fed by test data) of the site that trial users would see after logging in. The ride data can be accessed in real time, but also later on when both riders and researchers can go through the archive of rides that has been built up over time. Trial participants sign consent forms detailing the collection and use of their ride data.

The system is built using Python and the Django web framework, so as to give access to *Numpy*, a scientific computation package that is used for analysis of the sensor data. The core of the system analyses the GPS data, segments the data into separate trips and calculates statistics about each trip: length, duration, start time and end time. Trips are segmented using a time threshold, with gaps of more than 3 min between GPS reports marking the end of a trip. Trips are shown using a web interface, where the user can view individual trips on a map created with the OpenStreetMap API.

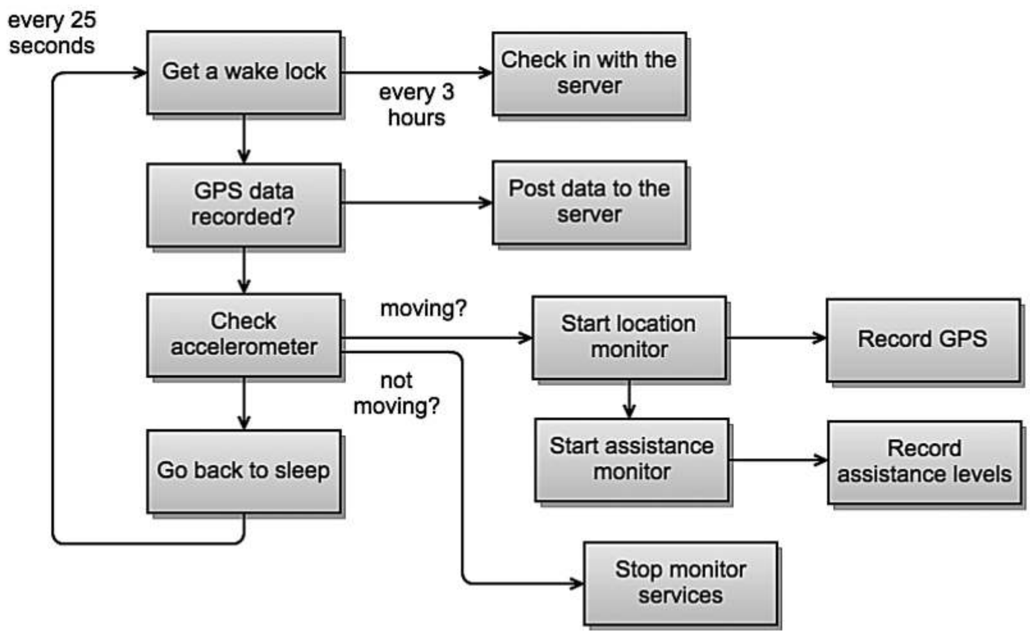

Fig. 8 *Design of the SEMS software*

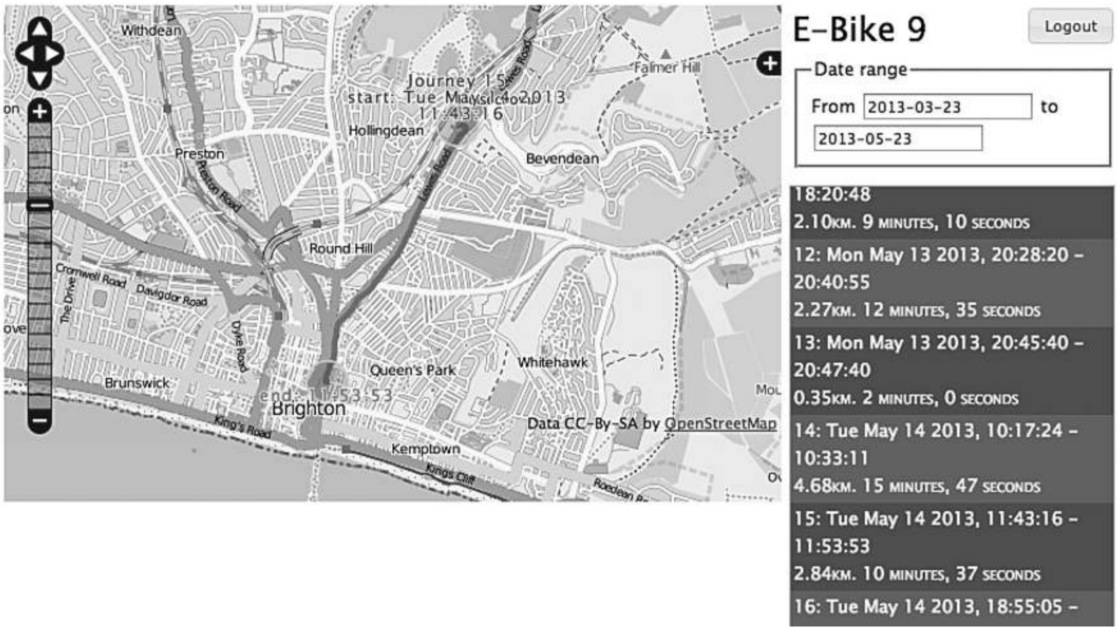

Fig. 9 *Trial participants can view their own ride data via an online interface with secure login*

A Twitter feed is used to share aggregated and anonymised information about the trial bike use within the group of trial participants and with the wider public (see Fig. 10). This is an automated daily summary of how many trial participants have used their bikes, how many trips they made and how many kilometres they covered collectively.

7 System in use

In 2012 and 2013, four phases of 20 participants from two large employers in Brighton trialled the bikes for a period of ~2 months each. Initial results of the 2012 commuter trials drawing on surveys [24] and interviews [25] have been reported; future analysis will include the GPS data collected by the SEMS. Furthermore, trials with participants from the local community took place in 2013, bringing the total number of trial participants using SEMS to 92. The system had a maximum of 30 riders using the system concurrently. Over the four phases, the system recorded 3645 trips, totalling 11,700 km, 775 h riding time and around 3,250,000 GPS data points.

Fig. 10 *Social media reporting of SEMS data via Twitter. Daily tweet conveys the overall milage of the fleet to trial participants and the wider public*

