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Comparison of Number of Waves Surfed and Duration Using Global Positioning System and Inertial Sensors

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Abstract**—**Surf is an increasingly popular sport and its performance evaluation is often qualitative. This work aims at using a smartphone to collect and analyze the GPS and inertial sensors data in order to obtain quantitative metrics of the surfing performance. Two approaches are compared for detection of wave rides, computing the number of waves rode in a surfing session, the starting time of each wave and its duration. The first approach is based on computing the velocity from the Global Positioning System (GPS) signal and finding the velocity thresholds that allow identifying the start and end of each wave ride. The second approach adds information from the Inertial Measurement Unit (IMU) of the smartphone, to the velocity thresholds obtained from the GPS unit, to determine the start and end of each wave ride. The two methods were evaluated using GPS and IMU data from two surfing sessions and validated with similar metrics extracted from video data collected from the beach. The second method, combining GPS and IMU data, was found to be more accurate in determining the number of waves, start time and duration. This paper shows that it is feasible to use smartphones for quantification of performance metrics during surfing. In particular, detection of the waves rode and their duration can be accurately determined using the smartphone GPS and IMU.

Keywords**—**Inertial Measurement Unit (IMU), Global Positioning System (GPS), smartphone, surfing performance.

I. Introduction

SURF has exponentially increased its participants and media coverage over the last few years and nowadays is a sport that has 84 Member Federations on all five continents and 35 million practitioners worldwide. Surfing is a 22 billion dollar business and the growth of this sport is not yet stagnant[1].

Companies nowadays reward higher level surfers with good sponsorship contracts, usually based on their results. This allures a large and increasing participation of new and young surfers, with expectations of reaching a higher competitive level. Surf is now a common recreational sport, enjoyed by people of all standards[2].

Surfing can be characterized as a series of exercises varying in intensity and duration, which require high muscular and cardio-respiratory endurance, as well as, considerable anaerobic power of the upper torso during short powerful bursts of paddling, in order to repeatedly catch waves. The four main activities that surfers perform during a surfing session have been described as arm paddling (lying in a prone position), stationary, wave riding and miscellaneous (other activities such as wading or ducking under water). Those activities will be affected by many factors resulting in different duration times and intensity in each activity. Wave formation, type of break wave, wave size, currents or geographic locations, are just some of the elements that will determine, or at least condition, a surfing session [2], [3].

While other sports, such as running, already have a certain amount of platforms (mostly in the form of mobile applications) that can help athletes to analyze and improve their abilities, almost entirely using a Global Positioning System (GPS) [4], surfing is still an uncharted ground that needs exploration. There are certain difficulties related to data gathering inherent to this kind of sport, mainly because of the underlying risk that sea water represents to almost every electronic devices and also, the fact that an extra equipment may be obtrusive to the practitioner when performing a nautical activity as demanding as surf.

This paper has the objective of comparing the detection of the waves rode during surfing sessions, their start times and duration. For that, a smartphone is used and two approaches are studied: one where only the GPS data is analyzed and other where that data is combined with the signals retrieved from the inertial sensors. In this paper, an analysis on the related work is firstly presented and then the methods used and approaches analyzed are described. The main results and the major conclusions are presented on the last sections of this paper.

II. Related Work

Recent developments in GPS technology provided means to quantify athlete locomotion and movement. Satellite tracking GPS units are commonly used nowadays during competition and training giving feedback and information about movement patterns and physical activities of athletes[3], [5].

GPS technology has been applied to a wide range of sport applications and is considered a reliable tool to determine outdoor speed [5], [6]. This metric is one of the most important when developing a detection system, such as the one described in this paper, which intended to detect and

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quantify surfing waves.

Lately, improvements of battery life and miniaturization of GPS units also have made performance tracking a more convenient and increasingly popular method to quantify movement patterns and all physical requests in a wide range of sport activities [7]. Likewise, the proliferation of smartphones had an important role in providing access to this kind of technology all over the globe and in lowering the prices for GPS receivers. The price of this kind of technologies continues to decrease and with further research into the area of the low-cost position and speed devices, newer techniques will continue to appear and to evolve[8].

A. Reliability and Validity of GPS Measurements

As this work used the speed retrieved from a smartphone's GPS as one of the metrics, it is important to know how accurate and reliable this value is. Also, the value of the refresh rate (or sampling frequency) may be of heavier or slighter importance, depending on the applications. Although it might be obvious to think that a higher refresh rate could be better for sports analysis, namely in speed calculations, this value can be highly affected by the accuracy of the signal.

