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Conceptual Model for Single-Lane Infrastructure-Less Tollgate System (Slits) Using IoT and GEO-Fencing

Garikayi Manjengwa*, Desiree Gandawa and Nicholas Taruvinga

Department of Applied Physics and Telecommunications, Faculty of Science and Technology, Midlands State University, P Bag 9055, Zimbabwe

Abstract

Zimbabwe Government invests significant amount of money is to construct tollgates infrastructure along its major roads with the intention of generating road maintenance revenue. This research exploits the use of Geo-Fencing (G-F) with the aid of GPS systems to create cheap infrastructure-less tolling system that is more efficient compared to the current ZINARA tolling system. The city geographical boundaries generate a digital G-F around it. The coordinates of the G-F that intersect with the road network on the digital map thus become the virtual toll points (tolling points). Vehicles equipped with active GPS systems linked to a toll-fee account, constantly communicates with the control centre, relaying real-time vehicle coordinates to the servers. Billing is affected every time a vehicle crosses the tolling point. Successful model functionality of the infrastructure-less tollgate system is presented and developed using Arduino micro-controllers and a modified GPS map-matching algorithm. The successful prototype functionality presented is proof of concept that reveals significant cost saving in improved tollgate system implementation, which enables an increased traffic flow rate, reduction in traffic delays and system scalability.

Keywords: Geo-Fence (G-F); Global Position System (GPS); Tollgate; Electronic transport monitoring system

Introduction

The use of tracking systems is a relatively mature technology that has been applied in vehicle fleet management, navigation, military, etc. [1]. However, design considerations continue being presented in various systems depending on the application and system requirement. Our research focuses on tracking vehicles using GPS data, monitoring whether or not a vehicle on a prescribed route passes a toll-point. Zimbabwe current tollgate systems slow down movement of vehicle services where motorist stop to make the toll payment [2]. The current system besides being expensive to construct and delaying users, it is inefficient for emergency vehicles especially during peak hours when traffic congestion is high [3-5]. With this broad range of current system shortfalls, thus a fast-autonomous tollgate system thus becomes a more preferred solution. The Central Vehicles Registry (CVR) of Zimbabwe recorded a total of 14 470 imported vehicles during the first quarter of 2017, evidence of an increase in the amount of traffic in our road network [6]. Tollgate gantry buildings (infrastructure) provide shelter, security for personnel and operating equipment but current research findings reveal that this requirement is unnecessary since it results in cumulative costs of salaries, equipment, security, maintenance etc. The use of an advanced autonomous tollgate system is a cheaper solution that potentially improves vehicle traffic monitoring, reducing the human interaction in the tolling system and increase traffic flow. Zimbabwean Government introduced the manually controlled tollgate revenue collection in year 2009, where twenty two (22) structures where constructed. The construction of each tollgate has an estimated cost of approximately $3 million through the loan facility from Development Bank of Southern Africa (DBSA) to Infra-link on a 70-30% joint venture between ZINARA and Group Five [7]. Map showing 22 Zimbabwean tollgates and showing a typical current infrastructure of Gweru-Kwekwe tollgate.

SLITS uses GPS's trilateration mathematical principle from satellites constellation to determine the position and movement of activated vehicles using the L1 frequency of 1575.42 MHz in the UHF band. Successful deployment of this system requires that all Zimbabwean registered vehicles should have the transponder device installed and have an active toll-fee account. Active GPS systems of vehicles, linked to a toll-fee account, constantly communicate with the central control, relaying real-time coordinates to the servers. Billing is affected every time a vehicle crosses virtual tolling point as shown in Figure 1.

Figure 1: Diagram showing vehicle movement tollpoint tracking at Gweru-Kwekwe tollgate to-and-from route.

***Corresponding author:** Garikayi Manjengwa, Department of Applied Physics and Telecommunications, Midlands State University, P Bag 9055, Gweru; Zimbabwe, Tel: +263773291068; +263736592301; E-mail: manjengwag@staff.msu.ac.zw

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Methodology

Hardware design implementation

The SLITS uses current wireless telecommunication technology to develop real time GPS based tollgate system using Geo-Fencing (G-F) to monitor vehicles on Zimbabwe's road network. The vehicle system constantly collects GPS data and transmits it to the central control centre server where a modified mapping- matching algorithm runs on the data to determine whether a toll-point has been crossed and determines vehicle route direction. When a match occurs, the system automatically affects a toll fee to the user toll- account depending on the vehicle class category. To achieve these, an Arduino Uno R3 micro-controller Atmega 328PU with GPS connectivity and Wi-Fi using a fourth generation (4G) mobile Huawei E589u-12 m was connected as shown in Figure 2. Table 1 summarizes the used modules functions and purposes.

