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Numerical Motion Analyzing Based on Recorded Empirical Data by Smartphone Features

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Abstract: This study presents a new method to analyse the motion of moving objects. The novelty of this study is that the presented work obtains your location based on the coupled measured data using the GPS and other motion sensors of a smart phone. This method can be used for GPS free navigations in future studies. The smartphone sensors measure the desired values and a developed Android application records this data. A developed MATLAB code analyses these values for car road travel using multiple coordinate transformations and removes the effects of Earth's gravity from the measured acceleration. It is recognized that the presented method can be used to analyse the movement and performance of the studied material. The obtained results show that the integration of data recorded by the accelerometer sensor integrates the effects of noise and this sensor is not a convenient feature to obtain the instantaneous location. Calculating the acceleration using GPS data may also not be accurate in this case. Getting the location and acceleration using a GPS sensor and accelerometer is more accurate.

Keywords: Global Positioning System, Motion Analysis, Sensor, Smartphone

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Research paper

1 INTRODUCTION

Advances in computer and electronic science in recent years have made smartphones an essential part of people's daily lives. Competition among manufacturers to improve performance and services has made it possible to use these devices in various fields. On the other hand, the development of the space industry helped with human transportation and exploration. There are no Global Positioning System (GPS) blind spots on the planet today. Industry Science Research Business Navigation is essential for most human activities such as transportation and travel. Autonomous devices in particular need navigation to manage constant motion. Motion analysis using smartphone sensors is a simple solution to this problem. So, computer electronics and aerospace technology have come together to solve this problem. The smartphone includes an on-screen display, haptic feedback system, processor, graphics and audio chipset and advanced connectivity as standard features. Some of these phones have additional features such as barometer and thermometer, or inertial motion unit (IMU) containing magnetometer, 3D accelerometer and gyroscope. This type of smartphone is great for analysing motion.

Several studies have investigated postural and gait control [1-2] or joint goniometry [3-4]. However, some researchers use expensive equipment such as aircraft black boxes or stationary equipment for laboratory studies [5]. Some researchers use smartphones for static and dynamic measurements in objects moving analysis. Rapid location acquisition [6] and data recording are important factors for intelligent transportation. Sensor networks are needed to observe traffic [7] or to detect traffic quality [8]. This is a new use of smartphones in the topic of traffic control. Then they analyse driver behaviour [9] or detect car accidents [10] using smartphone capabilities. Some reasons to explore new motion analysis methods are controlling an intelligent car, designing an autopilot system for an airplane or drone, testing the performance of a moving vehicle, controlling a multirotor self-balancing system for a bicycle or motorcycle system design, and clinical analysis using human behaviour. Smartphones are accessible and convenient devices, containing several sensors that can measure valuable data for motion analyzing purposes. It is important to study its ability to record data and motion analysis. In our previous study, we presented a novel approach for navigation of a vehicle using the smartphone sensors, with a low dependency to the GPS data [11].

The present study describes a new method for analyzing the motion of moving objects such as buses, cars, ships, motorcycles, multirotor, boats, helicopters, or airplanes. In this study, we present a new method to analyze the motion of these moving objects. The novelty of this study is that the presented work obtains the location of moving object based on the coupled measured data using the GPS and other motion sensors of a smart phone. It should be noted that in this method, it is possible to calibrate the sensors measurements using the converted data from GPS signals, and then this method can be used for GPS free navigations in future studies. Previous studies in this field have no attention to this matter. A JavaScript code has been generated and then the developed Android application is installed on a smartphone to record the values measured by its sensors for utilizing by a generated MATLAB code to analyze a car's trip.

2 METHODOLOGIES

2.1. Experiment

A Samsung smartphone (Galaxy S III I9300) was used in this study. The sensor measured parameters essential for analyzing the road journey of a Peugeot car (405 GLX) from Estahban to Neyriz in Iran. Android application is developed with homemade code using JavaScript. This application installed on the smartphone displays the necessary information on the screen, and writes it to an external memory. These data are time, data logging rate, latitude, longitude, altitude, acceleration in x_s, y_s, and z_s directions, roll and yaw, pressure, and temperature. The phone is mounted at the estimated center of gravity of the vehicle. Figure 1 shows the smartphone coordinate system (x_s, y_s and z_s directions) and the roll, pitch and yaw directions.

