

SMS-OPTIMIZED CONSUMER-GRADE TRACKING SYSTEM FOR LOW-COST MONITORING

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Abstract

Consumer grade tracking systems exist but are not optimally designed for low-cost operation in the Philippines setting. Tracking devices typically use Global Positioning System (GPS) and Global System for Mobile Communications (GSM) technologies. Commonly, for device management and real-time tracking, data are transmitted as General Packet Radio Service (GPRS) to a proprietary or third-party cloud service. This method is costly in the Philippines context as well as power consuming. This study was conducted to design a tracking system that is optimized for short messaging service (SMS) mode of data transmission. This study covered the design of a tracking device using consumer-grade hardware components, development of system interface to enable remote operation using commands sent as short message(s), development of a simple desktop client monitoring service and actual field-testing using land and water vehicles. Tests results showed a 100% tracking data delivery efficiency and small difference between Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) for each route indicating that there is a small variance in distance errors. The tracking device also performed well in a sea route which is comparable to a commercial standard GPS data logger. Test results also showed that the device can be used for tracking applications i.e., vehicle security, inland fleet management, monitoring of tourist boats, and research or field surveys, where GPS and GSM are available.

Keywords: GPS/GSM design, GPS tracking, Remote monitoring, SMS-based tracking, Tracking device

Introduction

Tracking systems are essential in the field of transportation, logistics management, security and research [1]. It has been proven that tracking systems can save lives especially in life-threatening situations. It can also prevent theft and loss of assets. Tracking systems can be attached to vehicles, field equipment, drone, fleet, people, heavy equipment and shipments [2], and other very broad applications. For example, being one of the 10 world's most beautiful islands, Palawan, Philippines [3], has the needs to track tourist boats to help regulate carrying capacity of sites commonly visited during island tours. In addition, tracking systems will also help business owners to keep track of their businesses such as guided tours and rentals for motorbikes, vans and boats [4].

The tracking systems available in the market commonly rely on Global Positioning Systems-Global Systems for Mobile communication (GPS-GSM) technologies [5-7]. Many of the existing systems usually utilize GSM networks' data service using General Packet Radio Service (GPRS) where the tracking device sends information to a third-party server in the internet that the user can visit to acquire location information usually displayed on a map [7]. In the Philippines, this method is usually costly as GSM networks usually charge higher rates for data services as compared with Short Messaging Service (SMS). Another disadvantage of GPRS data transfer is that it

consumes way more power than SMS data transfer due to the difference in radio channel utilization for the data transfer [8]. Using GPRS also requires client-server internet architecture wherein a remote monitoring web server is setup to receive, manage, and publish tracking data which are accessed by users or clients [9] which is an added complexity (infrastructure, and technical skills) and cost to users. The significant advantage of GPRS over SMS as a mode of data transfer is when real time tracking is required since significant amount of delay can be experienced using SMS.

There are existing GPS-GSM based tracking systems that utilize SMS for data transfers [10-15]. However, a lot of them are not optimized to function on a service-on-demand basis and cater varying tracking needs of users. In the Philippines, SMS promotional offers, i.e., unlimited texts to all networks, etc. are common, making data transfers using SMS cheaper. Mobile phones are also near universal, used by billions of people across the world making it easy to implement an independent real-time tracking system using SMS [14,16]. This study was conducted to design a tracking system that is optimized for SMS mode of data transmission to cater broader tracking use cases at an optimum cost. This study covered the design of a tracking device using consumer-grade hardware components, development of system interface to enable remote operation using commands sent as short message(s), development of simple desktop monitoring software and conduct of actual field testing.

Next to this section is the materials and methods which discusses the four phases of the design and implementation of the tracking system for low-cost monitoring. This is followed by the results and discussion section which covers findings on iterative tests during the hardware and software integration, testing the simple desktop monitoring service, and performance of the tracking device during field tests. And lastly, the conclusions and recommendations section.

Materials and Methods

The usability design introduced in this study is a tracking system which can be further refined and packaged according to needs and applications. The design of the tracking system for low-cost monitoring consists of four (4) phases: (1) the development of the system interface for SMS commands optimized for the Philippines use cases; (2) the design of the tracking device by integrating consumer-grade hardware components and tested open source third party software libraries; (3) the development of simple desktop monitoring service; and (4) the actual field testing of the prototype tracking device.