According to Ryan, Petersen, Peters and Grémillet, the ability of recording fixes at a high frequency, results in increased noise, and subsequently, less accurate calculations, so it is always very important to choose the sampling interval that best suits the final objective of each problem [9].

Shutz and Chambaz implemented a study where they recorded and analyzed the relationship between the speed retrieved from the GPS and the actual speed in three activities: walking, running and cycling. They determined that the difference between the true and the GPS speed was 1.1 km/h for walking, 0.7 km/h for running and 0.8 km/h for cycling [6].

Another study performed by Varley, Fairweather and Aughey intended to verify the reliability of GPS measurements measuring instantaneous velocities. They tested 5 and 10 HZ GPS units for measuring velocity during acceleration, deceleration and constant velocity while straight-line running. Three sport athletes perform a total of 80 straight-line running trials. They validated that the 10 Hz GPS units were two to three times more accurate than 5 Hz units when compared with a criterion value for instantaneous velocity. At 10 Hz GPS it was possible to accurately determine if an acceleration or deceleration had occurred. At 5 Hz, although the precision of data is reduced, team sport data could still be analyzed and used to determine running variability. The accuracy in changes in velocity during decelerations presented overestimations up to 19.3%, with errors on average of 17.4% greater than during accelerations [10].

An analysis of the validity and reliability of 1 Hz and 5 Hz Global Positioning Systems was performed by Portas, Harley, Barnes and Rush. The goal was to determine the accuracy of GPS devices for measures of total distance during linear, multidirectional and soccer specific motion at those frequencies. They concluded that 1 Hz and 5 Hz units could be used to quantify distances in soccer and similar field-based games, however they have a threshold beyond which reliability is compromised. The 1 Hz units are also less valid in complex courses and underestimates distance by moderate to large differences (approximately 4-11 %) [11].

Also analyzing total distance calculations, Johnston, Watsford, Kelly, Pine and Spurrs perform a study on 10 Hz and 15 Hz GPS units for accessing athlete movement demands. The study demonstrated that the 10 Hz GPS units provide a valid measure of total distance with less than 1% error, although for speed, the units used on this study were not capable of determine a valid value for this metric. They also refer that those results are in contrast with some of other studies that reported the validity of GPS units, even with less frequent values, such as the study performed by [4] or [7]. They also conclude that the results for the distance covered or time spend that were performed at low speed running or high speed running demonstrated a level of error relatively low (< 10%) for both 10 Hz and 15 Hz GPS units, which is a significant improvement from the errors that had been reported on [4], which were< 32.5% for 1 Hz and <17% for 5 Hz [12],within the same speed zones [13].

Recent smartphones using Android Operating System usually have a GPS refresh rate of 1 Hz. When it comes to speed measurement, this kind of frequency may result in some errors, mainly in higher speeds. So, in order to cope with this limitation additional sensors may have to be incorporated (GPS augmentation). Nevertheless, the studies described in this section shown that speed measurements at those refresh rates (around 1 Hz), are at least accurate enough to determine if the surfer rode a wave at a certain period of time.

B. GPS Augmentation

For many applications, standalone GPS may not be the best option. For Petovello and Lachapelle standalone GPS may produce unreliable information, due to the lack of accuracy of the device. The difference between the measured values and the true values can be quite large, due to several factors such as the quality of the signal or the quality of the device. In their study they claim that additional sensors should be used for applications that require critical and accurate information [14].

Oreskovic et al. performed a study where they combined the GPS and accelerometer data to determine the locations of physical activity in children. Accelerometers provide acceleration data and are commonly used worldwide for detecting movement parameters or other occurrences, such as falls [15]. They concluded that the combined data could not only be used to analyze the subject's physical activity parameters, but also the locations and speeds where they were more and less active [16].

Some other studies were based on combining gyroscopes and magnetometers with GPS for navigation. Ladetto, Gabaglio and Merminod used a system where they could compare and analyze the azimuth and the distance travelled in pedestrian navigation. The distance is computed by merging the accelerometer signal with a model that is calibrated online using GPS data. They conclude that those azimuth calculations could provide good solutions for reliable navigation systems [17].

III. Methodology

A. Data Collection

The tests were performed using a Google Nexus 5 smartphone, running Android 4.4.4. This device is equipped with an Inertial Measurement Unit (IMU) and a GPS unit. The device was protected by a waterproof case and placed on the surfer's back vertically (Fig. 1). In that position, the device accompanies the movements of the surfer's torso, facilitating the comprehension of the sensor data gathered.

