ADVANCING AQUATIC MOTION TRACKING THROUGH MULTI-SENSOR DATA FUSION SURFING THE GIANT WAVES OF NAZARÉ – STUDY CASE

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As we delve into the diverse applications of motion tracking from Space to Air and Land, we encounter distinct challenges and opportunities. However, the most significant arise in the aquatic domain, particularly in the maritime environment. The unique characteristics of water behaviour demand novel solutions for accurately tracking and interpreting movement in this dynamic environment. An outstanding outcome of my Sports Sciences PhD was the Fluid Flow Sensor. This groundbreaking multi-sensor innovation enables tracking data considering water flow, expanding research horizons of analytics in water sports. Notably, the technology showcased its exceptional potential through a successful pilot study during a surfing session in the extreme conditions of Nazaré Giant Waves (Portugal), illustrating its remarkable capabilities for advancing research in water sports and related fields.

KEYWORDS: biomechanics, fluid flow sensor, tow-in, surfboard, fluid dynamics, ocean.

INTRODUCTION: Local positioning and motion-tracking technologies have the potential to revolutionise various industries, such as healthcare, sports, virtual reality, robotics, and gaming, by enabling precise and real-time tracking of human movement. These technologies offer valuable insights into human behaviour, performance, and environmental interactions (Isaia & Michaelides, 2023). The rapidly growing world market for these technologies is projected to reach USD 7.3 billion by 2025 (MarketsAndMarkets, 2023), indicating a substantial demand for innovative solutions.
Evaluating performance under natural conditions is a common challenge across many sports (O'Shea & Moran, 2017), including aquatics, where this task becomes even more complex than in most other sports. This difficulty lies in implementing evaluation solutions for athletes, equipment, or the surroundings, which do not compromise efficiency and still resist this hostile environment for electronics. Applying tracking technologies in the water sphere introduces unique challenges (e.g., corrosion, sealing, infiltration, overpressure, data transmission, etc.), creating significant hurdles in advancing the science of aquatic motion.
Even using the most recent sensors and innovative methodologies, there is a noticeable gap when it comes to accounting for water flow or speed through water in tracking motion. This critical gap can result in biased, incomplete, or erroneous insights into performance indicators within fluid domains (Dalheim & Steen, 2021).
In 2015, during my doctoral studies focused on surf biomechanics and bioenergetics at the Porto Biomechanics Laboratory – University of Porto, we utilised state-of-the-art laboratory methodologies and equipment for water-based research. As a result of the study's impact, I received an invitation from the German television channel ZDF to participate in a documentary analysing the surfer Sebastian Steudtner, the world champion of giant waves, from a sports scientist's perspective (ZDF - Terra X, 2015). During our search to identify suitable technologies for instrumenting the equipment used by the surfer, we encountered a significant gap in the market: the absence of water flow sensors compatible with surfboards or small crafts. This challenge sparked the idea of creating the concept of the Fluid Flow Sensor (FFS), a multi-sensor innovation. The FFS integrates a two-dimensional water flowmeter, a three-dimensional inertial measurement unit (IMU), and a temperature sensor in one device. Notably, this ground-breaking technology has recently earned an international patent, encompassing the United States, Europe, and China, under the title 'Apparatus for sensing movement of an object relative to a fluid' (Borgonovo-Santos, 2023).

METHODS: The surfboard, equipped with cutting-edge technologies (Fig.1 a-e), featured components like the FFS from Riedel Communications (Germany), a Global Navigation Satellite System (GNSS), a microcontroller, a memory card, a telemetry radio, a Real Time Clock, and a battery, alongside two buttons (On/Off, Record/Stop). Particularly, the Central Microcontroller played a pivotal role, ensuring a unified timestamp for the data collected by all sensors. This synchronisation proved essential for aligning the data seamlessly, allowing for correlation with videos recorded using timecode or based on file creation time. This integration significantly bolstered the precision and coherence of the study.