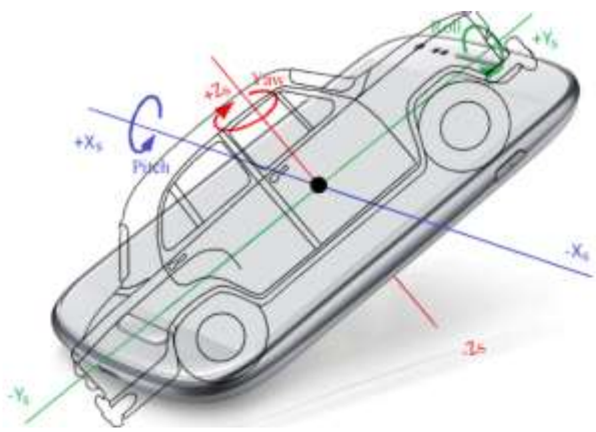

Fig. 1 The smartphone coordinate system in the car.

2.2. Coordinate Transformation

The coordinate transformation has been presented in “Fig. 2”, schematically. GPS data is in the world coordinate system, which designates each point with 3 elements as [12]:

$$\vec{P_g} = \begin{pmatrix} \lambda \\ \phi \\ \square \end{pmatrix} \quad (1)$$

Where, λ, φ and h are the longitude, latitude and height, respectively. The Earth-centered Earth-fixed coordinate system (ECEF) expresses this as [13]:

$$\vec{P_e} = \begin{pmatrix} x_e \\ y_e \\ z_e \end{pmatrix} = \begin{pmatrix} (N_e + \square)Cos\phi Cos\lambda \\ (N_e + \square)Cos\phi Sin\lambda \\ [N_e(1 - e^2) + \square]Sin\phi \end{pmatrix} \quad (2)$$

The origin of the coordinate system (x_e, y_e, and z_e) is located at the Earth's center of mass (see "Fig. 2"), which is not a sphere but a biaxial ellipse, therefore, $N_e = r_e/\sqrt{(1 - e^2)Sin^2\phi}$ and e=0.081819190842622 are inserted for correction. Where, r_e=6378137 m is the Earth's mean radius.

This point in the north east down (NED) coordinate system has been represented as [13]:

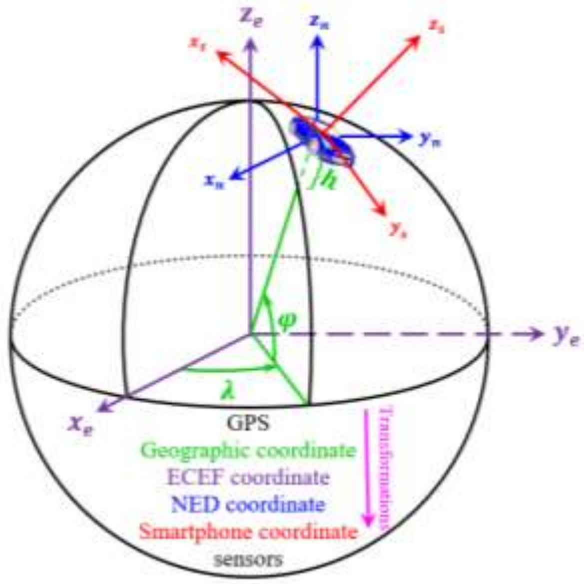

Fig. 2 The coordinate transformations.

$$\vec{P_n} = \begin{pmatrix} x_n \\ y_n \\ z_n \end{pmatrix} = \begin{pmatrix} -Sin\phi^{ref}Cos\lambda^{ref} & -Sin\phi^{ref}Sin\lambda^{ref} & Cos\phi^{ref} \\ -Sin\lambda^{ref} & Cos\lambda^{ref} & 0 \\ -Cos\phi^{ref}Cos\lambda^{ref} & -Cos\phi^{ref}Sin\lambda^{ref} & -Sin\phi^{ref} \end{pmatrix} \cdot \begin{pmatrix} x_e - x_e^{ref} \\ y_e - y_e^{ref} \\ z_e - z_e^{ref} \end{pmatrix} \quad (3)$$