One subject, a recreational practitioner with 25 years, performed two different surfing sessions in order to capture sensor data. The first one had the duration of 1:02:47, while the second one lasted for 1:10:00. The conditions were very different for the two sessions, especially at sea. The waves were significantly bigger in the second session, which hardened the process of catching waves by the casual surfer, resulting on fewer waves rode by the subject. Nevertheless, the second session was also very useful in the scope of this work.

The Android application developed stores the values received from each sensor on separated CSV (Comma Separated Values) files for later analysis. The sensor rate for the inertial sensors was 50 Hz, whereas the pressure sensor had a frequency of 33 Hz. The GPS, as mentioned in the Related Work section had a refresh rate of 1 Hz.

Fig. 1 Illustration of the smartphone positioning

A JAVA application was also developed in order to analyze the sensor data, to therefore detect the number of waves "caught" by the subject. Two approaches were then studied: One using only GPS data, while the other used sensor fusion data from all the five sources (IMU, GPS and barometer). In order to properly analyze the features extracted from the data signals, sliding windows of 1 second were used for the pressure and inertial data and 5 seconds for the GPS data.

B. Wave Detection and Duration Using GPS

The first method used to detect the waves rode by the surfer was to only compute the speed values retrieved from the GPS signal. After some analysis over the gathered data it was concluded that in order to detect all the waves, the minimum threshold of 10.8 km/h needs to be surpassed for a specific period where the GPS signal remained active (the signal was lost underwater). This automatically eliminates some false positives that were occurring. When a wave is detected, then other metrics are analyzed, such as latitude and longitude values, during that period, in order to determine the wave distance. This parameter is calculated using the Haversine formula, which can be defined by the following moments [18]:

First moment: a – the square of half the chord length between the position points;

$$\boldsymbol{a = sin^2\left(\frac{\Delta\varphi}{2}\right) + cos\,\varphi 1 \cdot cos\,\varphi 2 \cdot sin^2\left(\frac{\Delta\lambda}{2}\right)} \quad (1)$$

Second moment: c – angular distance in radians;

$$\boldsymbol{c = 2 \cdot atan2\left(\sqrt{a}, \sqrt{1-a}\right)} \quad (2)$$

Finally, d – distance in meters;

$$\boldsymbol{d = R\,.\,c} \quad (3)$$

where φ is latitude, λ is longitude and R is Earth's radius (R=6371000 m). These calculations are performed for all latitude/longitude pair points received during the period of the wave.

C. Wave Detection and Duration Using GPS and Inertial Sensors Combination

In order to detect the exact moment when the surfer stands up in the surfboard, sensor fusion is performed using the inertial sensors data. That way, the three-axis accelerometer data on Earth coordinate system is obtained allowing the vertical component of the acceleration to be analyzed, regarding the device position.

This component was used to reach the required goal at that phase. A 1 second sliding window (50 samples) of vertical acceleration values is used and some features were extracted during each window:

- Standard Deviation;
- Interquartile Range;
- Maximum value;
- Sum of Squares;
- Minimum Average;
- Absolute Value.

These metrics were compared every time the surfer was standing up in the surfboard, in order to correctly define the thresholds wanted for each one of those components.

After the beginning of a wave was detected, the algorithm waits for the moment when the surfer falls into the water again, meaning that the wave has ended. This was performed primarily using the accelerometer data.

The magnitude of acceleration could also be used to determine when the wave ended. The values of the magnitude are very different when the device is stationary and when the device is moving, such as in free fall. Knowing those parameters, it was possible to detect the end of the wave. Also using the accelerometer was possible to detect strong clashes between the surfer and the sea water surface.

Also, during the wave time,the values from the GPS signal are being stored, as well as the values from the inertial sensors. They will be computed if a wave is indeed detected by the algorithm.

There are a few factors that are analyzed in order to detect if a wave event occurs or not, such as:

- Wave duration – if the difference between the final and the initial time is less than 2 seconds, the event is discarded;
- GPS speed – the 10.8 km/h threshold needs to be surpassed for more than 2 consecutive GPS samples during the wave period.

If those conditions were met, a wave event is detected, and parameters such as wave distance, wave top speed or wave average speed are calculated.

D. Validation with Video Data

Video data was obtained for validation of the number and duration of the waves rode during the surfing sessions. A high-definition Canon Legria HF G10 camera was placed on the beach (Fig. 2) capturing the surfing sessions at 50 frames per second. In order to synchronize sensor data with the videos, the footage was analyzed with OpenShot Video Editor in order to determine how many waves were performed, as well as the exact moment when each wave starts and ends, by making a frame-by-frame analysis in that same software.