Figure 1 – a) GNSS and Telemetry Radio housed in the surfboard's nose. b) Waterproof central box for accessing electronics, battery, and memory card. c) Fluid Flow Sensor, positioned according to a previous Fluid Dynamics study. d) the top view, and. e) the bottom view of the surfboard. f) The surfed wave, on the critical moment, where the wave is twelve times bigger than the surfer in a squat position.

Moving on to the data collection and analysis phase, Sebastian Steudtner's surf session during a notable swell at Nazaré (Portugal) on March 21, 2021, amid the pandemic, served as a comprehensive case study (Fig.1-f). The integrated system diligently gathered detailed performance metrics, complemented by video recordings providing a visual reference for key events such as jet ski pulling, wave entry, speed variations, and completion. This visual support played a critical role in establishing correlations between instrumented data and specific occurrences, thereby enhancing the overall reliability and depth of the study.

RESULTS: Several key performance metrics were captured, providing valuable insights into the surfboard's behaviour and the dynamic ocean environment. The following results highlight the comprehensive data collected by the instrumented system:

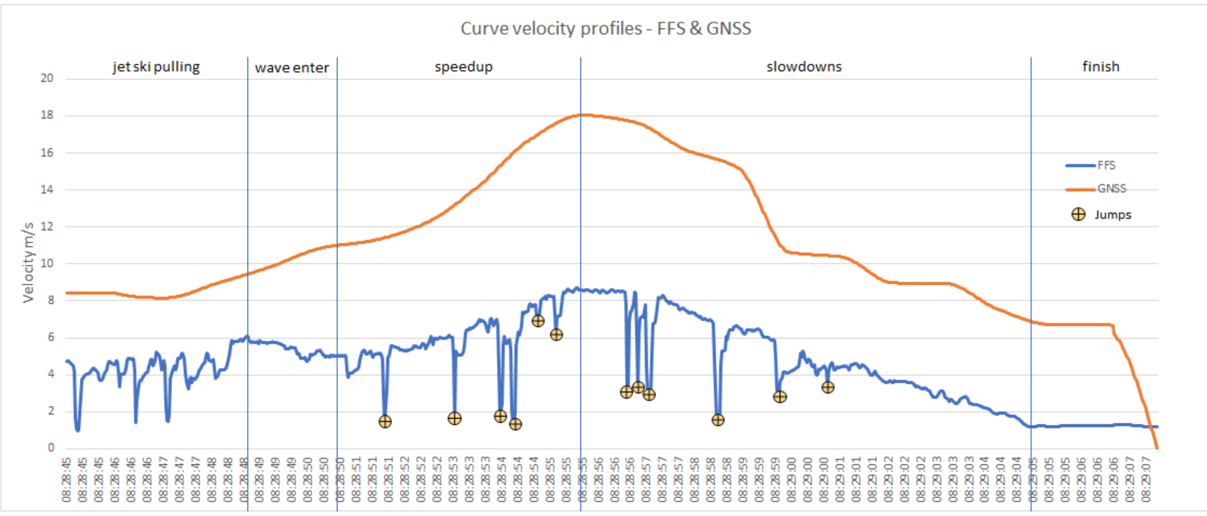

Figure 2 – Velocity profile comparison: FFS vs GNSS in a giant wave surf ride, with video annotated events.

The FFS showed 8.7 m/s top speed (Fig. 2), 110 m displacement, 5.69 m differential elevation (Fig. 3), -34° maximal surfboard inclination on the wave (Fig. 4). During wave riding, the surfboard either loses contact with the wave surface or is forcefully inclined backward, resulting in 12 jumps, with a total airtime of 1.815 seconds. The flying distance covered was 13,98 m. The mean water flow direction registered was 185° ± 16° (Fig. 4). The maximum G-force experienced was 9.2 g, lasting for 0.195 seconds. Additionally, 4 ejections reaching a maximum G-force of -3.55 g for 0.1 seconds, causing a contact loss between the surfer and the surfboard, mitigated by the feet fixation mechanism. From GNSS data, the top speed was 18.04 m/s (Fig. 2), displacement was 233 m, and differential elevation was 8.2 m (Fig. 3).

