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Cyclist 360° Alert: Validation of an Instrumented Bicycle Trajectory Reconstruction Mechanism Using Satellite and Inertial Navigation Systems

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Abstract

Cycling is an increasingly popular mode of travel in cities owing to the great advantages that it offers in terms of space consumption, health and environmental sustainability. However, the number of recent accidents between cyclists and heavy goods vehicles has increased substantially. Our study shows that one of the main causes of accidents is drivers not being able to observe cyclists. Thus, this research reported here involves the development of an innovative low-cost technological solution called Cyclist 360° Alert and as an integral part of this system, this paper focuses on the bicycle localization aspect and presents an approach based on low-cost micro-electromechanical systems (MEMS) sensor configurations on an instrumented prototype bicycle system, called “iBike”. The iBike has the capability of sensing its motion, which can be then analysed to compute the trajectory path. The paper describes the overall system of the instrumented bicycle which incorporates an Inertial Navigation System (INS) and a Global Navigation Satellite System (GNSS) receiver. The paper then evaluates and compare the accuracy of the three positioning systems using experimental field data. Finally, the paper also draws conclusions on the applicability of specific sensor configurations, both in terms of sensors’ accuracy and reliability with respect to the measurements of motion, and the ability of tracking trajectories based on the data gathered from the sensors.

1. INTRODUCTION

Cycling is an increasingly popular mode of travel in cities due to the great advantages that it offers in terms of space consumption, health and environmental sustainability, and is therefore favoured and promoted by many city authorities worldwide. The large number of recently introduced schemes in many cities (such as the Barclays Cycle Hire scheme, now sponsored by Santander, and the Cycle Super-Highway in London (TfL, 2010) (TfL, 2008)) demonstrates this trend. The European Cyclists’ Federation (ECF) is working on tripling cycling in Europe by 2020 (Kuster, et al., 2010). However, the relatively low perceived safety of cyclists from the users’ side currently presents itself as a major hurdle to the desired uptake of cycling as a viable alternative to the private car, with a particular source of hazard appearing to originate from the interaction of cyclists with Heavy Vehicles (HVs), i.e. buses, coaches, and Heavy Goods Vehicles (HGVs). Accident numbers, unfortunately, confirm this perception as reality: as reported in the Times, in 2012 there were 122 cyclist fatalities in the whole of Britain, almost a quarter of which (30) involved HVs (The Times, 2013) Related research analysing trends from previous years suggests that this figure is even higher in urban environments, namely of the order of 43% in the example of London (Morgan, et al., 2010).

Motivated by the poor safety record, this paper briefly presents the development of an innovative low-cost technological solution to tackle the cyclist-HV collisions problem, called Cyclist 360° Alert and as an integral part of this system, this paper presents an instrumented bicycle (iBike) which has been equipped with modern electronics sensors including low-cost Micro-electromechanical systems (MEMS) sensors to take sample measurements of its motion parameters such as steering and tilt angles. The ultimate idea is to use the sensors data to reconstruct the trajectory of the bicycle, hence, this paper then presents experimental results which has been based on ground-truth data in order validate trajectory reconstruction mechanism of the instrumented bicycle. Furthermore, to valid and to compare the accuracy of the iBike system with off-the-shelf positioning systems that can give latitude and longitude information, the instrumented bicycle is also equipped with a GPS receiver and a Spatial INS.

The paper is organised as follows: Section 2 reviews cyclist collisions and analyses their trends, thus establishing the necessity and importance of this project. In Section 3 the main conditions and occurrence of accidents are identified, and the novel Cyclist 360° Alert concept is introduced. Section 4 presents the overall concept behind the tracking of motion of bicycles, including the principle of a dead-reckoning technique suitable for the reconstruction of bicycle trajectories. Section 5 then presents the overview of the iBike system and the prototype instrumented bicycle developed for this project. Section 6 reports on the experimental results obtained from the iBike , INS and GPS systems and then evaluates the accuracy of each of the systems based on various control points which were obtained by conducting a survey prior to the experiment using a surveying equipment. Section 7 concludes the paper and outlines the next steps of the research.

2. BACKGROUND

In Britain, every year approximately 19,000 cyclists are killed or injured in road accidents, including around 3,000 who are killed or seriously injured (RoSPA, 2013). The Department for Transport (DfT) has recently released the quarterly provisional estimate of Q2 of 2015, which provides estimates of personal injury road accidents and casualties. The release covers the year ending June 2015, and includes accidents on public roads in Great Britain, which became known to the police within 30 days. The graph in *Figure 1* provides a comparison of reported killed or seriously injured road casualties by road user type for each year from 2006 to 2015. The road user type includes car, pedestrian, cyclist and motorcyclist. The graph clearly indicates a rise of cyclists' casualties in recent years while the trends for other road users are declining. In contrast, *Figure 2* compares pedal cycle casualties by severity with the cyclist traffic in Great Britain between 2000 and 2014. It is also clearly shown that the number of seriously injured cyclists has dramatically increased in relation to the increase in pedal cycle traffic.