System Interface for SMS Commands

The system interface of the tracking device operation allows the user to operate and access the tracking device remotely by sending appropriate commands as short messages. SMS is commonly used because it is convenient and accessible way of transferring and receiving data with high reliability [7]. The command contains keywords and parameters associated to functionality or service that the tracking device provides. The tracking device provides two main functionalities, load management and the tracking. Table 1 lists the functionalities and their associated keywords, parameters and descriptions of keywords.

The content of command SMS message must follow the format shown in Figure 1. For tracking services, the data transmitted by the tracking device follows the format shown in Figure 2.

Table 1. Tracking Device Management System Functionalities, Keywords, Parameters and Description of Keywords

Functionalities	Keywords	Parameters	Description of Keywords
Load Management	reg	(1) promo code (2) recipient number	Register a network promo code to a recipient number
	loc1	None	Single location only
Tracking	loc2	(1) number of locations	Number of locations, where each location is sent at every 30 seconds
	loc3	(1) number of locations (2) interval (<i>seconds</i>)	Number of locations, where each location at specified time interval

```
<Password><space><Keyword><space><Parameter1><space><Parameter2>
```

Figure 1. Format of the command SMS

```
C?value,value;D?mm/dd/yyyy;T?hh:mm:ss+cs
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Figure 2. Format of the tracking device response for tracking services. C?value,value represents the string for coordinates expressed as longitude and latitude, D?mm/dd/yyyy represents the string for date expressed as a decimal value for month, day, year respectively, and T?hh:mm:ss+cs represents the string for time expressed as hour, minute, seconds, and centiseconds respectively

Design of the Tracking Device

The design of the tracking device involved hardware integration, software integration, and hardware and software integration.

Hardware Integration

The tracking device is composed of several hardware components [13], the GPS receiver, GSM modem, and a microcontroller unit (MCU) which were connected to the microcontroller board which includes a power module to power these components. The MCU used in this study was ATmega328/P a low-power CMOS 8-bit microcontroller based on the AVR® enhanced RISC architecture. “AVR” is a registered trademark of the Atmel Corporation. It features a 32KBytes of In-System Self-Programmable Flash program Memory, 1kB EEPROM, 2kB Internal SRAM. It has a clock speed of 20MHz.

For faster prototyping, this study used microcontroller board that was readily available, the Arduino Uno R3 board shown in Figure 3. It is an ATmega328 development board which also comes with ATmega16U2 programmed as a USB-to-serial converter that acts as a bridge between the computer's USB port and the ATmega328/P serial port enabling the user to upload new code directly from the computer via USB port. It also comes with a built-in power regulator that has a recommended input range of 7 to 12V DC and is able to supply a 3.3V or 5V to the board and components connected to it.



Figure 3. Arduino Uno R3

For the GSM module, the Geeetech GSM module shown in Figure 4 was used. It includes SIM900 from SIMCom GSM/GPRS, SIM card slot, antenna interface, serial port select to choose between hardware serial and software serial, LEDs to indicate device activity and power, microphone and speaker jack for voice call functionality, power key to power up and down the module, and different pins that can be connected to Arduino Uno.

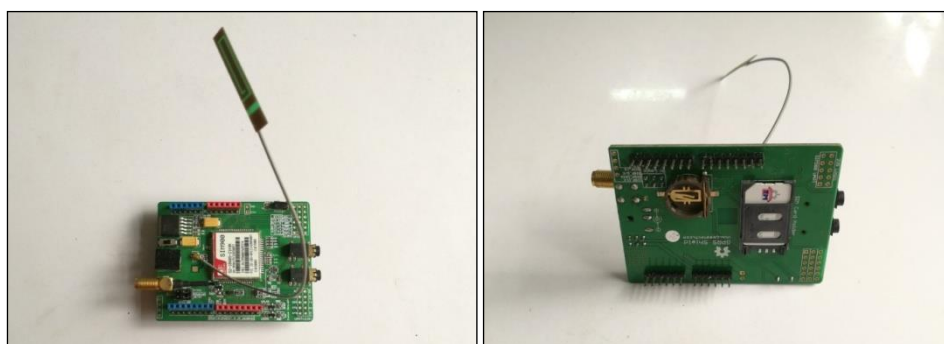


Figure 4. Geeetech SIM900 Global Systems for Mobile communication (GSM) Module. Left photo shows the front of the GSM module and right photo shows the back side of the GSM module.

