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Kivi: the smartest of pebbles

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Abstract
Kivi is a new smart pebble sensor designed to simultaneously capture impact (1kHz) and inertial and pressure measurements (100Hz) in geomorphological studies. This paper presents the design and development of Kivi, which is available as either a 55mm diameter sphere or as an ellipsoid with dimensions of 80mm x 63mm x 56mm. The sensor is equipped with a microcontroller and rechargeable battery, and has a storage capacity of 8GB. Preliminary testing, including static pressure measurements, impact tests, and flume laboratory experiments, demonstrates Kivi's ability to accurately capture sediment behaviour in riverine environments. The sensor holds significant potential for enhancing our understanding of fundamental sediment transport and erosion processes, with applications in environmental protection and infrastructure development.

Keywords: Kivi, sediment transport, smart pebble, geomorphology, hydraulics

1. INTRODUCTION

The quantification and measurement of sediment movement are indispensable for deciphering the intricate processes that govern geomorphological systems, and have far-reaching implications for understanding habitats, identifying hazards, and ensuring infrastructure resilience. By accurately measuring sediment behaviour, it is possible to assess the stability of riverbeds, riverbanks, beaches and hillslopes, predict erosion and deposition patterns, and pinpoint areas vulnerable to natural hazards, such as landslides and floods. Moreover, a comprehensive understanding of sediment dynamics is crucial for ecological studies, given that sediment movement can shape aquatic habitats and influence the distribution of flora and fauna. In terms of infrastructure resilience, quantifying sediment transport plays a pivotal role in informing the design and maintenance of structures, including bridges, dams, and river and coastal embankments, guaranteeing their durability and resilience against geomorphic processes. Consequently, employing cutting-edge technology to quantify sediment movement is vital for advancing our knowledge and management of geomorphological systems, leading to significant benefits in environmental protection and infrastructure development.

In recent years, there has been a significant increase in the use of MEMS (Micro Electronic Mechanical System) IMUs (Inertial Measurement Units) in geomorphological studies, with applications ranging from single grain flume experiments to full-scale landslide motions, and from capturing rock falls to measuring flows in glacial environments (Akeila et al., 2006; Biggs et al., 2022). These developments in "geomorphic" IMUs typically involve constructing a bespoke enclosure that emulates the properties of a natural sediment grain, although enclosures are often idealised shapes.

Historically, the deployment of IMUs in geomorphology has followed three parallel paths, focusing on detecting mobility states, characterising incipient sediment motion, and capturing forces applied on grains during transport (Olinde et al., 2015; Valyrakis and Alexakis, 2016; Gronz et al., 2016; Al Obaidi et al., 2020; Maniatis et al., 2020). Sensors have been developed with "off-the-shelf" IMUs, purpose-specific electronics, and/or modified commercially available IMUs, with attention given to the effect of the sensor assembly's physical properties on the derived measurements (see the commentary of Maniatis 2021 for further details). The technology has developed over the past two decades, with a trajectory towards smaller sensor pebbles, higher data recording frequencies, greater data storage capacities, higher ranges of measured accelerations, and the addition of sensors to the devices.

In addition to these three primary paths, recent publications have also explored the deployment of IMUs in conjunction with telemetry systems (radio or GPS) for "live" tracking of instrumented particles (Dini et al., 2021) or to facilitate their retrieval after surveys or deployments (Biggs et al., 2022). Furthermore, there is a significant body of work on rock fall identification (Caviesel et al., 2021), which focuses on the analysis of impacts and energy dissipation and is relevant to acceleration frequency and drop experiments. Finally, IMU technology has been deployed to measure turbulence in fluvial environments using IMU-instrumented "drifters" (Tuhtan et al., 2020). These studies demonstrate technological developments that directly apply to monitoring grain dynamics and are relevant to the broader context of IMU applications in geomorphological research.