As shown in the "Fig. 2", The origin of the vehicle-mounted NED coordinate system (x_n, y_n, and z_n) is on the smartphones center of mass. The starting point and angle of the smartphone in this road trip in the local NED coordinate system is x_e^{ref},y_e^{ref}, z_e^{ref}, ϕ^{ref}, and λ^{ref}. Each point in our trip now has a 3D displacement vector from the starting point, which the slope of this displacement vs. time defines the vehicle velocity (V_n, in the NED coordinate system). All coordinate conversion steps up to this section use only GPS data. We can use position measurements and convert them to the phones coordinate system (V_s) using the following Equation [14].

$$\vec{V_s} = \begin{pmatrix} V_{sx} \\ V_{sy} \\ V_{sz} \end{pmatrix} = \begin{pmatrix} Cos\theta Cos\psi & Cos\theta Sin\psi & -Sin\theta \\ Sin\varphi Sin\theta Cos\psi - Cos\varphi Sin\psi & Sin\varphi Sin\theta Sin\psi + Cos\varphi Cos\psi & Sin\varphi Cos\theta \\ Cos\varphi Sin\theta Cos\psi + Sin\varphi Sin\psi & Cos\varphi Sin\theta Sin\psi - Sin\varphi Cos\psi & Cos\varphi Cos\theta \end{pmatrix} \cdot \begin{pmatrix} V_{nx} \\ V_{ny} \\ V_{nz} \end{pmatrix} \quad (4)$$

As shown in "Figs. 1 and 2", V_{sx}, V_{sy}, and V_{sz} are components of the car velocity vector in the x_s, y_s and z_s directions, and ϕ, θ and ψ are roll, pitch and yaw angles, respectively. The slope of V_s vs. t defines the car acceleration (a_{GPS}, in the smartphone coordinate system) which is in a same coordinate system with $a_{accelerometer}$ (the measured acceleration using the accelerometer sensor). Calculating a_{GPS} requires double differentiation (the slope of the displacement vs. time gives the velocity and the slope of the velocity vs. time gives the acceleration), but, $a_{accelerometer}$ has been measured directly. Therefore, we can validate the a_{GPS} and clear its immediate error. As shown in "Figs. 1 and 2", accelerometer sensors provide acceleration vector components (a_{sx}, a_{sy} and a_{sz}) in the smartphone coordinate system, which are affected by the local gravitational acceleration (g) that has the following various with changing altitudes [15]:

$$g = g^{ref}\left(\frac{r_e + \square^{ref}}{r_e + \square}\right)^2 \quad (5)$$

Where, g^{ref} is the gravitational acceleration at the beginning of the road trip (at h^{ref}). To remove this effect, a_{sx}, a_{sy}, and a_{sz} were transformed from the smartphone coordinate system to the NED coordinate system (see "Fig. 2"), using φ, θ and ψ angles, as below [15]:

$$\vec{a_n} = \begin{pmatrix} a_{nx} \\ a_{ny} \\ a_{nz} \end{pmatrix} = \begin{pmatrix} Cos\psi Cos\theta & Cos\psi Sin\theta Sin\varphi - Sin\psi Cos\varphi & Cos\psi Sin\theta Cos\varphi + Sin\psi Sin\varphi \\ Sin\psi Cos\theta & Sin\psi Sin\theta Sin\varphi + Cos\psi Cos\varphi & Sin\psi Sin\theta Cos\varphi - Cos\psi Sin\varphi \\ Sin\theta & Cos\theta Sin\varphi & Cos\theta Cos\varphi \end{pmatrix} \cdot \begin{pmatrix} a_{sx} \\ a_{sy} \\ a_{sz} \end{pmatrix} \tag{6}$$