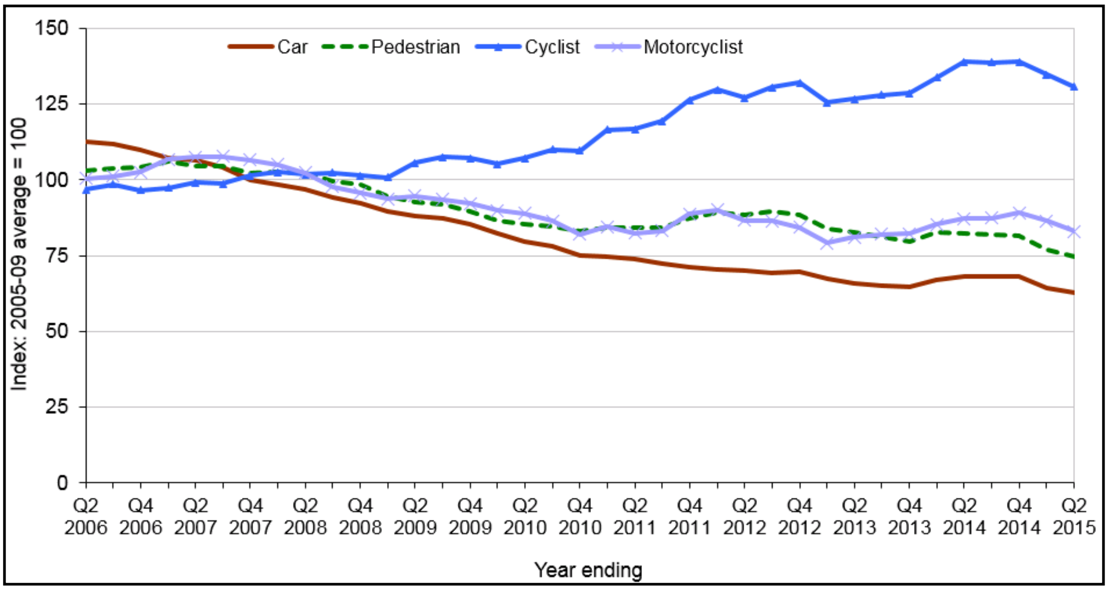

Figure 1: Reported killed or seriously injured (KSI) road casualties by road user type (DfT, 2015)

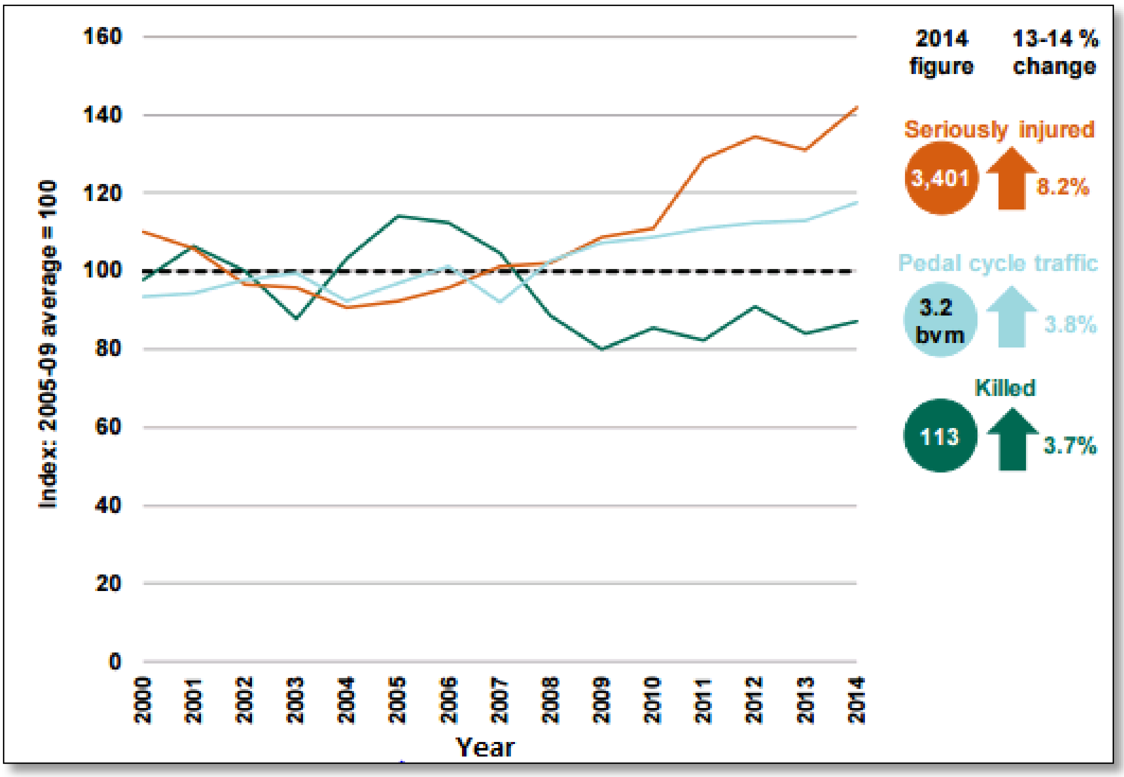

Figure 2: Pedal Cycle Traffic and Reported Casualties by Severity in Great Britain (DfT, 2015)

As can be seen, cyclist casualties are a serious and growing problem, especially when many authorities are promoting cycling through a number of related schemes. As a result, many cycling proponents, such as the European Cyclists' Federation (ECF), ask for measures to be implemented in order to reduce injury and fatality rates for cyclists (Kuster, et al., 2010), and many stakeholders are keen on finding solutions that can achieve that, and thus help promoting cycling.