In this paper, we introduce Kivi, a novel smart pebble sensor designed to simultaneously capture inertial, impact, and pressure measurements in geomorphological studies, effectively consolidating advances implemented in previous works into a single sensor. The unique feature of Kivi is the integration of two pressure sensors, alongside an IMU and a high-g accelerometer, enabling a comprehensive and accurate analysis of sediment behaviour. The scope of this paper is to present the design and development of Kivi, and to demonstrate its potential through preliminary data obtained from static pressure measurements, impact tests, and flume laboratory experiments. As a first reference for the sensor, we demonstrate the potential of Kivi to enhance geomorphological studies in the context of fluvial sediment transport and erosion processes.

2. SENSOR SPECIFICATIONS AND DESIGN CHARACTERISTICS

The sensor is available in two form factors: a sphere with external diameter 55mm and an ellipsoid with dimensions of 80mm x 63mm x 56mm (length x width x height , **Figure 1**), making it suitable for parametrising the movement of natural sediments, such as those found in gravel bed rivers (median grain size, D50, typically 20 to 200mm). Kivi is equipped with an efficient microcontroller, a rechargeable battery offering 6 hours of continuous logging, and 8GB storage capacity. With data logging rates of 100Hz for the IMU and pressure sensor and 1000Hz for the high-G accelerometer, Kivi provides a wide range of sensor output variables across a temperature range of -40°C to 85°C . The sensor is also equipped with a high-performance double pressure O-ring seal (IP8), a magnetic switch and multi-coloured LED light integrated into the housing, to provide the user with on/off control and sensor status information (on/off, low battery, recording data, charging battery). The simple design allows the sensor to be deployed by non-expert users, making it suitable for large-scale studies involving citizen science. The detailed specifications are provided in **Table 1.**

1.1 The Pressure Sensors

Installed at both the top and the bottom of the Kivi sensor (for both the ellipsoid and sphere enclosures) are two digital total pressure transducers (**Figure 1**). These transducers measure the sum of atmospheric, hydrostatic, and hydrodynamic forces, and are based on the custom design of the Barotrauma Detection System (BDS; Pauwels et al., 2020), which has been used in fish studies. The transducers have a maximum pressure of 200kPa (MS5837-2BA, TE Connectivity, Switzerland) and a rated sensitivity of 0.002kPa (~0.2mm water column). All data were recorded at a 0.001kPa resolution with 0.1kPa (~10mm water column) accuracy. The accuracy was determined by laboratory testing the BDS sensor in a barochamber up to 550kPa, which is 2.75 times the maximum rated pressure of the sensor, and was evaluated using a calibrated commercial pressure sensor (HOBO U20-001-02, Onset Computer Corp., USA).

As these transducers have not been previously deployed in geomorphological applications, we present data from a simple hydrostatic pressure experiment. The spherical sensor was placed in a 3L borosilicate glass container, which was progressively filled with water (**Figure 2**). The measurements demonstrate the accurate recording of depth increase as well as the difference between the top and bottom sensors. Both total depth and the across-sensor differential are particularly valuable in hydrodynamic studies, which may include partial submergence of sediment grains and/or changes in grain orientation.

1.2 Impact measurements

The optimal frequency for geomorphic applications using accelerometers remains an open debate, with early studies suggesting a sampling frequency of 50Hz for capturing coarse particle travel during bed-load transport (Drake et al., 1988). However, this frequency may not be suitable for capturing riverine or coastal turbulent structures (Diplas et al., 2008) or impacts, as observed in rockfall experiments and industrial applications. The motivation behind deploying two accelerometers is the decoupling of these two vastly different requirements, with the high-g accelerometer solely devoted to impacts (e.g., Caviesel et al., 2021) and the low-g accelerometer to motion detection/capture and orientation estimations.