SIM900 provides a way to access services provided by GSM cellular networks, i.e., SMS, Voice Call, MMS, and GPRS. SIM900 supports quad-band frequencies 850/900/1800/1900MHz, which would work on GSM networks in all countries across the world. Its small form factor and low power consumption are ideal for machine-to-machine (M2M) applications.

The SIM900 module uses the so-called AT commands to communicate with other devices [7]. AT commands are used to access the different functionalities available in SIM900 following the so-called AT command syntax. The AT command set implemented by SIM900 is a combination of GSM 07.05, GSM 07.07, and ITU-T recommendation V.25ter and the AT commands developed by SIMCom [17].

The GPS module used in this study, as shown in Figure5, was built with a standalone GPS/GNSS NEO-7M module from u-blox. The NEO-7M GNSS receiver is able to receive signal from GPS, GLONASS and QZSS. It has a sensitivity of -168dBm to -158dBm for tracking and navigation and is able to acquire a fix within 29s to 30s from cold start and reacquire within 1s to 3s. The voltage rating for the module ranges from 1.65V to 3.6V DC.

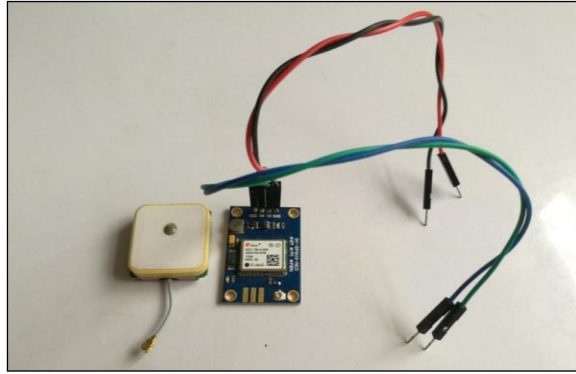


Figure 5: u-blox NEO-7M module

After verifying and testing individual modules, they were integrated based on their specifications as shown in Figure 6. The tracking device prototype was powered through the Arduino Uno USB interface connected to an external power source.



Figure 6. The tracking system device hardware

Software Integration

In developing the software program of the tracking device, properly tested and well-documented open-source software libraries were used. These are the SoftwareSerial, TinyGPS++, and Seeed Studio GPRS libraries.

The SoftwareSerial library is part of the Arduino Standard library. It was developed to allow serial communication on digital pins other than 0 and 1 of the Arduino, using software to replicate the functionality of the native serial that happens via a piece of hardware called a UART. With SoftwareSerial, having multiple software serial ports with speeds up to 115200 bps is possible [18].

TinyGPS++ is an Arduino library for parsing GPS data. It simplifies the task of parsing NMEA strings received by GPS modules. The library provides methods to extract GPS data, i.e., latitude, longitude, date, time, etc. [19].

The Seeeduino GPRS library enables GSM modems to be controlled by MCUs using abstracted AT commands. The library provides methods for common GSM phone functionalities, i.e., making/answering voice calls, sending/receiving SMS messages, TCP connection, etc. [20].

These libraries were integrated to the tracking device software program. Shown in Figure 7 is the pseudocode of the software program. When the tracking device was turned on, the MCU turned on the GPS and GSM modules where initialization subroutines run to check several parameters. The microcontroller then proceeded to check for SMS at every message index of the SIM card. If an SMS message was encountered, it was read, extracted, and deleted. The cycle of read, process, and delete continues as long as the tracking device is turned on.

The tracking device software program was developed in Arduino IDE. Two versions of the system were developed. The first version of the system was with a debugging mode used during the iterative software development cycle during which includes hardware and software integration. For this version, important parameters were displayed in the Arduino Serial monitor for diagnostics purposes and troubleshooting. The debugging mode allowed fine tuning of the software program. The second version was the final version of the software program where the components for diagnostic purposes were removed and the device can now only be operated using SMS-message based commands.