The reliability of the system was tested through triangulation between the different datasets that were collected for each trial participant: surveys (before and after), interview or focus group, odometer mileage and SEMS data. This reflects the mixed-method approach of this interdisciplinary research project. As one check, people's assessment of the average mileage that they cycled on the e-bike during a typical week of the trial (survey) was plotted against the total mileage (based on GPS) recorded by the SEMS. This shows a reasonable, though not perfect correspondence. As a second check, the GPS readings from the bikes were assessed against the interview data, to see if there was a correspondence between the distance reading, and what people said about their use. No obvious discrepancies were identified. While longitude and latitude measurements were satisfactory, there were some issues with variance in altitude data quality, as illustrated in the example in Fig. 11. This could be corrected by using the *Ordnance Survey Terrain 50* dataset as a ground truth.

Three iterations of the SEMS were used on the trial during 2012 and 2013 (the SEMS described in this paper is the third and final iteration) and this is reflected in the data collected. Iteration one of SEMS was used by 29 participants and did not monitor assistance (this was still under development) and used a non-auto-rebooting phone (see Section 4.2) which resulted in some GPS data not being recorded for some participants. The researchers received automated alerts from the server if a participants monitoring system was close to running out of battery (because the bike battery had not been recharged for a time) and contacted the relevant trial participants to ask them to either place a charged battery on the bike or to keep a paper record of their trips, with almost full compliancy. For the participants that used the first SEMS iteration and where some of the GPS data was lost, a mix of paper records (verified as described above) and GPS data is used for analysis. Iteration two of the SEMS used an auto-rebooting phone (see Section 4.2) and no significant GPS data gaps occurred during the trial use by 20 participants,