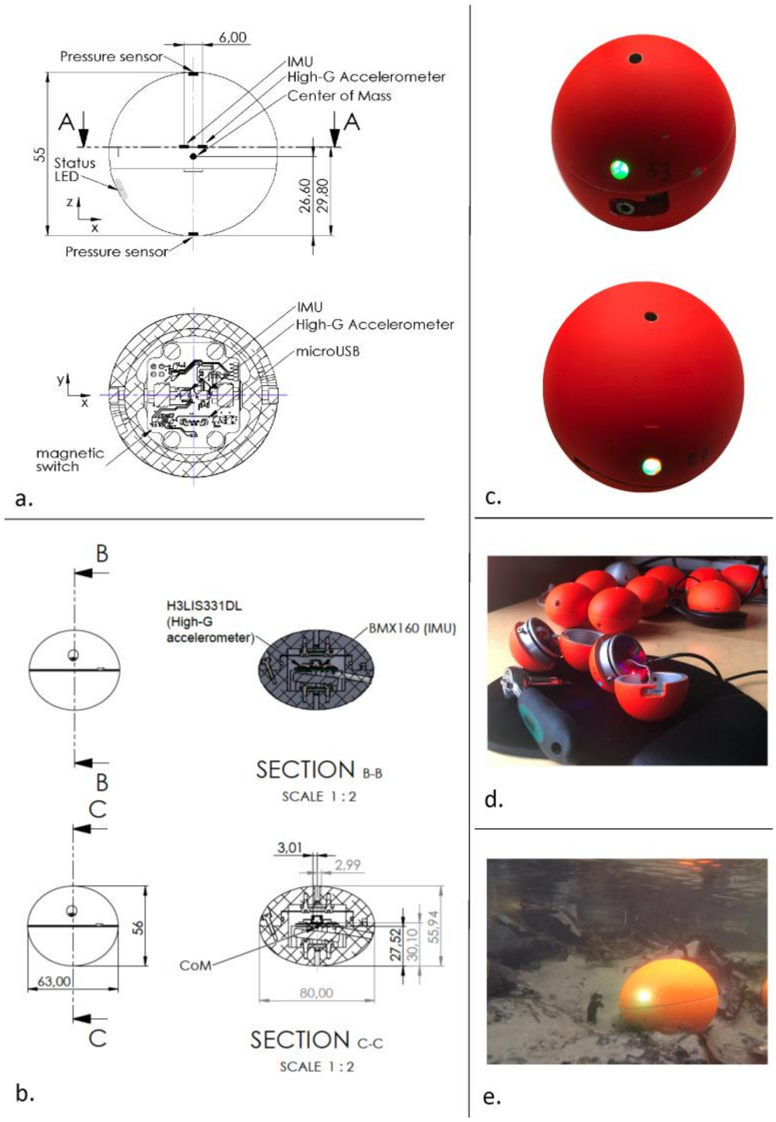
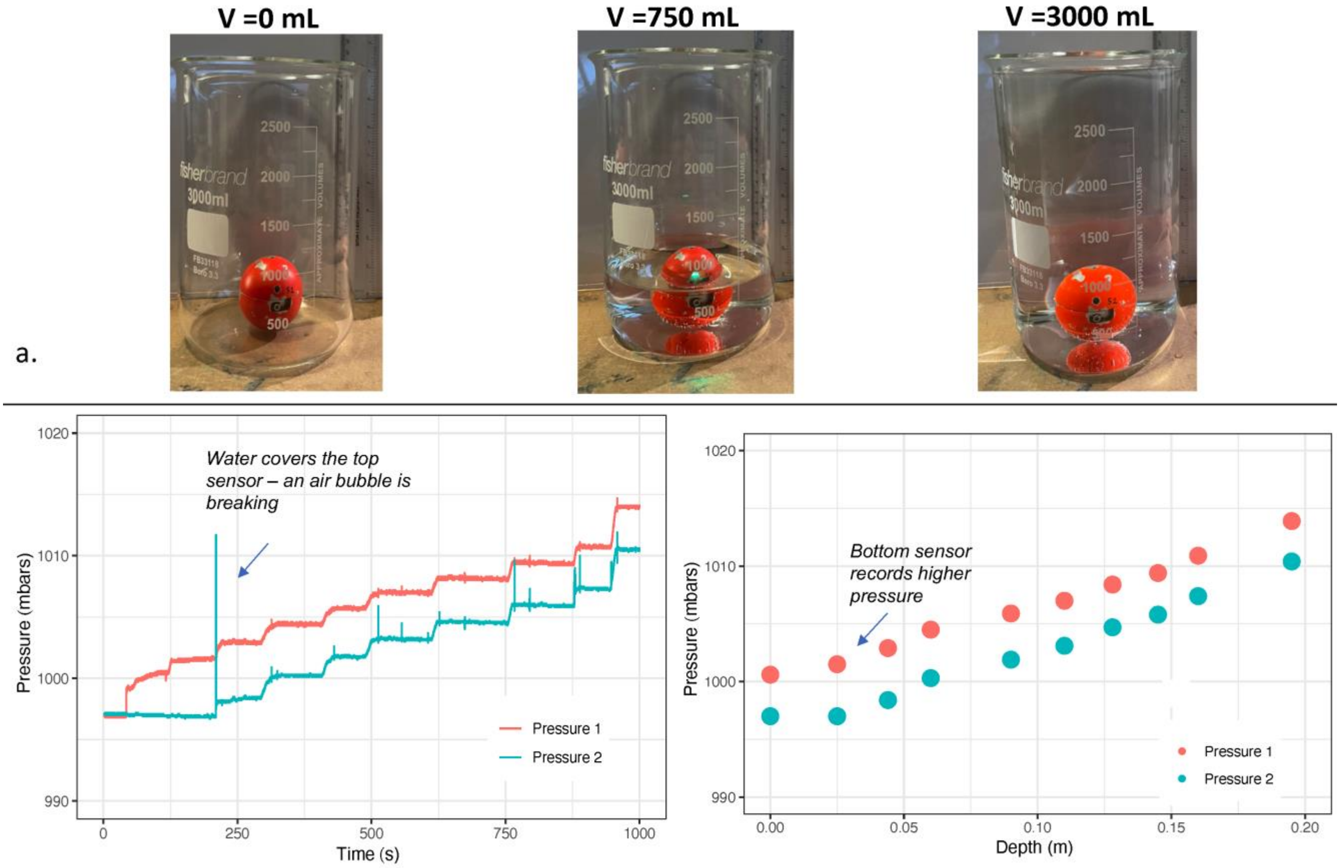