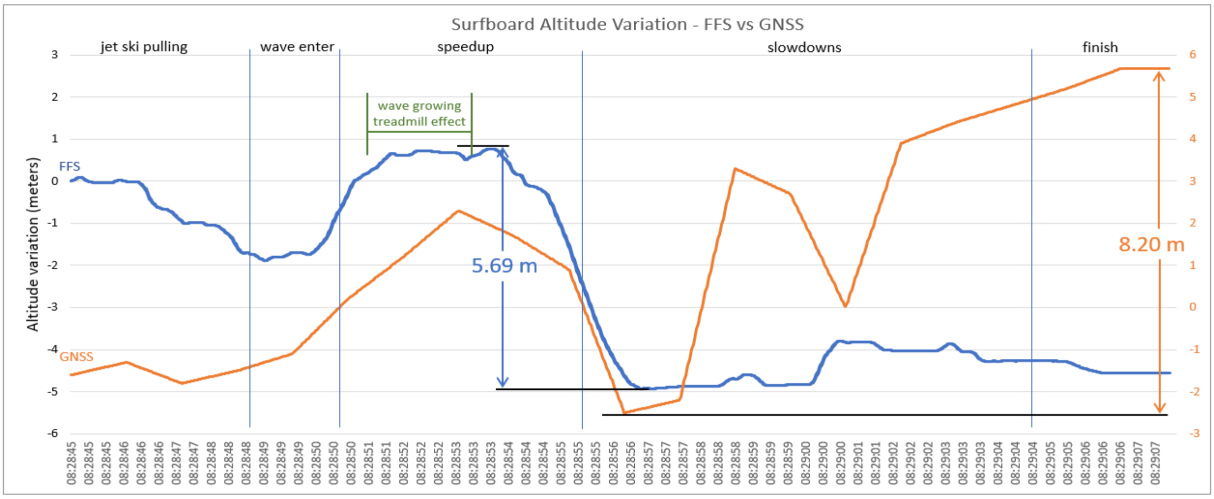

Figure 3 – Altitude variation comparison: Fluid Flow Sensor (FFS) vs. GNSS in a giant wave surfing ride with video annotated events.

The surfboard attitude was represented by Roll and Pitch (Fig. 4), where the average values were, respectively, 89° ± 16° and 1.2° ± 10°.