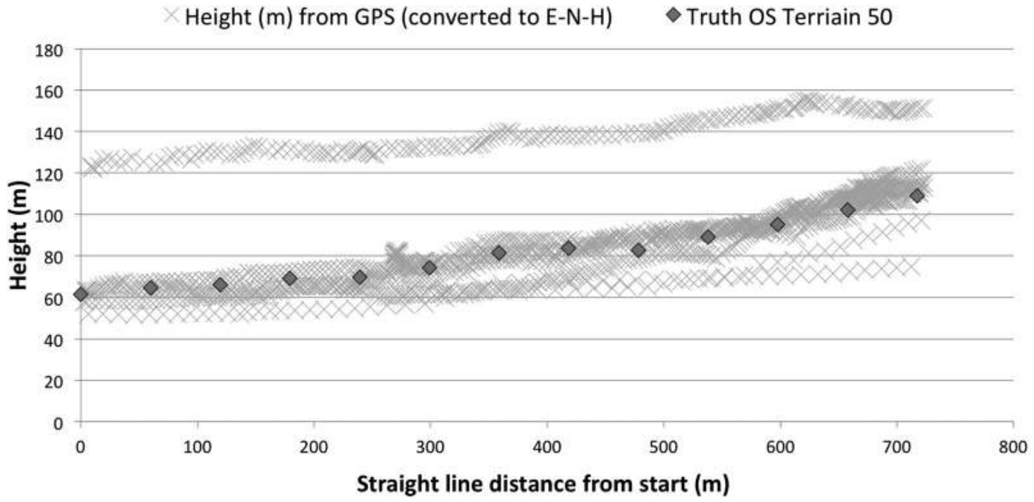

Fig. 11 *Example of GPS height data for journeys on a hill in Brighton*

evidenced through triangulation as described above. Iteration three of the SEMS featured assistance monitoring and was used by 43 trial participants. The assistance monitoring was tested prior to the trials on each SEMS through an experiment by the researchers where they cycled a set course and used a set sequence of assistance levels that were recorded on paper and through the SEMS and subsequently compared. Fig. 12 shows an example of assistance data collected with iteration three of SEMS.

The GPS data is analysed by using python code for cleaning, summarising and segmenting into trips (see also Section 6). Drawing on all three iterations of the SEMS, as a minimum, for all participants, we have two headline figures: the number of days that the bikes were used during the trial periods, and the total distance travelled by the bikes. For sub-sets of trial participants (see above), we have a much more detailed dataset. The assistance data is recorded with a time stamp, and can therefore be analysed in conjunction with the GPS data.

8 Discussion

The SEMS is a reliable way of collecting, analysing and displaying e-bike usage data. Initial teething problems have been eliminated through several design iterations, and the SEMS has proved stable during several months of trials over 2 years. Some key issues that have emerged during the design, implementation and trial usage of the SEMS are discussed before contemplating future work.

The SEMS represents a trade-off between autonomy and data quality on one hand and affecting the battery life of the e-bikes on the other hand. The system, and especially the phone that is part of it, runs down the e-bike battery over time, which affects the battery life in different ways than usual e-bike use. A normal e-bike battery runs out depending on how much it is used while riding, with a number of variables affecting this, including how much the ride assistance is switched on, what level of assistance is selected, the length of the ride, the topography of the ride, the weather conditions (especially the wind direction and speed) and the weight carried on the bike (rider and cargo). The SEMS runs down the e-bike battery in a different way, as it mainly consumes battery over time, rather than only depending on the ride. If a normal e-bike is left parked up for several days or weeks, the battery level will be (almost) the same when the bike is used again after the break in usage, as no bike battery is used when the bike is stationary. An e-bike with the SEMS slowly uses up the e-bike battery to establish whether the bike is moving or not.

SEMS has two power consumption modes: when the bike is not moving as little power as possible is used when checking for movement with the accelerometer. During movement, more charge is used because the GPS receiver is powered and data is transmitted over the cellular 3G network. If a SEMS bike is left