Figure 1. **a and b**; cross-sections of the spherical (a.) and the ellipsoid (b.) enclosures. **c.** and **d.** are "dry" photographs of the sensors and the charging functionality respectively. **e.** shows Kivi in action during preliminary testing in a small artificial stream in Tallinn.

Calibrating these multi-accelerometer assemblies remains a challenge without access to specialised IMU calibration equipment (e.g. 9DoF calibration tables, or advanced piezoelectric impact apparatus). Free fall drop tests can offer a solution, but the analysis must consider factors, such as the force measured during free fall and the effect of mechanical properties on acceleration values during impacts (e.g. Gadd and Maniatis, 2022). Ultimately, it is crucial to calibrate accelerometers within their deployed dynamic range and against an independent measurement, such as an external force impact sensor or an ultra-high-speed camera.

The principal challenge in evaluating collision measurements arises from the complexity of differentiating between sensor inaccuracies or biases and the innate variability of impact forces. In **Figure 3d**, this issue is exemplified by the bimodal distribution of impact magnitudes for rigid collisions (Kivi signal samples consisting of 11 measurements in the vicinity of the peaks, 1000Hz). Since the parameterisation of non-elastic collisions also necessitates advanced, specialised equipment, it is more practical to design a setup dedicated to elastic collisions, primarily due to the significantly lower rebound times that are easier to capture.



b.

c.

Figure 2. Submergence experiments for preliminary pressure calibration **a.** different degrees of submergence for the Kivi sensor; **b.** raw pressure signals during the experiment. **c**. averaged pressure for every change in depth ("steps" in b) vs depth.

In this context, we develop free fall/drop calibration experiment (drop height of 0.35m) to evaluate the performance of the high-g accelerometer in the Kivi sensor (Figures 3a to c). A Phantom V12.1 high-speed camera, capturing at 1,200 frames per second, recorded the impacts in detail. The impact parameters are extracted from the high-speed video footage using the simplified equation:

$$a\_impact = \pi/T * \sqrt{(g/2)} * (\sqrt{d2} + \sqrt{d1}) \quad \textbf{(1)}$$

where g is the acceleration due to gravity, *d1* and *d2* are the drop and rebound heights, respectively, and *T* is the pulse width of the impact, approximated here as the rebound time of the elastic collision. The material of the rebound surface is a High-Density EVA foam, which allows for rebound that lasts for 5-7 frames and can be captured manually (hence without the use of a tracking algorithm). The comparison with the Kivi high-g accelerometer shows good agreement and we are working on increasing the sample sizes for this calibration and reducing the errors due to misalignments of the accelerometer axes with the direction of the free fall and user bias.