```

Turn on the tracking device
  Initialization
  Check for messages in all message indexes
    Validate the message
      If tracking command
        Get GPS data
        Send GPS data
      Else if other valid commands
        Process command
        Delete message
  Continue checking for messages

```

Figure 7. Pseudocode of the tracking device software program

Hardware and Software Integration

After the tracking device hardware integration and software program development, the next step was the hardware and software integration. The developed software was first compiled through the Arduino IDE, and the system software was then uploaded to the ATmega328/P memory.

The tracking device was tested for the actual delay between SMS and the total time to complete the request to know its delivery efficiency. This delivery efficiency test was performed by comparing the number of requested to counted number of SMS messages received from tracking device in the phone that made the request. The response tests comprising the delay between SMS and the total time to complete the request were done using a smartphone stopwatch.

Development of Simple Desktop Monitoring Service

The simple desktop monitoring service consists of a GSM modem and a desktop software application. The modem consists of a Geeetech GSM module (Figure 4) attached to Arduino Uno R3 microcontroller board shown in Figure 3. The modem is powered by the desktop computer through the microcontroller board power module as shown in the block diagram in Figure 8. The modem receives/sends short messages from/to the tracking device. The modem communicates with the software application running in the desktop via the serial interface.

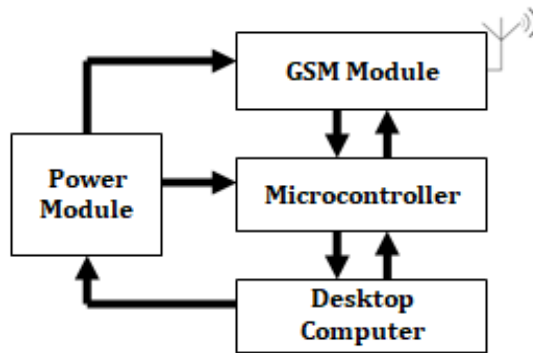


Figure 8. Block diagram of GSM modem for the desktop computer to receive/send short messages

Through the GSM modem, tracking data received as short messages were processed by the desktop software and saved to the local database. The mechanism for processing SMS data at the desktop application is shown in Figure 9. At the desktop computer, the data coming from or going to the GSM modem were accessed using the Python pySerial API [21], then parsed, and then JSON encoded [22] and saved to the flat file database.

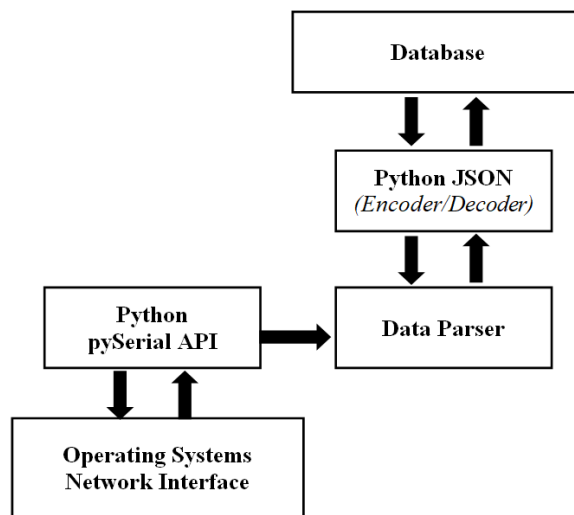


Figure 9. Block diagram of short message data processing at the desktop application

The database was updated every time a tracking data was received via the modem. These data saved in the local database were viewed using Microsoft Power BI Desktop Map Visualization.

Field Testing

The field testing was performed by placing the tracking device in a car and in a boat at predetermined routes. Before performing the actual testing, the tracking device was allowed to initialize for few minutes. The device was then tested by sending a command. This was to check if the GPS has gotten a fix such that the time, date, and location are valid or sensible.

The tests were performed in 5 routes. Figure 10 shows the four routes in land while Figure 11 shows the route in sea. Route 1 is a typical suburban area. The road is a 2-lane concrete with houses, small buildings and short trees on both sides of the road. The route is a mix of plane and hilly roads. For route 1 only, two sets of tests were carried out to compare