The vehicle unit collects GPS NMEA data, which contains position coordinates, date and time as vehicle travels on the road network. The Arduino extracts and processes collected data, then sends it wirelessly to the central control station server. A backup micro SD storage system was included to increase system reliability in case of network failure. The control station servers are also connected to databases for registered users, predefined toll-point(s) and a digital road network interface upon which a G-F is drawn. The algorithm continuously mines the received GPS data and compares the data with any of the predefined toll-points for a match. When the GPS data matches that of any predefined toll-points, the vehicle is said to have crossed the G-F and charge is applied for that vehicle depending on the ZINARA vehicle classification. The toll amount is debited on user's toll-account and a user toll history is created. The system allows the user to receive notifications, route toll-access history, and access and manage the toll-account.

Module	Function
Microcontroller	Coordinates and controls the vehicle unit modules
GPS module	Captures continuous route vehicle GPS coordinates
Wireless Wi-Fi Arduino shield	Provides a connection platform for Wi-Fi module to the microcontroller
Wireless mobile Wi-Fi router	Provides vehicle unit a mobile wireless 4G connection to internet
Wi-Fi module	Provides vehicle unit LAN Wi-Fi connection
4G MIMO vehicle antenna	It strengthens the mobile Wi-Fi connection

Table 1: Module functions.

Human machine interface configuration

To configure an interface that creates the G-F, modules libraries were imported, the variables for storing GPS location declared and set pins to connect the Cellular+GPS (FONA 808) breakout board. Next, an instance of the FONA808 was created and initialized. A watchdog was enabled that would reset the Arduino if it is stuck. For location monitoring the GPS was enabled to increase tracking accuracy of the float variables containing the location coordinates. The GPS fix is set to track the vehicle, using the loop () function of the sketch, if the location matches the boundary coordinates then an instruction of billing is effected to the user toll-account. The system is integrated with Adafruit IO to display the location of the vehicle in real time on a digital map and sends alerts in case the G-F is crossed. For alerts and communication, the GPS parameters and vehicle module ID are entered and initialized.

The modified map-matching algorithm with route direction determination

This algorithm was modified so that at any given time the amount of GPS data instances being handled by the central control servers is kept minimal (Figure 3). This ensures that that system runs efficiently through minimizing memory utilization all the time. The assumption was keeping a complete route GPS data for the vehicle was not necessary for this research. Of importance are the three instances when the vehicle crossed the G-F shown in Table 2. However, route direction is also important and should be included on the user toll-report. For this reason, a modified map-matching algorithm was designed to capture and temporarily store the only four most recent GPS data instances. When a toll-point match occurs, the direction of route could be determined from these recent instances i.e., location instance before match, toll-point match instance and the first instance after toll-point. For a vehicle, in a toll route from point X to point Y, real time GPS data set is collected automatically in a table as shown in Table 2 where, t_{c-0} becomes the current instantaneous time. The system identifies the points where the Geo-Fence intersects the major highways and saves those coordinates as a toll-point La_{τ}; Lo_{τ}. The algorithm mines recorded data in real time continuously searching location coordinates that match those of the toll-point. For simplicity we let $\{G_i\}$ represent a set of instantaneous GPS received data and thus G_{τ} represents the toll-point location coordinates.

If at any time, the location GPS coordinates matches any predefined toll-points, i.e., $G_i=G_{\tau}$ then the vehicle is located at the toll-point and three sets of location coordinates are automatically captured and saved