Attending to the parallel directions of a_{nz} and g vectors, it is possible to remove the mentioned effect as $a_{nz}^{cor} = a_{zn} - g$, and then, transfer the corrected acceleration from the NED coordinate system to the smartphone coordinate system (see "Fig. 2"):

$$\vec{a_s^{cor}} = \begin{pmatrix} a_{sx}^{cor} \\ a_{sy}^{cor} \\ a_{sz}^{cor} \end{pmatrix} = \begin{pmatrix} Cos\theta Cos\psi & Cos\theta Sin\psi & -Sin\theta \\ Sin\varphi Sin\theta Cos\psi - Cos\varphi Sin\psi & Sin\varphi Sin\theta Sin\psi + Cos\varphi Cos\psi & Sin\varphi Cos\theta \\ Cos\varphi Sin\theta Cos\psi + Sin\varphi Sin\psi & Cos\varphi Sin\theta Sin\psi - Sin\varphi Cos\psi & Cos\varphi Cos\theta \end{pmatrix} \cdot \begin{pmatrix} a_{nx}^{cor} \\ a_{ny} \\ a_{nz} \end{pmatrix} \tag{7}$$

It should be noted that a_{nx} and a_{ny} are perpendicular to the g direction, and therefore these parameters are free from the g effects.

2.3. Predictions of Pressure and Temperature

Pressure and temperature sensors are a common feature of today's smartphones. The used smartphone has a pressure sensor. Nevertheless, this phone does not have a temperature sensor. Therefore, the external thermometer (Testo 905i) is connected to the smartphone using a Bluetooth connection. Sometimes the measured temperature and pressure are ambient (external) values, e.g., a bicycle or car with the windows open. In this case, these values can be used to calculate outdoor air properties such as density or viscosity. In other cases, such as in jet aircraft, this measurement is an indoor value. Comparing the indoor and outdoor values of this parameter yields some of the stresses contained within the material body, such as normal and thermal stresses. The following Equations estimate the outdoor values of temperature and pressure at each altitude [16]:

$$\begin{bmatrix} T^{est} \\ P^{est} \end{bmatrix} = \left\{ \begin{array}{ll} \begin{bmatrix} T^{ref} - 0.0065\square \\ P^{ref}\left(\frac{T^{est}+273.15}{288.16}\right) \end{bmatrix} & \square < 11000 \\ \begin{bmatrix} -56.49 \\ P^{ref}\left(\frac{T^{est}+273.15}{216.16}\right) \end{bmatrix} & 11000 < \square < 25000 \\ \begin{bmatrix} -56.49 + 0.003(\square - 25000) \\ P^{ref}\left(\frac{T^{est}+273.15}{216.16}\right) \end{bmatrix} & 25000 < \square < 47000 \\ \begin{bmatrix} -9.51 \\ P^{ref}\left(\frac{T^{est}+273.15}{282.66}\right) \end{bmatrix} & 47000 < \square < 53000 \\ \begin{bmatrix} -9.51 + 0.0045(\square - 53000) \\ P^{ref}\left(\frac{T^{est}+273.15}{282.66}\right) \end{bmatrix} & 53000 < \square < 79000 \\ \begin{bmatrix} -107.49 \\ P^{ref}\left(\frac{T^{est}+273.15}{165.66}\right) \end{bmatrix} & 79000 < \square < 90000 \\ \begin{bmatrix} -107.49 + 0.004(\square - 90000) \\ P^{ref}\left(\frac{T^{est}+273.15}{165.66}\right) \end{bmatrix} & 90000 < \square \end{array} \right\} \tag{8}$$

3 RESULTS AND DISCUSSION

Figure 3 shows the data recorded in the external memory in a road trip, i.e., rate of data recording, pressure, temperature, role, pitch, yaw, three components of acceleration vector, altitude, latitude and longitude. This Figure shows that this smartphone records about 25 data in external memory every second in its normal activity mode. Increasing the data logging rate increases power consumption and reduces the time available to experience a fully charged battery. This is the average value measured by the speed sensor and the data received from the GPS unit. As mentioned earlier, the speed of measuring values by the sensor is about 200 samples per second in the normal activity mode of the smartphone used. However, the speed (and accuracy) of receiving data from a GPS unit depends on the number of visible satellites. As the number of visible satellites during the flight varies from 4 to 12, the rate (as well as the accuracy) is low in some locations. There is apparently reasonable agreement between the values recorded for pressure altitude and temperature. It agreed on the dependence of pressure and temperature on altitude.