how the SMS tracking message frequency affects visualization of tracking data in a mapping platform, i.e., Google Maps and Microsoft Power BI Desktop Map Visualization. Route 2 is a representative of a countryside drive. There are sections of the roads where canopies of tall trees covered the road spanning for 1-3 kilometers. This route was chosen as representative of roads with impeding line-of-sight reception for GPS communications [23]. There are also sections of the road that are in between rice fields spanning 5-10 kilometers. This represents good line-of-sight reception for GPS communications. Route 3 is a typical major city road transitioning from suburban roads and countryside roads. The road profile is similar to that of route 1 except that route 3 has long stretches of 4-lane roads. Route 4 is a busy major urban 4-lane road where 10-20 meters from the sides of the road are 2-3 storey buildings. The road condition also provides good line-of-sight reception for GPS communication [23]. Route 5 is an open sea boat ride where reception for GPS communication is excellent. This route is representative of use cases where the tracking system is used for monitoring water vehicles. Testing in this route was aided with a commercial standard GPS data logger.



Figure 10. Routes in land where the tracking device prototype was tested. Upper left: Route 1 (a typical suburban area). Upper right: Route 2 (a representative of a countryside drive with tree canopies). Lower left: Route 3 (a typical major city road transitioning from suburban roads and countryside roads). Lower right: Route 4 (a busy major urban road).



Figure 11. Route 5, open sea boat ride

The received tracking data were processed by the simple desktop monitoring service. The parsed location data stored in the database were then viewed in the third-party desktop or web mapping service using Microsoft Power BI Desktop and Google My Maps respectively for validation and analysis. For Routes 1 – 4, each coordinate was measured for their difference from the ideal path which constitutes the error using the “Measure distances and areas” tool in Google My Maps and also computed using the Haversine formula (Equation 1):

$$d = 2R \sin^{-1} \left(\sqrt{\sin^2 \left(\frac{\varphi_2 - \varphi_1}{2} \right) + \cos(\varphi_1) \cos(\varphi_2) \sin^2 \left(\frac{\lambda_2 - \lambda_1}{2} \right)} \right) \quad (1)$$

where d is the distance between two GPS coordinate points, R is the radius of the sphere equal to 6371 kilometers, φ_1 and φ_2 are the latitude of points 1 and 2 respectively, and λ_1 and λ_2 are the longitude of points 1 and 2 respectively [24].

To summarize the errors, the mean absolute error (MAE) and the root mean square error (RMSE) were computed. For Route 5, visual comparisons were performed between the received tracking data and the logged data from a commercial standard GPS logger.

Results and Discussion

Hardware and Software Integration Iterative Tests

After coding and compiling the debugging mode of the software program for the tracking device, it was then uploaded to the microcontroller’s memory. The debugging mode shown in Figure 12 was done through the Arduino Integrated Developer Environment (IDE) serial monitor. Important parameters were printed in the serial monitor to determine whether or not the device behaves as designed and the data collected matches expectation.