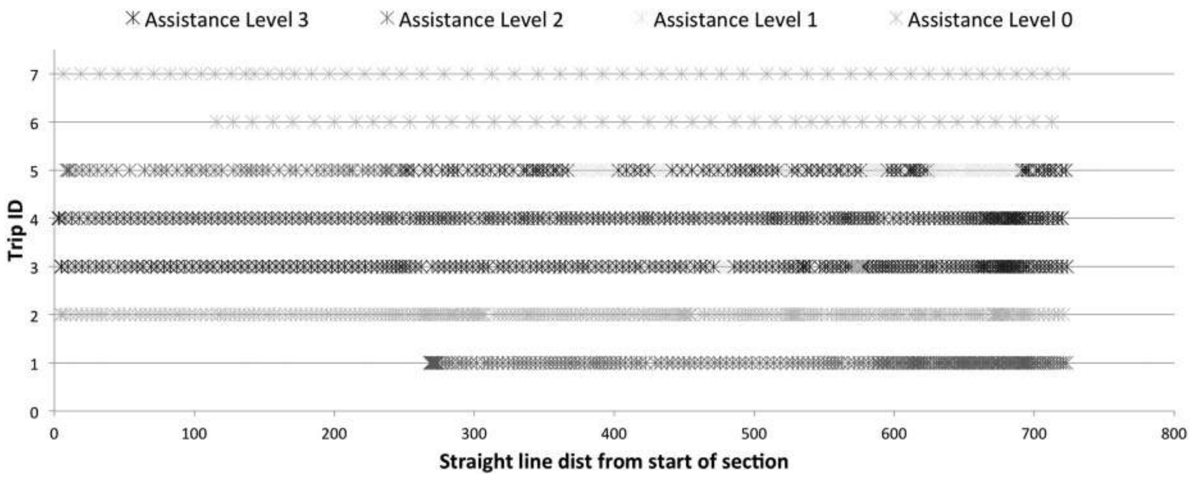

Fig. 12 *Example of results from assistance monitoring, for journeys on the hill detailed in Fig. 11*

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unused, with the bike battery plugged into the bike, the e-bike battery will be slightly less charged if a rider comes back to the bike after several days of non-usage, and after about 10 days of non-use, the bike battery will be empty. After taking a break in using the e-bike (e.g. due to holidays or illness), a trial participant has to recharge the bike battery before taking the first ride. Alternatively, trial participants can remove the bike battery from the e-bike, and plug it back on the bike when resuming use (when the battery is not connected to the bike, the SEMS cannot run it down). Trial participants are made aware of this battery behaviour, and how it differs from an off-the shelf e-bike. The vast majority of trial participants are very happy to compromise battery life in return for the ease of data collection. However, post-trial, many trial participants also report that they would find full battery life very useful if they were to own an e-bike themselves.

One of the unintended benefits of the SEMS became apparent when one of the e-bikes was reported stolen by a trial participant and the location of the bike could be determined by the researchers via the online interface. After consultation with the police the e-bike could be safely retrieved. The use of locational data for bicycle safety is important for private owners and for fleet bikes.

9 Future work

There are several ideas for future extensions and iterations of the SEMS. These draw on the experience gained from running the system for 2 years, on feedback from trial participants and from the companies involved with the commuter trials as well as from discussing early findings with other researchers. One of the areas we are particularly interested to develop further is the use of SEMS and the e-bike fleet as part of a sensing network to collect local environmental data. For example, we could attach sensors to monitor noise pollution [26] or air pollution [27]. Another area of interest for future development is to extend SEMS to measure health variables such as heart rate monitoring and torque sensor data [28]. This would represent a mobile health use case of SEMS. An example could be smart e-bikes being used by those currently physically inactive, as part of a health programme at work or through a doctor (similar to current interventions with gym memberships). The combined bike use data and health data could then also support the economic case for this kind of health intervention.

The system could also be developed to read detailed data about the e-bike battery usage. This could be of interest to a range of stakeholders, including e-bike manufacturers, battery manufacturers and those purchasing or using fleets. Fleet management of public or private e-bike fleets could also be part of future developments. This use case concerns a fleet of public bikes that are available for hire through public bike stations. Using a public fleet with SEMS would enable crowd sourcing of bike and sensor data at scale as it would engage with a large number of bike users and with usage over time. Another potential use case is the area of cargo e-bikes for urban goods delivery. In this case, the SEMS could be developed to interface with the goods management system and the battery use to calculate optimum routes, to visualise goods progress in real time to customers, and to calculate carbon savings compared with other modes of transport. Another potential use case for SEMS is intermodal transport. This would involve the integration with other modes of transport via systems such as smartcards or mobile phone ticketing and payment systems. Due to the modular design and the open source nature of SEMS, some or all of these areas could be integrated and several of the use cases could be explored in more detail. This would work towards a toolkit of e-bike data that can be combined as needed.

10 Conclusion

The SEMS is a stable platform for collecting, analysing and sharing data about a fleet of e-bikes. The design, development and implementation of the system contributes to understanding e-bikes as a distinct mode of transport, and to conceptualising a fleet of e-bikes as a distributed network, or an Internet of Things. The current status of the SEMS fulfils the design aims set out in advance, with the system running stable over extended periods of time and with large numbers of e-bikes in use simultaneously. The system works autonomously, resulting in high-quality and real-time data about each bike's location and the level of assistance chosen by trial participants. It is always on and requires no interference from researchers that might influence normal participant behaviour. The open source approach in designing the SEMS makes the system replicable by other research projects, following the details on our online repository [5]. Future developments of the SEMS could include research into health, environmental factors such as sound and pollution, battery usage and fleet management, by implementing the relevant sensors.

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