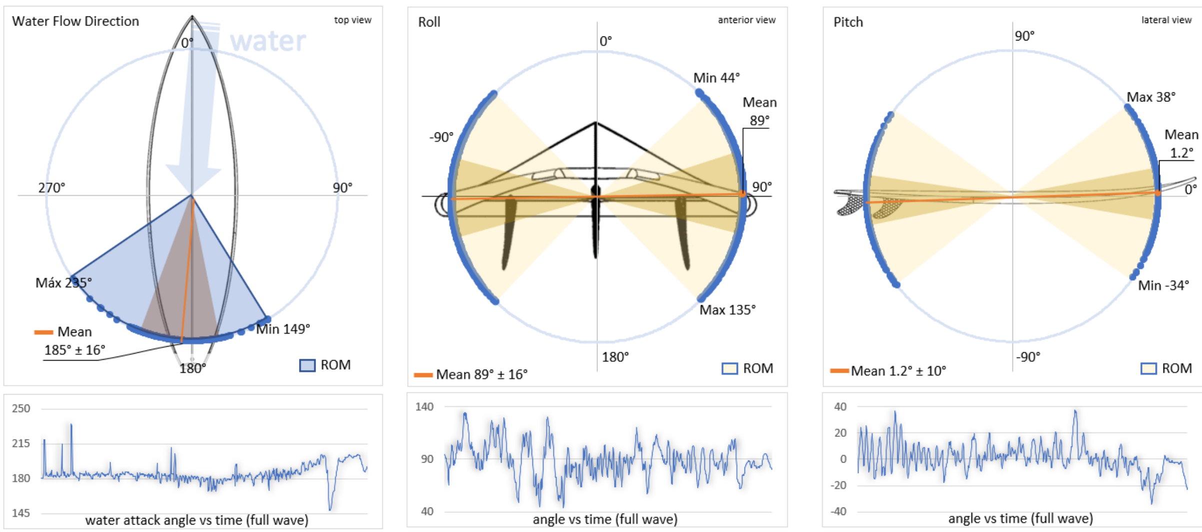

Figure 4 – Left: Top-view depiction of a surfboard with flow angular metrics and angle. Middle and right: Variation in Roll and Pitch angles. Below each graphic: Respective curve profiles of the entire surfed wave.

DISCUSSION: The initial point of interest was the disparities in velocities recorded by the FFS and GNSS. GNSS relies on ground references, whereas the FFS accounts for velocity through water. Concerns about potential calibration errors prompted us to collect data using the same equipment during a wake-surf session in flat water. As expected, no significant differences were observed between the two devices' maximum and average velocity profiles. This suggests our data are correct and that when a surfer rides a wave, they experience both the velocity of wave propagation towards the coast and the velocity relative to the water on the wave face – two distinct parameters that the system was able to differentiate.

To delve deeper, the formation of a wave crest and its subsequent break hinge on the overlap of the wave's posterior section onto its anterior part. Essentially, the uppermost layer or surface of the wave's face, the water tissue, remains free of current or acceleration. This unprecedented finding, quantitatively measured, sheds new light on the behaviour of giant waves. Altitude variation reveals another dimension of divergent measurements. The Fluid Flow Sensor (FFS) calculates this variation through inertial acceleration data over time. Conversely, while reliable, the robust GNSS sensor is prone to errors and interferences, especially at water level. Negative altitude variations suggest the surfer's position below sea level, accurately reflecting the trough of a wave formation. During wave entry, as the jet ski positions the surfer from the back to the front of the wave, both systems recorded negative altitudes. However, in the acceleration phase (dropping down), the two sensors yielded distinct measurements. Upon video analysis, the increase in the surfer's height relative to the wave entry was observed, aligning with the expected behaviour measured by the FFS. Interestingly, we also identified a phenomenon that we named "the treadmill effect." This occurrence was characterised by the wave's growth rate matching the surfer's velocity increment while descending the wave. As a result, to an external observer, it created the impression that the surfer remained stationary during this window time. The wave was a left one. It signifies that the wave face was predominantly open on the left side, free of white water. The water angle measurement becomes meaningful upon the surfer's departure from the wave. This implies that, beyond manoeuvres for surfboard adjustment, the essential trajectory adheres to a leftward direction based on the surfboard orientation reference. When interpreting performance metrics, it's crucial to consider the intricate interplay between wave dynamics, the surfer, and equipment. Correlating these results with health parameters, such as exertion levels and injury risks, allows for a comprehensive understanding of the sport's impact on surfer well-being. This approach enhances the validity of the findings and provides valuable insights for optimizing both performance and safety in the challenging environment of giant wave surfing.

CONCLUSION: The groundbreaking multi-sensor FFS, showcased in extreme conditions at Nazaré Giant Waves, demonstrated exceptional capabilities in tracking water-based movements. Disparities in velocities recorded by the FFS and GNSS highlighted its ability to differentiate wave propagation from relative water velocity on the wave face. Quantitative measurements shed new light on the understanding of giant wave formation, revealing the intricate relationship between surfer movement and wave dynamics. Additionally, these measurements contribute significantly to understanding velocity variations in tow-in surfing sessions. Moving forward, these insights can inform advancements in technology and safety measures in water sports, ultimately optimizing both performance and safety for athletes in risk conditions. Additionally, the study's implications extend to technological advancements in water sports, offering valuable insights for researchers, athletes, and professionals. Furthermore, the international patent for the FFS underscores its innovative nature, with potential applications across various fields.

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