```

COM9 (Arduino/Genuino Uno)

*****INITIALIZING*****

GSM Ready...
GPS Ready...

*****DONE*****

MsgIndex #: 1
From number: +639271623592
Datetime: 17/09/19,10:31:03+32
Message: trackingpass loc3 3
Keyword: loc3
Parameter1: 3
Parameter2:

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Coordinate #1:
Lat: 0.000000, Lng: 0.000000
Date: 00/00/2000
Time: 00:00:00+0
Coordinate #2:
Lat: 0.000000, Lng: 0.000000
Date: 00/00/2000
Time: 00:00:00+0

```

Figure 12. Tracking device software program debugging mode in Arduino Integrated Developer Environment serial monitor

After several iterations and modifications, the hardware and software were properly integrated and each hardware component properly interacts with one another and the overall behavior of the tracking device met the design specifications. Afterwards, the SMS-based management system keywords were tested and optimized. The tracking device showed 100% delivery efficiency for each tracking keyword during the tests (Table 2).

Table 2. Keywords and Delivery Test

Keyword	Keyword test	Number of SMS text(s) Expected	Number of SMS text(s) received	Delivery efficiency (%)
loc1	loc1	1	1	100
loc2	loc2 5	5	5	100
loc2	loc2 10	10	10	100
loc3	loc3 10 10	10	10	100
loc3	loc3 10 20	10	10	100
loc3	loc3 10 30	10	10	100

Table 3 shows that the delay for each message is around 6 to 7 seconds between messages while the time between the request and the first response is around 16 to 18 seconds. The delay was due to two factors: first, internal processes in the tracking device to create and send the short messages; and second, the GSM network latency. The first factor is dependent on the number of location data i.e., GPS coordinates included in the message. The test results in Table 3 were performed using short messages containing one location data and this delay will increase as more location data are contained in each short message. The second factor is greatly contributed by signal reception, network interchanges, network traffic e.g., higher network latency is expected during holiday seasons and condition of mobile device used.

Table 3. Keywords and Response Test

Keyword	Keyword Test	Introduced delay	Average actual delay between SMS	Total time to complete
loc2	loc2 5	30	36.500 sec	162.75 sec
loc2	loc2 10	30	36.370 sec	343.38 sec
loc3	loc3 10 10	10	16.356 sec	163.39 sec
loc3	loc3 10 20	20	26.279 sec	254.01 sec
loc3	loc3 10 30	30	36.220 sec	342.82 sec

Testing the Simple Desktop Monitoring Service

The desktop service efficiency was tested by comparing the number of location data requested (as previously proven that the tracking device has a 100% delivery efficiency) and number of location data saved in the database as well as comparing the actual travel route and the plotted route in mapping tools. Evident to the data stored in the database during testing, the desktop service efficiency was 100% and points are accurately mapped in the mapping software like the Microsoft Power BI Desktop as shown in Figure 13.

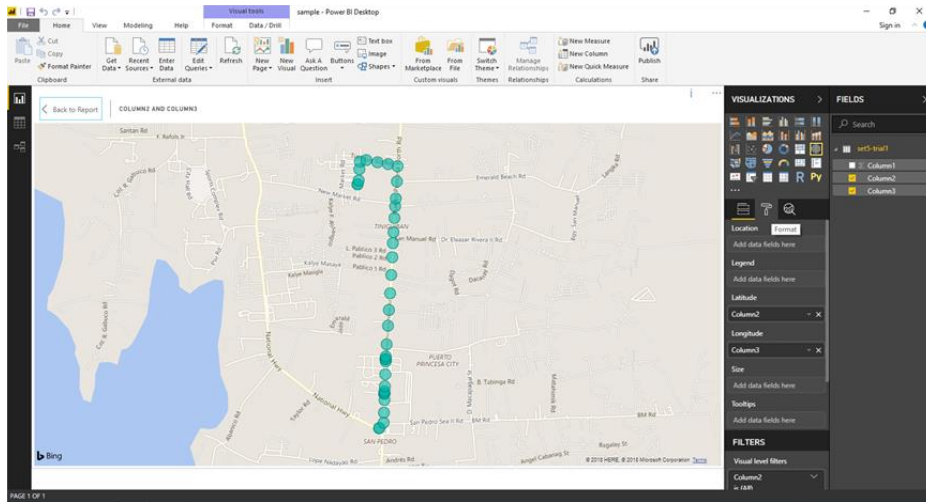


Figure 13. Tracking data in Microsoft Power BI Desktop

Performance of the Tracking Device During Field Tests