Figure 4 shows the *x-y* plot obtained for this trip. A satellite image is applied to the background. The *x-y* plot taken in the NED coordinate system exactly matches the path on the map. This proves the validity of this method. Common navigation applications map your trip by comparing GPS data of your location and pre-recorded values for each point on the map. This study is not an exploratory method test. This paper presents a new and simple method to analyze the motion of moving objects. For this purpose, smartphones are a cheap combination of expensive sensors. This study confirms this ability.

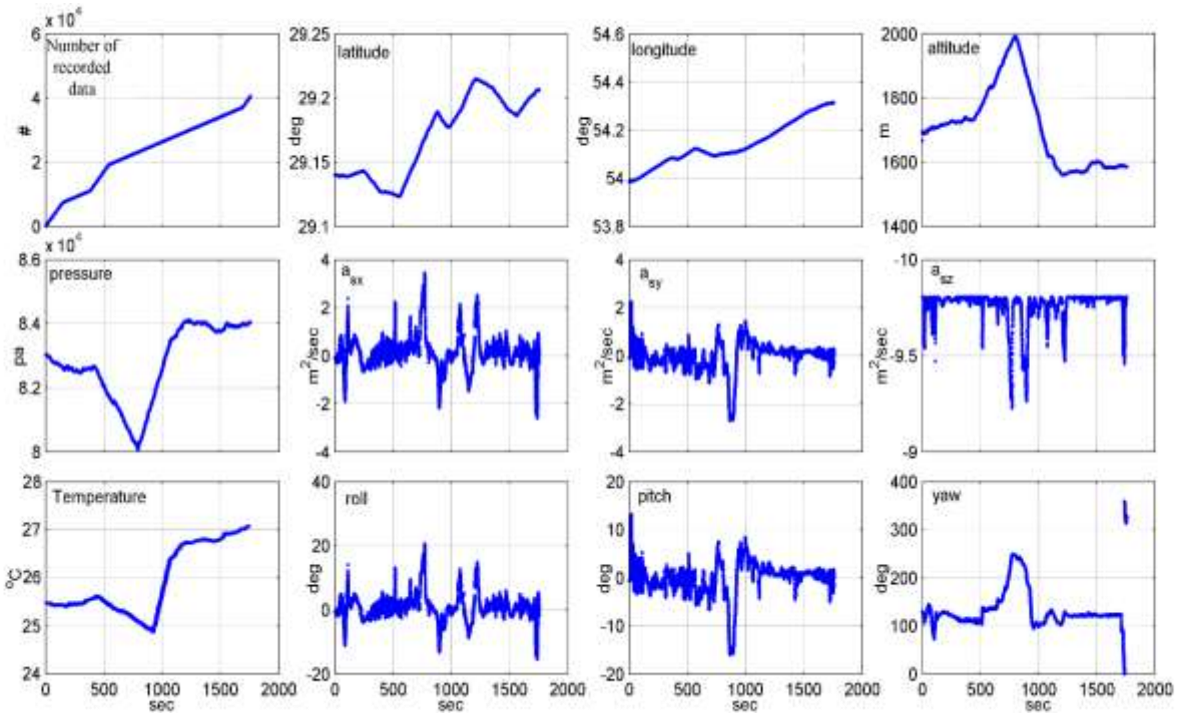

Fig. 3 The recorded data in the external memory.

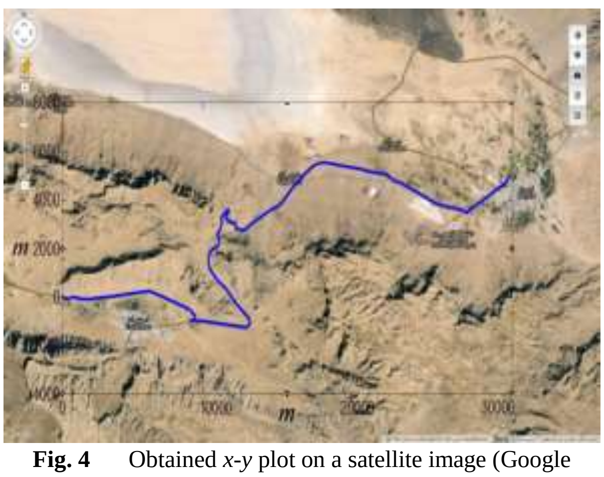

Fig. 4 Obtained *x-y* plot on a satellite image (Google Maps).