A number of factors are associated with a collision but one issue that is common with bicycle-related accidents is the blind spot areas around large vehicles. Blind spots are regions of the road that the driver is not able to see by looking directly or through a mirror. Blind spots are also created by the chassis of the vehicle, and especially the windscreen pillars and the area under the windscreen, because of the driver's higher seat position. Typical regions of blind spots surrounding a lorry are illustrated in Figure 3 (a), where the pink-shaded regions on the figure are the blind spots. For example, the four cyclists in the figure are completely obscured by the blind spots, and so the driver would not see them from their normal driving position, as only the green-shaded areas are visible to the driver. In particular the left-hand side blind spot is most hazardous to the cyclists, because the driver sits on the opposite side and is unable to observe the blind spot area by look down the window directly. Furthermore, the side mirrors of an articulated lorry become even less beneficial when it is partially turned, such as at an intersection where the lorry needs to turn left. This is where the most common type of fatal collisions for cyclists could take place.

Moreover, despite measures to improve the HV driver's field of vision, there is still an area around the vehicle that the driver is unable to see through the windows or with the help of mirrors and cameras. In addition, the mirrors may not always be adjusted properly, which unnecessarily increases the area not visible to the driver. Above all a HV driver has to contend with a heavy mental burden when they want to turn: the driver must keep an eye on all the traffic at the junction by looking through the windows and in all mirrors. However, not all of the mirrors are in the same direction of view and the eyes take time to change between the mirrors and this may give rise to a situation where a cyclist is overlooked (SWOV, 2012). Although the common perception is that the cyclist-HV related accidents can be solved by utilising more mirrors, this observation is not reflect in the accidents statistics (Schoon, 2006).

3. PROPOSED APPROACH

The solution to the problem of cyclist-HV collisions proposed in this study is to give HV drivers an aerial view of their vehicle so that they are able to observe the blind-spot regions, hence to detect cyclists in their vicinity. The system is called Cyclist 360° Alert, and its concept of operation is illustrated in *Figure 3* (b). As it can be seen, the idea is to enable 360° viewing for HV drivers through an in-vehicle or potable display unit, such as a smart-phone, allowing them to perceive potential hazards earlier, hence be prepared to stop, if necessary, in order to prevent a collision. The system should be able to function in all conditions and environmental settings, as it needs to reply on non-line-of-sight technology. It is also to be integrated with additional features, such as trajectory or path modelling and non-visual interfaces (e.g. auditory and haptic feedback), so as to facilitate more effective warnings to both HV drivers and cyclists.

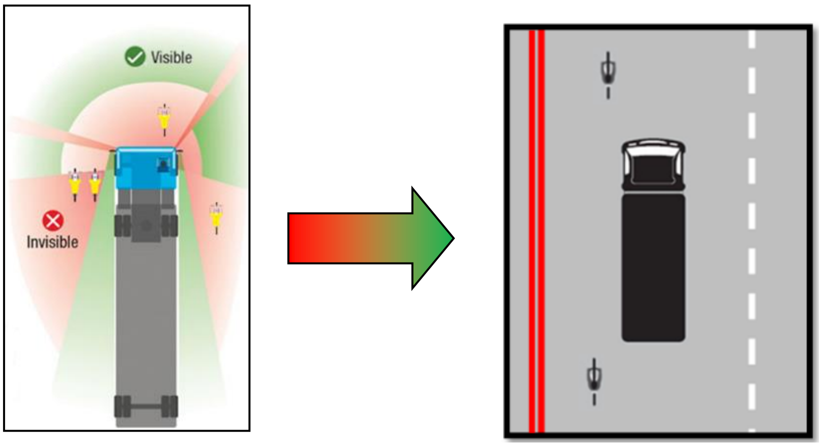

Figure 3: (a) Blind Sports Surrounding a Lorry, (b) Cyclist 360° Alert Driver's Display View

The Cyclist 360° Alert system requires the localisation and tracking of bicycles, as well as vehicles, in real-time, in order to deliver the proposed 360 view graphical representation, and the main challenge associated with this goal is the high positioning accuracy required for both road users groups. Specifically, Cyclist 360° Alert requires positioning with precise coordinates rather than merely an approximate location indication, and targets a minimum accuracy of 1m at a speed of 32 km/h, as lower accuracy than this may result in large positioning errors. However, bicycles are significantly smaller in comparison to HVs, only occupy a small amount of space and are able to move more freely than vehicles on the road, which makes their real-time tracking to the desired accuracy a difficult task. To the best of the authors' knowledge, a single system fulfilling this requirement is not available as yet; hence a new approach is needed to achieve this. This should rely on existing technology, with cost being a major constraint on the development, as Cyclist 360° Alert needs to be a cheap solution that can eventually be integrated in all bicycles and HVs.