Fig. 2 Illustration of the images obtained of a surfer riding a wave

IV. Results

The results obtained in terms of number of waves detected using video, GPS data only or GPS and IMU data, for the two surfing sessions are shown in Table I.

TABLE I
NUMBER OF WAVES DETECTED

	Session	Video	GPS	GPS& IMU
Number of Waves	1	10	10	10
	2	3	9	3

Although in the first session, the algorithm using only the GPS detected the true number of waves, in the second session the accurate results were only achieved with all the sensors combined. The sea conditions in the second session were bad for surfing, so the subject attempted to catch a wave numerous times, but was unsuccessful in some of them. This resulted on a speed increase, but did not result on a wave rode. Sometimes the subject fell right after rising up on the surfboard, while other times he could not even get up. This behavior made the algorithm to be right only 3 out of 9 times using the GPS data alone, which means that 6 false positives were detected. The results were far better by combining all the sensors (3 out of 3).

Wave duration was also a subject of study in this work. For that, the video was reviewed and when a wave was detected on the footage, a frame-by-frame analysis was performed in order to obtain the most accurate duration, in milliseconds (ms), of each wave detected. The duration obtained from the algorithms was calculated as the difference between the final time and the initial time of the wave. That way, it is possible to compare wave duration times between the different algorithms and the real duration. The results are on Tables II and III.

TABLE II
TIME AND DURATION DIFFERENCE BETWEEN WAVES - SESSION 1

Wave Number	Time (min:s)			Duration (ms)		
	Video	GPS	GPS & IMU	Video	GPS	GPS & IMU
1	10:29	10:30	10:29	6020	7000	6297
2	21:35	21:36	21:35	4040	6000	4369
3	22:02	22:05	22:02	4920	5000	5020
4	26:11	26:12	26:11	3260	5000	3376
5	35:22	35:23	35:22	4440	5000	4927
6	44:52	44:53	44:52	4340	6000	4918
7	49:14	49:15	49:14	5400	8000	6462
8	51:33	51:33	51:33	3880	5000	3884
9	54:47	54:48	54:47	7260	9000	7348
10	1:00:45	1:00:45	1:00:45	3400	6000	4286

TABLE III
TIME AND DURATION DIFFERENCE BETWEEN WAVES - SESSION 2

Wave Number	Time (min:s)			Duration (ms)		
	Video	GPS	All	Video	GPS	GPS & IMU
1	14:17	14:18	14:17	6500	8000	6777
2	33:15	33:15	33:15	3700	6000	3986
3	49:45	49:47	49:45	8900	11000	9293

By analyzing the initial wave times, it was possible to verify that the algorithm that used the GPS values alone, had a mean delay of **1 ± 0.78s** for all the 13 waves detected, whereas no difference was perceived combining all the sensors. The GPS algorithm only detected the wave once the surfer was already riding it. This delay proves that fact. According to[10], GPS, especially at lower frequencies, is not adequate to measure accelerations an decelerations, but once the surfer is at a constant velocity, those errors diminish and the values are much more accurate.

Regarding the wave duration, the error between the real duration and the durations calculated by the two approaches were quite different. The mean error using only the GPS was

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1610 ± 704 ms, whereas combining all the data resulted on a mean error of **360 ± 293 ms** difference. The surfer's movements during a wave may not be similar among different waves, especially at the final stages, namely the falls into the water that actually, were verified to be very different. The GPS alone had a harder task, considering its delay retrieving the speed values, resulting on a much higher mean error on the wave duration. The GPS alone approach was calculated to be about **4.57 times** less accurate than the GPS & IMU approach, which by itself had a total duration only **7% higher** than the real total duration. On the other hand, the algorithm with only the GPS had results **32% higher** on the same value.

V. Conclusions

This paper performed a comparison between two approaches that quantify surfing sessions. One used only the GPS data, while the other used a combination of GPS and inertial sensors.

Overall, both approaches can be used to estimate the number of waves rode during surfing sessions. However, merely analyzing GPS data resulted in 6 false positives for the used dataset. This is due to the fact that using only the speed as metric for wave detection it was not possible to eliminate the times when the surfer tried to "catch" a wave but could not. Although the speed increased over the predefined threshold, the wave was not effectively "caught". This was resolved by the second approach, using the inertial sensors to detect the exact moment when the surfer rose and fell over the surfboard.

The approach with the combined data also approximate the time wave duration values to the real duration of each wave. Although this was just a proof of concept and the investigation needs to include other subjects and more surfing sessions, the results revealed that those sessions can be accurately quantified using the methods described in this paper.

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