Figure 14 shows tracking in route 1 at the average speed of 35 kph and frequency of 1 SMS message per 30 seconds (Set 1). The points enclosed in the green oval shown in the figure were points at the start and end of the route. As shown in the figure, the points lie closely to the road. At the frequency of 1 SMS message per 30 second, the average distance between each point is approximately 250 meters. It can also be seen that points close to each other represent a deceleration, which is common in intersections. Points that are far from each other represent acceleration which is common in straight and wide roads, i.e., the national highway (shown as yellow road or path). The test done in route 1 was repeated at the average speed of 35 kph at the frequency of 1 SMS message per 10 seconds (Set 2). For set 2, the average distance between each point is approximately 120 meters. The two sets of tests showed that the tracking device is consistent. The tracking device has a MAE of 2.02 meters and RMSE of 2.60 meters in route 1 (Figure 14 Right).

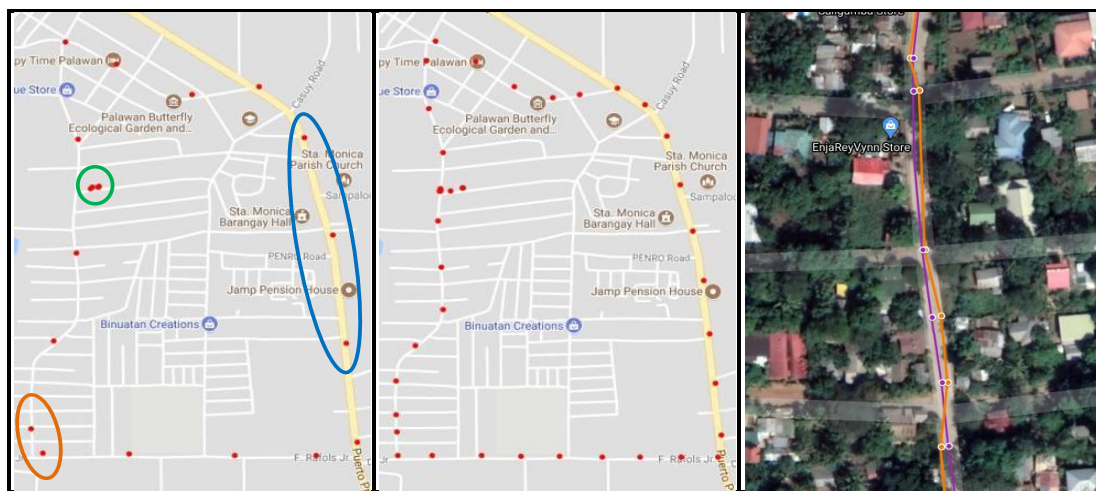


Figure 14. Left: Set 1 in route 1(suburban road) at the average speed of 35 kilometers per hour (kph) and frequency of 1 SMS message per 30 seconds (Green oval –start and end point; Orange oval – deceleration; Blue oval – acceleration). Middle: Set 2 in route 1 at the average speed of 35 kilometers per hour and frequency of 1 SMS message per 10 seconds. Right: Sample of actual map showing the coordinates sent by the tracking device (orange) and the ideal path (purple).

The test shown in Figure 15 was done in route 2 at the average speed of 45 kph and frequency of 1 SMS message per 10 seconds. The points tightly close to each other were gathered from a police checkpoint for vehicles coming from the southern part of the province, moderate traffic congestion in major intersections and stop over areas. The trials in route 2 had an overall MAE of 1.91 meters and RMSE of 2.53. In sections of route 2 with tree canopies the device had a MAE of 3.30 meters and RMSE of 3.60 meters.

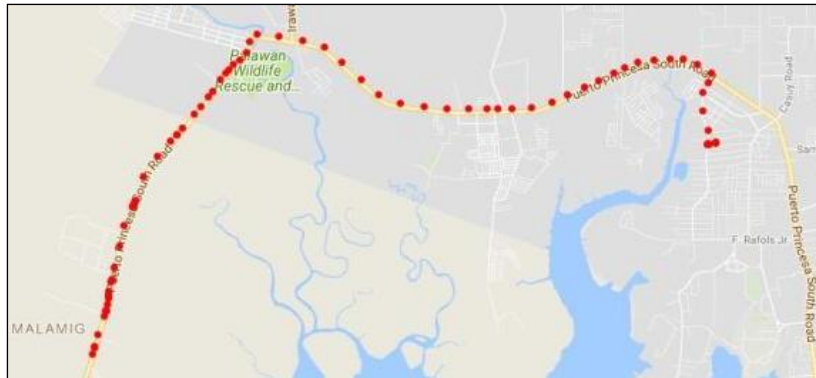


Figure 15. Test in route 2 (countryside road with tree canopies) at the average speed of 45 kilometers per hour and frequency of 1 SMS message per 10 seconds.

Figure 16 shows the test conducted in route 3 at the average speed of 45 kph at the frequency of 1 SMS message per 10 seconds. Trials in route 3 had a MAE of 2.17 meters and RMSE of 2.80 meters.

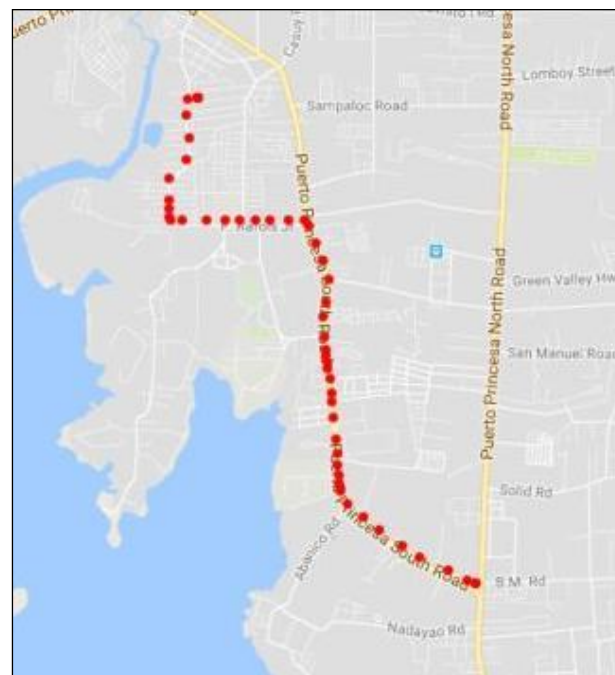


Figure 16. Test in route 3 (suburban to urban transitioning road) at the average speed of 45 kilometers per hour and frequency of 1 SMS message per 10 seconds

The test shown in Figure 17 was done in route 4 at an average speed of 45 kph at the frequency of 1 SMS message per 10 seconds. Trials in route 4 had a MAE of 1.23 meters and RMSE of 1.80 meters.

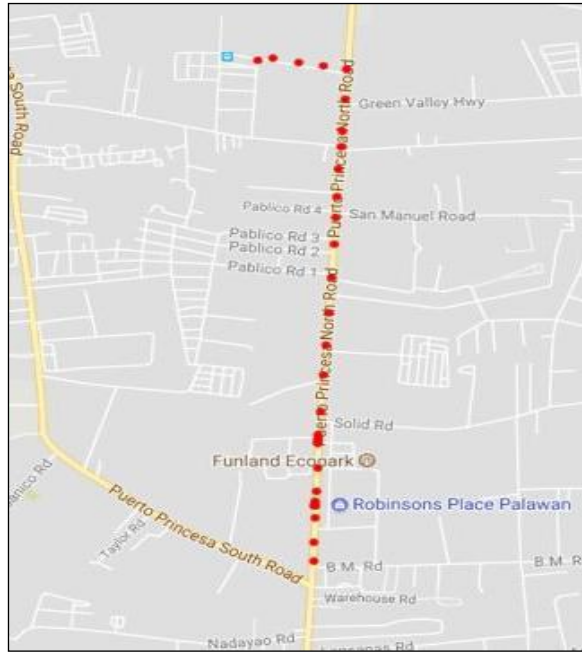


Figure 17. Test in route 4 (urban road) at the average speed of 45 kilometers per hour and frequency of 1 SMS message per 10 seconds

As shown in Figure 18, the prototype tracking device performed well in a sea route which is comparable to a commercial standard GPS data logger. The figure also shows that the tracking device is excellent for tracking water vehicles where there is GSM reception.



Figure 18. Tracking data during a boat ride. Green track represents the tracking device and the red track represents data from a commercial global positioning system (GPS) logger