A review of existing localization technologies was conducted to assess if the current localization technologies can be used to locate the bicycle with an accuracy of 1m, and it was found that although most of the technologies, such as GPS, Wi-Fi and radio-frequency identification (RFID), can be utilized to estimate the location of the bicycle, they do not provide sufficiently high resolution and accuracy to locate and track a bicycle in real-time mainly, due to its size and manoeuvrability. A technology, on the other hand, that could satisfy this technical requirement is ultra-wideband (UWB), which has a maximum accuracy of 30 cm (10); however, current legislation restricts it to indoor usage only, in order to prevent harmful interference with other radio wave communications. As such, a single technology alone cannot be utilized to track a bicycle with a good accuracy to satisfy the requirements of the Cyclist 360° Alert system, and instead a hybrid localization system approach needs to be adopted. This involves bicycles instrumented with low-cost sensors, such as the ones commonly found in smart devices, to monitor its motion and to sense the surrounding local sensors, such as Wi-Fi signals. Using an appropriate sensor fusion technique, the sensor data can then be combined to reconstruct the trajectory path or localization information of the bicycle. This method can provide the desired localization accuracy in a cost-effective way for the cyclists, i.e. riders' smart phones can be used to substantially reduce the cost of the system on-board the bicycle as smart phones already have most of the necessary sensors and processing tools.

4. BICYCLE TRACKING AND POSITIONING

Bicycle localization accuracy can be increased if the trajectory can be reconstructed based on its motion parameters. On that basis, a method to predict the trajectory of a bicycle between two known points from the various motion parameters can be developed, which can be utilized to reduce the localization error through a relevant mathematical model. Thus, the focus of this paper is the reconstruction of the bicycle ground-path trajectory based on a dead-reckoning technique, and therefore this section briefly describes this concept.

The kinematics of bicycles are far more complicated than of other vehicles due to the fact that when a bicycle stands still its dynamics are analogous to an inverted pendulum: it is a nonlinear, non-minimum phase system, and is therefore unstable when not controlled appropriately. In other words, a detailed model of a bicycle is complex, as the system has many degrees of freedom and there are not many studies that can adequately illustrate the working principles of a bicycle. Furthermore, the front wheel mechanism of a bicycle is much more complex than the rear wheel one, as the wheel can be steered and tilted simultaneously. Therefore, to reconstruct the bicycle trajectory, only the rear wheel path is traced, using the dead-reckoning technique described as below.

Equation (2) represents the geometric relationship of the rear wheel yaw angle (ψ), where: d_r represents the distance covered by the rear wheel between two points, W is the wheelbase and β is the effective steering angle of the bicycle, which is based on the tilt angle and the handle bar steering angle according to (Yi, et al., 2006). Equation (2) can be used in conjunction with equation (1), which is the generalised formula for radius of curvature for vehicles, to compute the radius of curvature of the rear wheel, as portrayed by Eq. (3):

$$Radius\ of\ Curvature\ (R) = \frac{Length\ of\ Vehicle\ (L)}{tan(Steering\ Angle)} \tag{1}$$

$$\psi = \frac{d_r \cdot tan(\beta)}{W} \tag{2}$$

$$R = \frac{d_r}{\psi} \tag{3}$$

So, depending on the rear wheel yaw angle, the bicycle trajectory can be computed as follows:

- For yaw angles of less than a certain tolerance, it can be simply approximated as a straight line given by equation (4):

$$\begin{aligned} X_{[n]} &= X_{[n-1]} + d_{r_{[n]}} \cdot sin(\psi_{[n-1]}) \\ Y_{[n]} &= Y_{[n-1]} + d_{r_{[n]}} \cdot \cos(\psi_{[n-1]}) \\ \psi_{[n]} &= \left(\psi_{[n-1]} + \frac{d_{r_{[n]}} \cdot tan(\beta_{[n]})}{W}\right) mod 2\pi \end{aligned} \tag{4}$$

- For yaw angles of more than the tolerance, it can be approximated with a two-step method – firstly by computing the coordinates of the centre of a circle with equation (5) and then by computing the distance travelled in the circumference through Equation (6):

$$\begin{aligned} Cx_{[n]} &= X_{[n-1]} - R_{[n]} sin(\psi_{[n-1]}) \\ Cy_{[n]} &= Y_{[n-1]} + R_{[n]} cos(\psi_{[n-1]}) \\ \psi_{[n]} &= \left(\psi_{[n-1]} + \frac{d_{r_{[n]}} \cdot tan(\beta_{[n]})}{W}\right) mod 2\pi \end{aligned} \tag{5}$$

$$\begin{aligned} X_{[n]} &= Cx_{[n]} + R_{[n]} sin(\psi_{[n]}) \\ Y_{[n]} &= Cy_{[n]} - R_{[n]} cos(\psi_{[n]}) \end{aligned} \tag{6}$$

The above equations were utilized to compute the trajectory of the bicycle in the iBike architecture, described next.