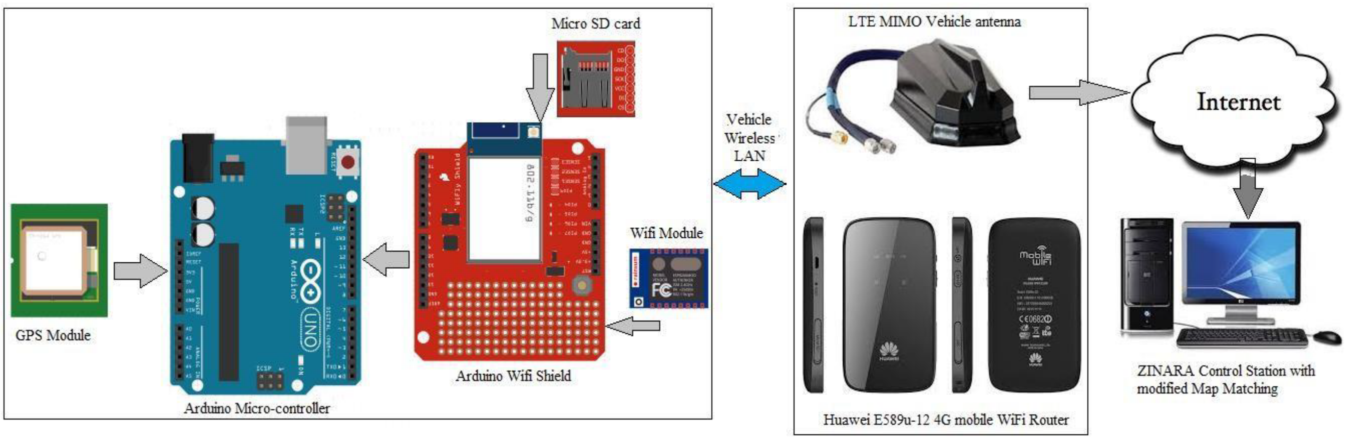

Figure 2: Block diagram of the SLITS system.

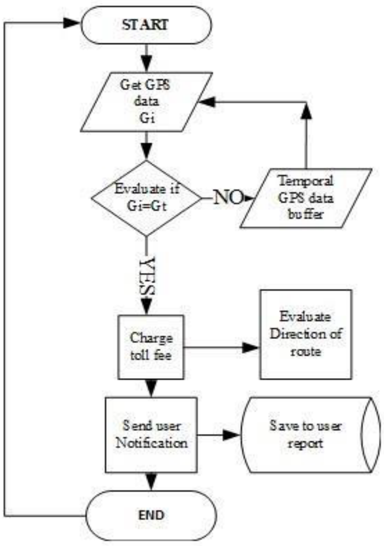

Figure 3: Flowchart of the modified GPS data matching algorithm.

Time	Latitude	Longitude
$t_{(c-0)}$	$La_{(v-0)}$	$La_{(v-0)}$
$t_{(c-1)}$	$La_{(v-0)}$	$La_{(v-0)}$
$t_{(c-2)}$	$La_{(v-0)}$	$La_{(v-0)}$
$t_{(c-3)}$	$La_{(v-0)}$	$La_{(v-0)}$

Table 2: Table of the four vital most current vehicle locations.

Time	Latitude	Longitude	Toll-point Match?
$t_{(c-0)}$	$La_{(v-0)}$	$La_{(v-0)}$	No
$t_{(c-1)}$	$La_{(v-0)}$	$La_{(v-0)}$	Yes
$t_{(c-2)}$	$La_{(v-0)}$	$La_{(v-0)}$	No

Table 3: Table of route direction determination.

as shown in Table 2. The system saves the time of match and the first set of instances before and after the toll-point i.e., $G_i \neq G_\tau$ thus how the direction of vehicle route is determined. The user toll-fee account profile is updated, toll fee is charged depending on vehicle classification and the direction the vehicle is travelling. The system was also designed to minimize saved GPS data. Only four current location coordinates are kept within the system as it continuously searches for a match as shown in Table 3. Coordinates that do not match that of the toll-point are automatically deleted after t_{c-3}. This ensures that the system data storage does not get overwhelmed quickly especially during map matching for multiple vehicles.

Results and Discussion

Figure 4 shows the SLITS prototype, which comprises of modules described in Table 1. Figure 5 showing SLIST Wi-Fi antenna design interface. The system autonomously monitors the movement of a single vehicle on a to-and-from Kwekwe-Gweru route in real time (Tables 4 and 5). However increased system sensitivity of 1 sec update interval yielded track points that are erroneous that may cause the system not to detect vehicle G-F crossing at the toll-point as shown in Figures 6-8. Relevant references are listed [8-13].