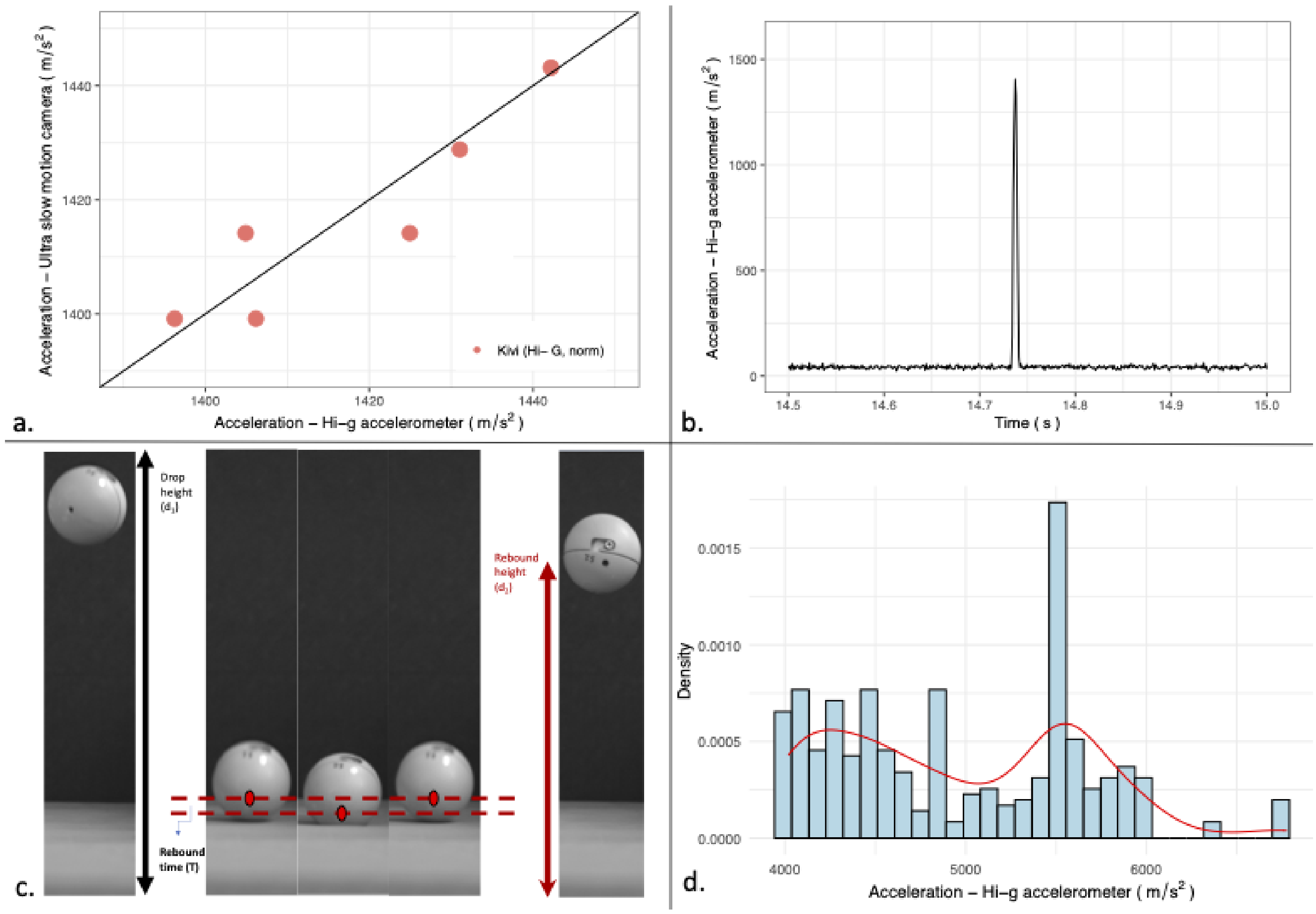


Figure 3. Drop impact measurements **a.** 7 comparisons of the high-g accelerometer norm with the impact acceleration as calculated using the high-speed camera (elastic collisions, 1200fps, 1000Hz) **b.** one drop impact as captured by the high g accelerometer (norm, drop height 0.35m, impact surface HD EVA foam, elastic collision, 1000Hz) **c.** schematic depiction of the parameters used for calculation of impact accelerations using the high-speed camera. The red dots indicate the approximate position of the centre of mass of the object, used distance/length calculations within the scaled video frames. **d.** impact magnitude distribution of 34 collisions on a rigid surface (concrete, drop-height 0.45m, 11 samples per impact, 1000Hz).

3. USING KIVI IN A FLUME LABORATORY

To demonstrate its potential in fluid environments, Kivi was also tested in a short series of flume experiments (University of Brighton, flume laboratory). The ellipsoid Kivi was placed on a rough bed (D50 c.13mm, D84 c.23mm) at the centre of a 0.45m wide recirculating flume. Discharge was gradually increased up to the point of entrainment (shear stress ranges from 0.007 to 0.011N/m^2 at the point of entrainment in **Figure 4**). The results allow us, for the first time, to decouple (qualitatively at this stage) turbulent fluctuations in the flow (recorded by pressure measurements) from the inertial kinematics (IMU measurements) and the impacts using the same sensor.