5. OVERVIEW OF THE ON-BOARD SYSTEM OF THE INSTRUMENTED BICYCLE

Based on the method described in section 4, the two main motion parameters, which are required in order to reconstruct the trajectory based on the dead-reckoning technique, are the yaw angle and the distance covered by the rear wheel of the bicycle. As stated in the previous section, the yaw angle can be found indirectly using the measurements of the handle bar steering angle, tilt angle, and distance covered by the rear wheel. For this purpose, a ‘Santander Cycle Hire’ bicycle has been supplied by TfL and has been equipped with an absolute encoder, a Hall Effect sensor and two sets of MEMS gyroscopes and accelerometers. For the iBike system, an Arduino microcontroller board is employed to continuously fetch the raw data from the input sensors and to transmit the data to the laptop at 66Hz. The data acquisition software on the laptop then stores the data on a database in real time in a synchronised manner.

Figure 4 illustrates the complete on-board system of the instrumented bicycle. For validation purposes and to compare the accuracy of the iBike system with off-the-shelf positioning systems, the instrumented bicycle is also equipped with a GPS receiver and a Spatial INS (Advanced Navigation., 2015) systems. As can be seen in the diagram, a smartphone together with an app called GPSLogger was utilised to gather the raw GPS data which was locally stored during the experiment. On the other hand, a data acquisition software was developed in order to capture the raw data from the Spatial INS system, hence, the laptop was also used to store the INS data on a database.

Two of the outputs of the GPS and INS systems are latitude and longitude information, thus, the trajectory information was relatively easy to gather from the stored data during the experiments. On the other hand, iBike system is only designed to output the raw sensors data and it does not contain the latitude and the longitude information. Therefore, a MATLAB script was developed to convert the raw data and to use the model stated in the previous section to compute the trajectory based on the motion parameters.

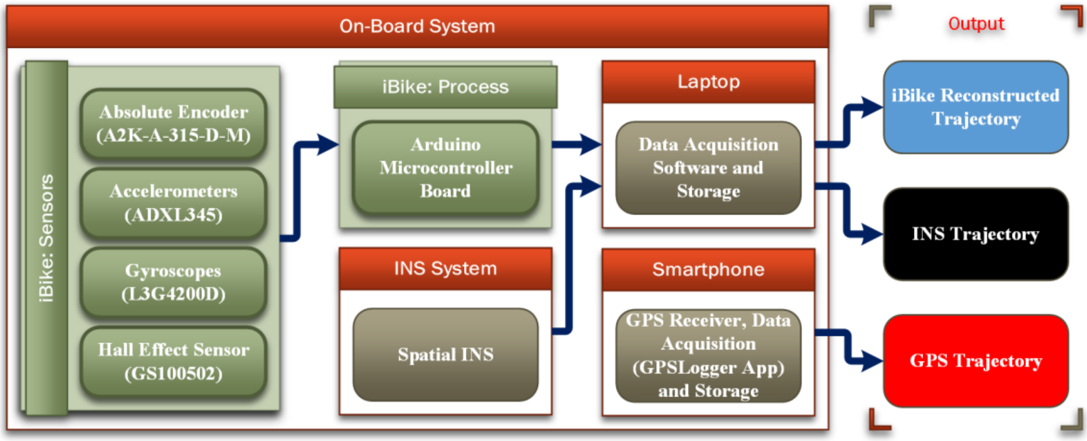

Figure 4: iBike System Diagram

FIGURE 5 illustrates the actual instrumented bicycle with the sensor configuration and shows the actual positioning of the each of the sensors or systems. In addition to the sensors and system modules described above, the instrumented bicycle also has a camera which records the rear wheel path so that the information from the captured footage can be used to validate the trajectory.