In geodetic measurements, a distance between two points can be calculated using the length of a straight line that connects these two points ($d = \sqrt{x_n^2 + y_n^2 + z_n^2}$) or using the length of the existed road between these two points ($d_t = \sum d$). Figure 5 compares these values in the road trip test. Comparing d_t with d clears that the mazes of the road increase the mentioned distance. The slopes of this curve show the mean value for the car speed (about 90 *km/hr*). The instantaneous car speed vector has been presented in "Fig. 6". These two values have been calculated based on the GPS data. Attending to the forward motion of the car, it was expected that V_{sy} and V_s would be similar, except in some climbing or turning around cases.

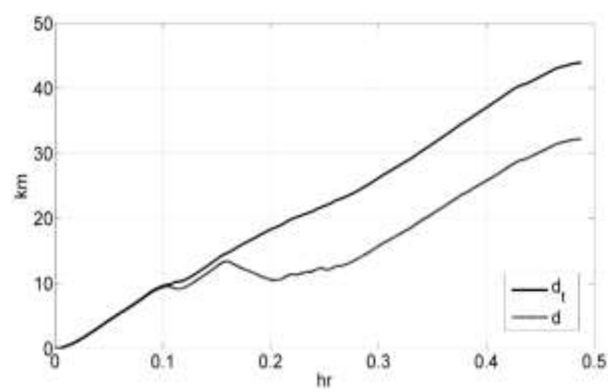

Fig. 5 Covered distance in the road trip test.

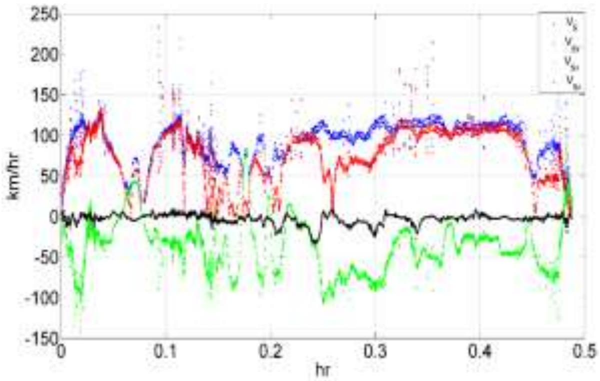

Fig. 6 Instantaneous speed in the road trip test.

Figure 7 compares the uncorrected and corrected values of the measured accelerations. It is observed that the corrected a_{sz} is smaller than the corrected values of a_{sx} and a_{sy}, attending to the low acceleration of the car in the vertical direction in this road test. Figure 8 compares $a_{GPS} = d^2(d_t)/dt^2$ with $a_{Accelerometer} = (a_{sx}^{cor\,2} + a_{sy}^{cor\,2} + a_{sz}^{cor\,2})^{0.5}$, which are near together, occasionally. Nevertheless, the noisy GPS data have low accuracy for calculating the acceleration. Therefore, obtaining a location using the GPS and obtaining acceleration using accelerometer sensor are more accurate.

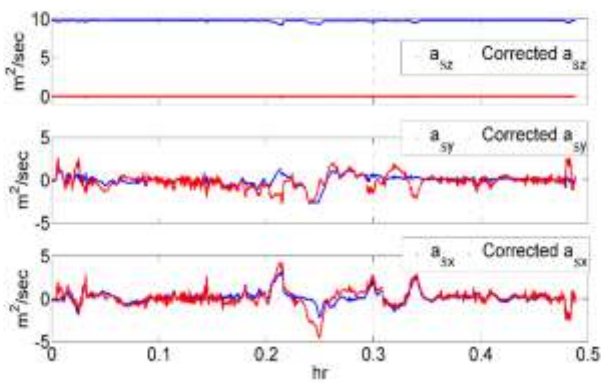

Fig. 7 The measured and corrected values of components of acceleration vector (using accelerometer sensor).