Conclusion

A Single Lane Infrastructure-less Tollgate system was developed and tested. The successful operation on the model using GPS data

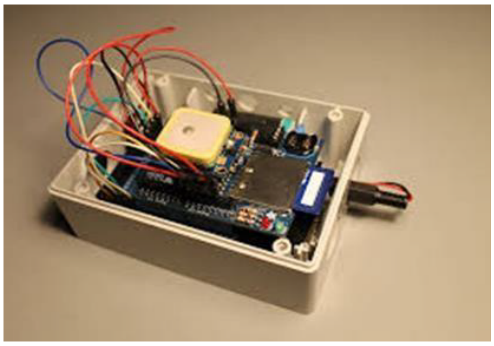

Figure 4: Diagram of the vehicle unit for the SLITS prototype.

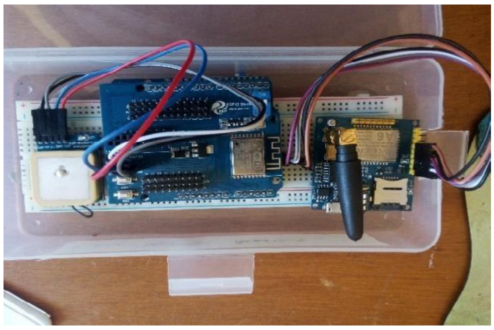

Figure 5: Diagram showing SLIST Wi-Fi antenna design interface.

Time	Latitude	Longitude	Altitude	Speed
21:55:41	-19.312322410	29.794230630	1416.1	19.6
21:55:44	-19.312224420	29.794133100	1416.0	18.3
21:55:47	-19.312117030	29.794035770	1415.6	19.1
21:55:50	-19.312010540	29.793981520	1414.8	12.2
21:55:53	-19.311947480	29.793959240	1414.5	7.4
21:55:56	-19.311935180	29.793954820	1414.0	0.0
21:56:41	-19.311935180	29.793954820	1414.1	0.0
21:56:44	-19.311935180	29.793954820	1414.2	0.0
21:56:47	-19.311749860	29.793844790	1414.3	6.0
21:56:50	-19.311635320	29.793751970	1414.2	11.7
21:56:53	-19.311482470	29.793644660	1413.4	16.4
21:56:56	-19.311245540	29.793593430	1411.9	21.6

Table 4: Table of vehicle GPS data on Gweru-Kwekwe route.

Time	Latitude	Longitude	Altitude	Speed
07:15	-19.311677970	29.794014420	1406.6	20.4
07:15	-19.311729050	29.794029380	1406.1	19.4
07:15	-19.311777220	29.794042910	1405.8	18.4
07:15	-19.311825190	29.794055950	1404.8	15.7
07:15	-19.311825190	29.794055950	1404.8	0.0
07:15	-19.311825190	29.794055950	1404.8	0.0
07:17	-19.311825190	29.794055950	1404.6	0.0
07:17	-19.311825190	29.794055950	1404.3	0.0
07:17	-19.311875880	29.794008320	1401.5	15.4
07:17	-19.311930100	29.794034760	1400.3	23.8
07:17	-19.311989500	29.794057960	1400.3	25.5
07:17	-19.312053170	29.794092230	1400.5	28.3

Table 5: Table of vehicle GPS data on Kwekwe-Gweru route.

and Geo-Fencing confirms a reduction in construction expenditure, increased traffic flow rate, an increase in emergency vehicle movement efficiency, a real time lane monitoring of vehicles. To improve on the

Figure 6: Vehicle route tracking on Gweru-Kwekwe route.

Figure 7: Vehicle route tracking on Kwekwe-Gweru route.

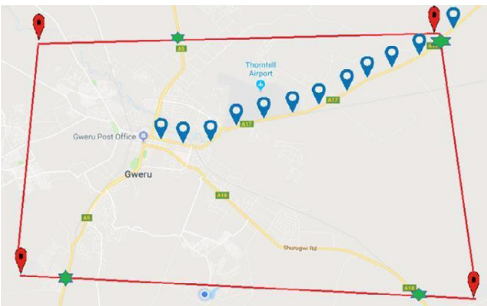

Figure 8: Diagram of a typical G-F superimposed over Gweru road network and showing the four-current toll-points on all highway roads connecting to the City.

error of missing the toll-point, we reduced accuracy resolution and EGM96 correction could be included in the map-matching algorithm.

Comments and Project Outcomes

This project successfully investigates and presents as a plausible proof of GPS based tolling concept that can be applied in developing countries at reasonable initial cost. For countries that already have the manual toll-gate system, such a concept can be adopted on other road networks as ways to increase revenue collection and increase traffic flow rate.

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