On all the tests, the tracking device has demonstrated a consistent performance on the trials conducted. The tracking device exhibited a MAE of 1.26 meters and RMSE of 1.77 meters in major urban roads, i.e. in route 4 and portions of route 3, a MAE of 2.04 meters and RMSE of 2.67 meters were observed on suburban roads, i.e., in route 1, portions of route 2 and route 3, while a MAE of 3.30 meters and RMSE of 3.60 meters in roads with forest canopies, commonly encountered in countryside roads. The small difference between MAE and RMSE for each route indicates that there is a small variance in errors. Based on the performed tests, it is observed that the MAE increased as vehicle moves from areas with good line-of-sight reception to areas with forest canopies.

As shown in the plotted points for all the trials, points getting closer to one another are indicative of a brief stop-over, traffic, or deceleration at intersections or sharp curves. Also, points that are far from one another indicate acceleration. It can also be observed from the two variations of the frequency of sending short messages containing location data that the course that the vehicle travelled is easily visualized at higher frequencies. To get evenly spaced tracking data points during visualization irrespective of geography, the frequency of sending SMS tracking data must be based on the vehicle's velocity. Studies have shown that GPS receivers velocity data is sufficiently accurate even at a high-multipath environment [28,29]. Comparing the operations cost between the SMS optimized tracking system and the GPRS based tracking system for continuous tracking, a minimum of 30% is saved by using the former. A problem encountered for SMS based data transfer running on a promo subscription is in the aspect of fair use policy. The network provider deactivates a promo subscription when it detects a usage that is significantly higher than normal. This was overcome by decreasing the frequency of location data being sent by the tracking device as well as aggregating multiple location data in one short message. In general, this tracking system can be added to previously introduced low-cost tracking systems [4, 11, 25-27].

Conclusions and Recommendations

The tracking system that is optimized for SMS data transmission has been created. It has been shown that the tracking system can be operated at a low cost since the tracking device can be managed remotely making it flexible to fit broader use cases. Tests on the performance and reliability of the tracking device were successfully conducted showing small difference between MAE and RMSE indicating a small variance in errors on each of the selected routes representative of the different road conditions in rural and urban areas.

It is recommended that the tracking device interface should be improved to fully manage it remotely, i.e., adding GPRS mode of data transmission. Additional test profiles should be carried out, i.e., test of its efficiency during peak seasons when significant network traffic is experienced, test of tracking efficiency in driving in highly urban places where tall buildings are a common view, etc.

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