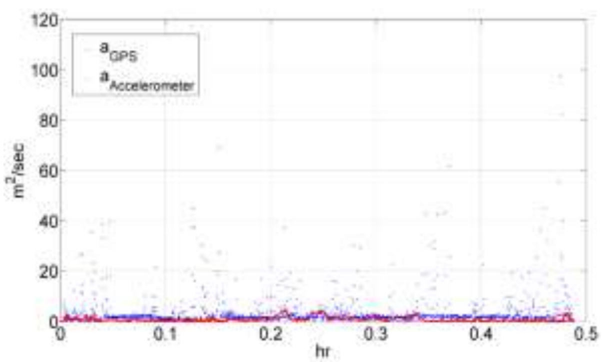

Fig. 8 The obtained acceleration of the vehicle by GPS and Accelerometer sensor.

Temperature and pressure are two valuable parameters for analyzing the performance of vehicles. The influence of the atmospheric conditions on the performance of a vehicle was studied previously [17]. It is resulted that this performance to be more affected by changes in the atmospheric pressure than in the temperature. In addition, effect of the atmosphere on the performances of aviation turbine engines were investigated [18]. In the open cabin vehicles, such as multirotor, bicycle or the used car, the sensed values of these parameters are equal to outside values. The outside values are usable for investigating the performance of multirotor propellers or a car's motor. This is a simple method for validating estimating Equations for these values. Figures 9 and 10 compare the measured temperature and pressure using the external thermometer and smartphone's pressure sensors, respectively, with the estimated values using Equation (8). A low variation of altitude in this road trip caused low variation in these two parameters. Nevertheless, there are acceptable accordance between these values and their estimations. This comparison gives valuable information in a long travel using a jet airplane, which compares the indoor and outdoor environments of a close cabin. These parameters have different values for inside and outside closed cabins. The sensors measure the inside values and the outside values are estimated using suitable Equations. The differences between the inside and outside values obtain the entered stresses on the physical structure of cabins.

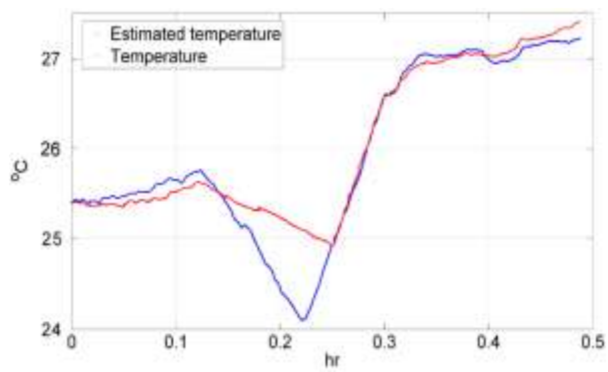

Fig. 9 The measured and estimated values of temperature.

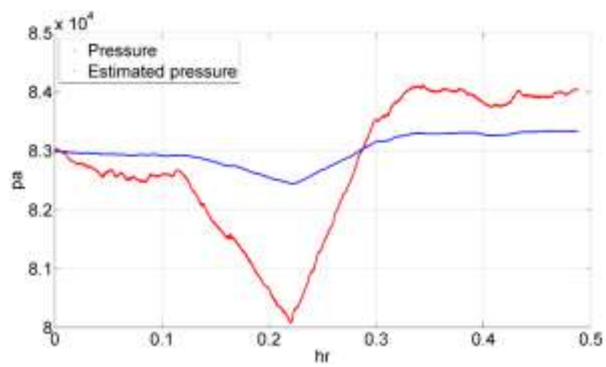

Fig. 10 The measured and estimated values of pressure.

4 CONCLUSIONS

In this study, a novel method for objects motion analyzing was defined. A JavaScript code was developed as an Android application that was installed on a smartphone to record the measured values by its sensors. In addition, a MATLAB homemade code was developed to analyze a road trip test using a car. Several coordinate transformations were utilized for this purpose. The effects of the gravitational acceleration were removed from the measured accelerations. It is observed that the obtained *x-y* plot had been matched on the road. It is concluded that the integration or differentiation improves the noises effects in the obtaining of the car location and acceleration using the accelerometer sensor and GPS unit of the smartphones, respectively. Considering low variation of altitude in this road trip, there was acceptable accordance between the measured and estimated values of temperature and pressure.

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