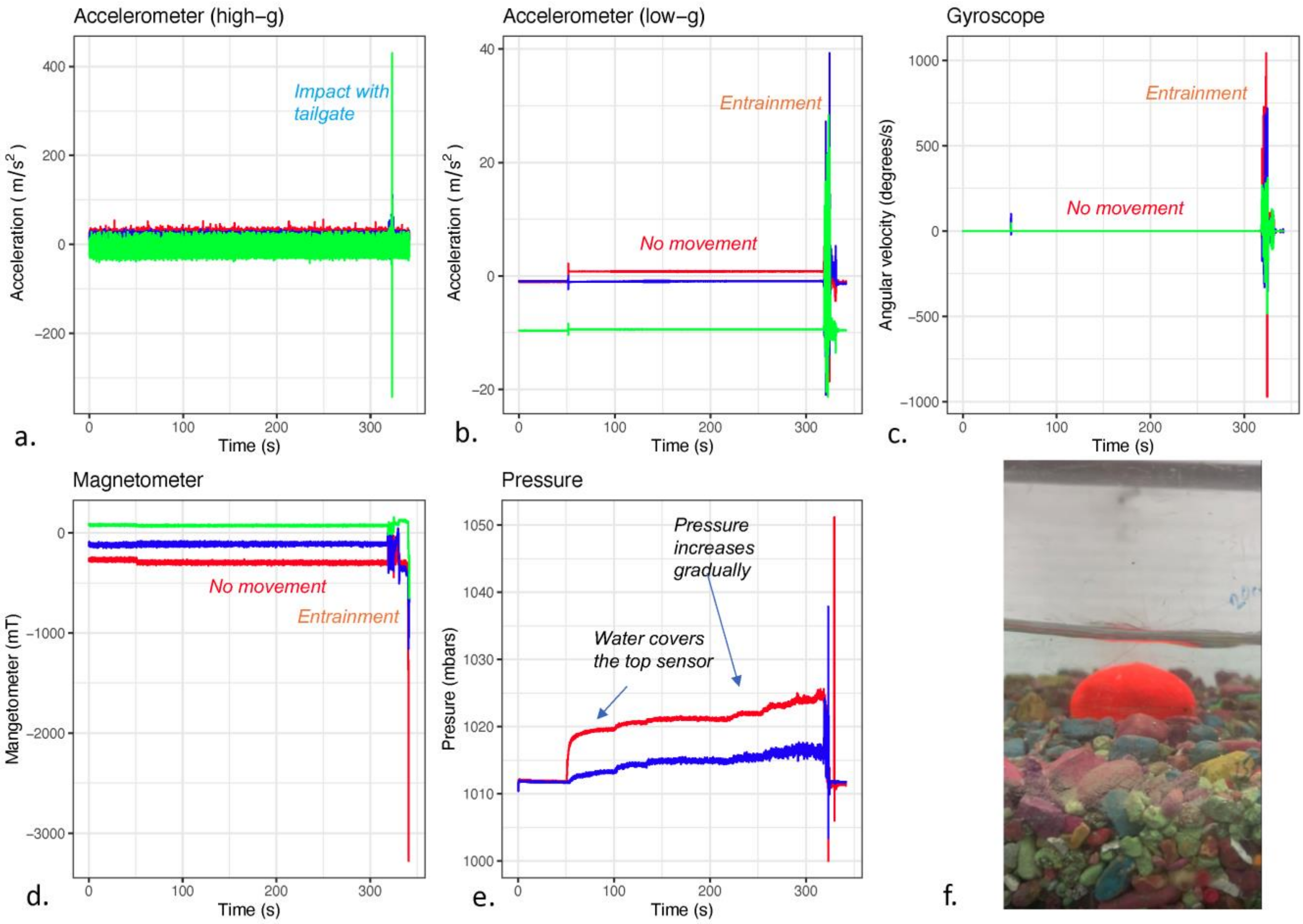


Figure 4. Flume data – University of Brighton flume laboratory. All the plots of the inertial sensors (accelerometers, gyroscope and magnetometer) show triaxial measurements (x- blue, y-red, z-green). **a** and **b**. High g and IMU accelerometer, respectively, the z-axis is approximately aligned with the direction of gravity ($g=9.81m/s^2$). **d.** the magnetometer captures the local magnetic field and can be used as a global orientation estimate (to the North Pole) **e.** the difference in water pressure scales with sensor thickness and can be used for estimating the in-channel orientation of the sensor in relation to the direction of the flow.

4. CONCLUSIONS

In conclusion, the new Kivi smart pebble sensor presented in this paper has demonstrated potential to significantly enhance our understanding of sediment behaviour and geomorphological processes. The sensor's unique combination of inertial, impact, and differential pressure measurements offers an integrated solution for capturing the complex dynamics of sediment transport in a range of natural and artificial environments. Preliminary testing, including static pressure measurements, impact tests, and flume laboratory experiments, have displayed Kivi's versatility and reliability in capturing high frequency data with a high signal:noise ratio. The sensor's design, featuring a robust enclosure, efficient microcontroller, and rechargeable battery, ensures its practicality and durability for various geomorphological applications. Our ongoing research is expanding the sensor's capabilities and testing it in different environments to further validate its performance and explore its potential to advance our understanding of sediment dynamics and erosion processes.