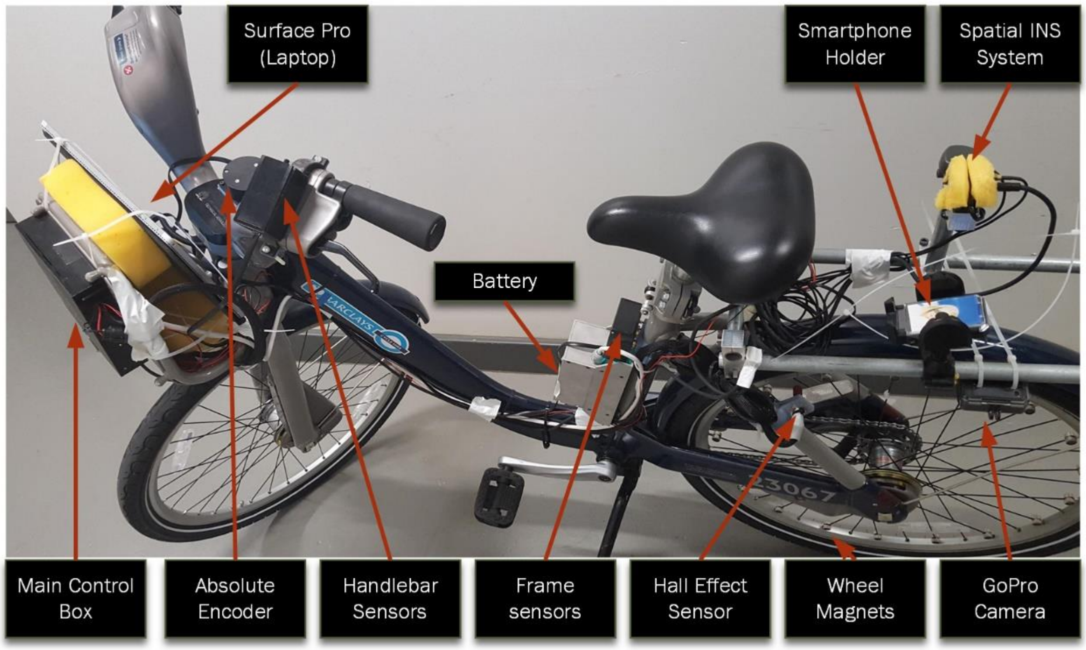

FIGURE 5: The Prototype Instrumented Bicycle (iBike) with INS and GPS System

6. EXPERIMENTAL SETUP AND RESULTS

For the experimental setup, a route was selected and surveyed using a Leica TCRA1103plus electronic tacheometer and this was done prior to the actual experiment with the instrumented bicycle. During the survey, a number of control points were measured and their coordinates in terms of Ordnance Survey (Easting and Northing) were recorded and then the recorded data were later transformed to latitude and longitude (Ordnance Survey , 2016). This was done in order to validate the computed trajectory based on the sensor configuration discussed above and to measure accuracy of the iBike system with the on-board INS and GPS systems. Thus, during the actual experiment with the instrumented bicycle, the bike was ridden over the set of control points or as close as possible to the points. As a result, the true position of the bicycle at the control points were available and this enabled to approximate the accuracy of each of the systems on board as the latitude and longitude information of the control points were known prior to the experiment. The selected survey route consists of Myddelton St, Gloucester Way and Whiskin St in London EC1R. *Figure 6* illustrates: (Top) two control points along the selected route with their ID, (Bottom Left) the surveyed route in OS map and (Bottom Right) the satellite aerial view of the experimental area.

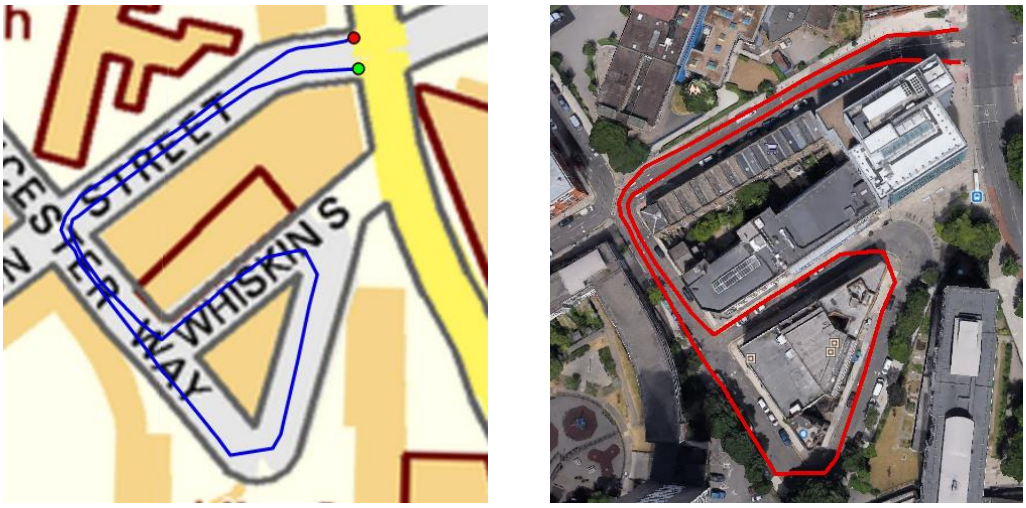

Figure 6: Top - two control points along the survey route, Bottom Left - OS map with Survey Path, Bottom Right - Satellite view of the experimental route

The graph in Figure 7 illustrates the results obtained from a single Journey ID 10013 along the surveyed route shown above. In the graph, the blue line with stars represents the computed path from the iBike sensors data, the pink line with squares represents the trajectory based on the control points established prior to the experiment, the red line with circles represents the GPS trajectory based on the collected data using the smartphone's GPS receiver and finally the black line with plus signs represents the INS trajectory based on the Spatial INS system. As can be seen from the graph, the trajectory for each system differs to each other. However, the reconstructed trajectory based on the iBike data is more consistent with the survey path that incorporates the control points whereas the GPS and INS have a large discrepancy. Furthermore, the reconstructed trajectory from the iBike system is also more smooth and it resembles natural behaviour that a bicycle would follow while being ridden but the INS and GPS trajectories do not illustrate these features throughout the trajectory.

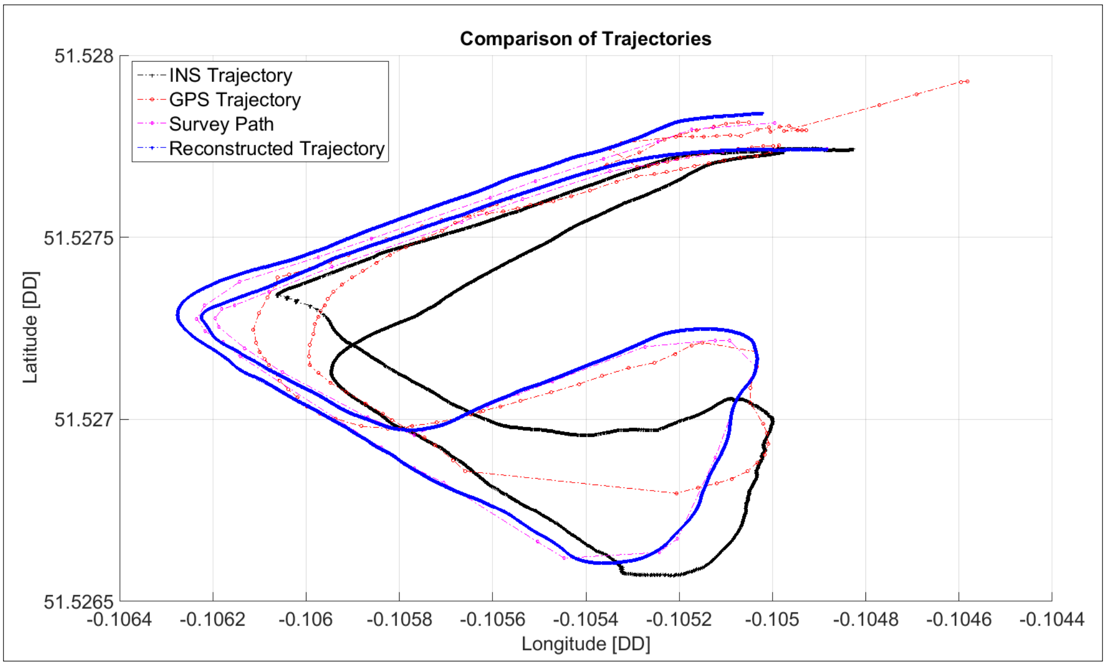

Figure 7: Comparison of INS, GPS and iBike trajectories with the Survey Path

For the Journey ID 10013 there were in total 46 control points, 257 sample points from the GPS system, 6482 points collected from the INS system and 6482 points collected from the iBike system. However, as there were only 46 control points, a method had to be developed to compare the three trajectories and to compute the mean positioning error at each of the control points. As a result, sample points associated with the control points were extracted from from the data using a k-nearest neighbours algorithm, available through MATLAB's "knnsearch" function. Thus, the extracted points using the algorithm are illustrated in *Figure 8*, where the blue line with stars represents the extracted iBike data, the pink line with squares represents the actual coordinate of the control points, the red line with circles represents the extracted GPS data and finally the black line with plus signs represents the extracted INS data.

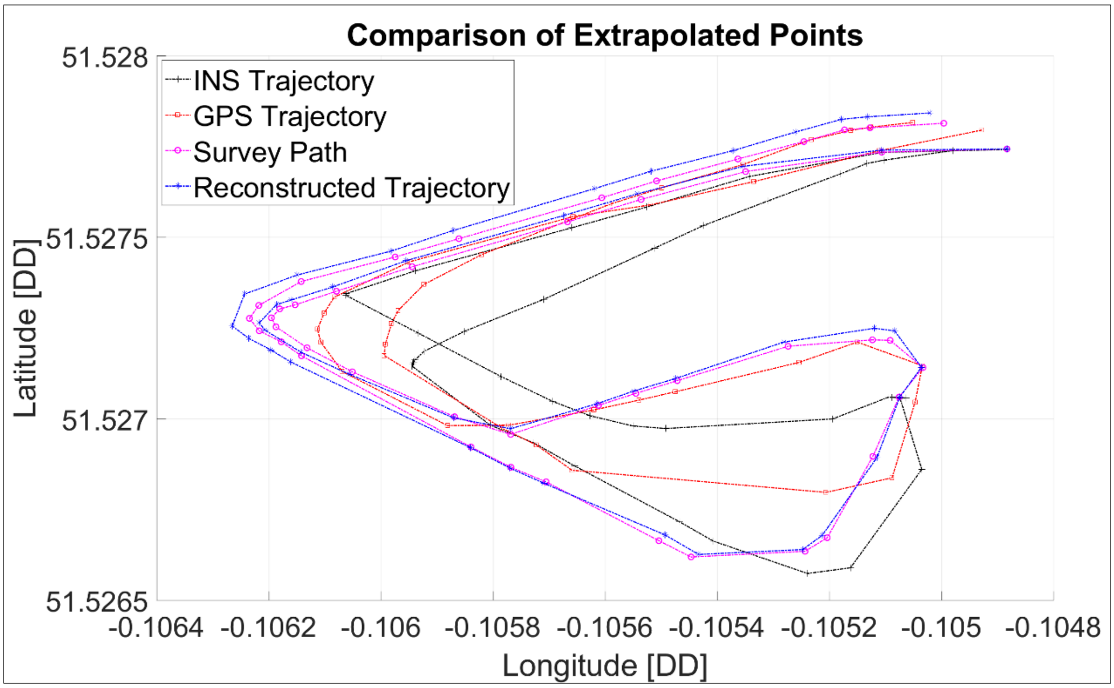

Figure 8: Comparison of Extrapolated Control Points for INS, GPS and iBike trajectories

Furthermore, error values were computed at each of the control points with their corresponding extracted points for each of the system and were then compared with the control points; the error values, along with the mean error, are shown on the graph in *Figure 9*. As can be seen, although, the mean error falls slightly above the target accuracy for the iBike system, results are promising, as the iBike system appears to be capturing the bicycle trajectory fairly satisfactorily and it already proofing to be a better system in comparison with Spatial INS and GPS system.