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Table 1. Kivi specs.

Feature	Description
Product name	Kivi
Pressure sensor	MS5837-2BA (TE Connectivity, Switzerland)
Range	10 - 2000 mbar
Inertial Measurement Unit (IMU)	BMX160 (Bosch Sensortech, Germany)
Accelerometer range	±16g
Gyroscope range	2000°/s
Magnetometer range	±2500µT
High-g Accelerometer	H3LIS331DL (STMicroelectronics, Switzerland)
Acceleration range	±400g
Microcontroller	ARM® Cortex®-M0+ based ATSAMD21G18 @ 48MHz (Microchip Technology Inc., USA)
Dimensions	Sphere: Diameter = 55mm; Ellipsoid: 80mm x 56mm x 63mm (length x height x width)
Weight	Sphere: 175±5 g; Ellipsoid: 330±5 g
Supply voltage	+3.3v with USB charging
Battery technology	Rechargeable Lithium-Polymer (charging time of 60 minutes at 20°C)
Battery lifetime	6h continuous logging at full charge (water temperature of 20°C)
Battery charging time	1h (at 20°C)
Storage interface	SD card
Storage capacity	8 GB
Communication interfaces	Micro USB connector, USB 2.0
Data logging rate	100 Hz for IMU and pressure sensor, 1000 Hz for high-G accelerometer
Sensor output variables	Total water pressure (mbar), linear acceleration (m/s²), rate of rotation (deg/s), and magnetic field intensity (mT)
Other output variables	Time stamp in ms, battery voltage
Temperature range	-40°C ~ 85°C (-40°F ~ 185°F)