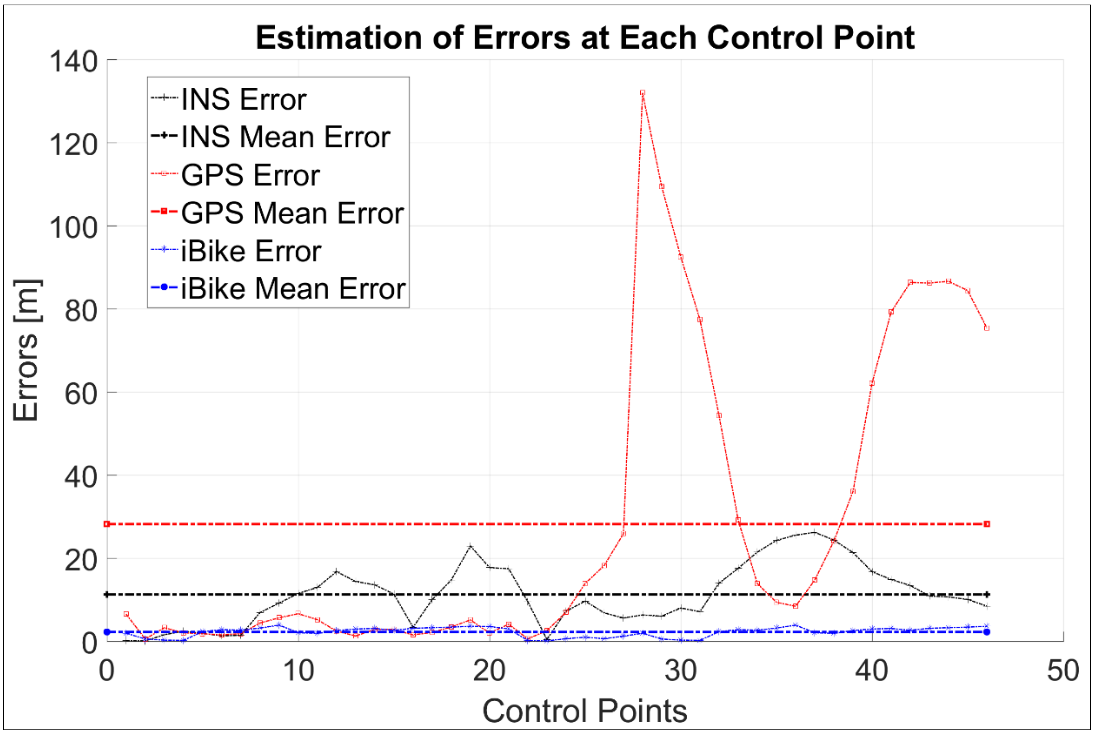

Figure 9: Error Estimations at each control point for INS, GPS and iBike with Mean Errors

Table 1 summaries and compares the mean positioning errors for each of the positioning system with Journey ID 100013. It is clear from the results that the iBike system performed better in this experimental setup than the INS and GPS systems. On the other hand, the INS system also performed better in relation to GPS, and this is an expected result as using a GPS receiver by its own in urban areas can lead a very high inaccuracy from its actual true position.

Estimation of Mean Errors (m)			
Journey ID:	**iBike:**	**INS:**	**GPS:**
10013	**2.2318**	**11.2598**	**28.1825**

Table 1: Comparison of Mean Errors

7. CONCLUSION AND FUTURE WORK

With bicycle-related accidents with HVs, especially in cities, being a growing problem in modern society and many stakeholders seeking to find solutions, this paper presents the first stage of the development of the timely Cyclist 360° Alert system, which aims at addressing this problem. Considering that one of the main causes of accidents between cyclists and HVs is that the driver cannot see the cyclist due to their small size and their erratic movement, a system architecture design was formulated, which is to provide the driver with an aerial view of their vehicle through the use of localisation systems. The system relies on an instrumented bicycle (iBike) MEMS sensor configuration, and preliminary results obtained through the instrumented bicycle demonstrated the appropriateness of the approach and illustrated it is possible to achieve high accuracy using the developed sensor configuration. Furthermore, it can be concluded from the results that the mechanism which is employed for the reconstruction of trajectories based on the sensor data is valid and that the mean accuracy of the iBike system is better in comparison with the Spatial INS and GPS systems on-board. However, our aim is to achieve approximately one metre accuracy in order to avoid false alerts being triggered by the system due to positioning error which can be distractions for drivers and false alerts could be dangerous in some cases as drivers may fail to see an obstacle. Therefore, it has already been identified that a KALMAN filter could be incorporated in the post-processing algorithm to improve the positioning errors and work has already began to implement this with further field trials data.

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