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On the use of IMU (Inertial Measurement Unit) sensors in Geomorphology

Running title

IMUs in geomorphology

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Title:

On the use of IMU (Inertial Measurement Units) sensors in geomorphology.

Abstract:

Inertial Measurement Units (IMUs) are mobile sensors assemblies constructed using a combination of MEMS (Micro Electrical Mechanical Systems) accelerometers, gyroscopes and magnetometers. Both the technology and its applications to geomorphic problems are developing rapidly, since they demonstrate the prospect of monitoring individual sediment grains, of various sizes, *during* transport and at high frequency. This prospect has numerous implications which range from hazard identification and warning to complex theoretical derivations for sediment transport modelling. At the same time, the deployment of IMUs needs to be underpinned by a number of technical considerations regarding the limitations of the technology and the physics of the inertial measurements. IMU measurements should be reported in a manner that allows for clear understanding of the scope of the study, with sufficient detail for repeatability and clear error characterisation. At a secondary level, IMU measurements should be linked clearly with the physics of sediment motion. Here the author highlights five technical issues which can lead to the misinterpretation of IMU measurements. His scope is to begin a dialog towards a collective agreement on a presentation/reporting protocol for IMU measurements in geomorphic studies that will allow for the coherent contextualisation of the technology and accelerate its scientific impact within geosciences.

Introduction

The idea of measuring the inertial dynamics of sediments is not new (Ward, 1969). Capturing the force that mobilises the sediments directly has been a target for a lot of researchers despite the many difficulties posed by the available technology (e.g. Ergenzinger and Jupner, 1992). However, it is fair to say that this idea begun to materialise during the last 15 years. The first, known to the author, particle instrumented with IMUs (Inertial Measurement Units) that was developed specifically for monitoring sediment motion was introduced by Kularatna et al. in 2006. Akeila et al. (2010), present the first set of fluvial measurements using an IMU and deployments in flume incipient motion experiments. Frank et al. (2014) present the first deployment of IMUs in a regime that relates to coastal environments and oscillatory flows and Harding et al. (2014) a deployment focusing on debris flow. After 2015 the uses of IMU in geomorphology can be split in 3 groups. One group comprises of works such as the one from Olinde et al. (2015) who deploy IMUs (accelerometers in that case) as complementary start and stop motion sensors. For those works the objective is not to measure the dynamics but to detect mobility/non-mobility states and derive probabilities for bedload transport. A second group focuses on the development of purpose-specific electronics and the development of fully new instrumented particles. Here, the derived measurements, including the dynamics, are used to characterise the initiation of sediment motion across environments (e.g. Valyrakis and Alexakis, 2016, Weerasinghe et al., 2018). Finally, a third group of works implements existing, commercially available, IMUs with minor modifications on the electronics but a strong focus on the physical characteristics of the sensor assembly and the physics of the derived measurements (e.g. Gronz et al., 2016, Maniatis et al., 2017), mainly within the context of studying bedload transport.

The above, brief and not exhaustive, literature review indicates how quickly the rate of IMU deployments increases in geomorphology. The author has counted eight publications that focus on the deployment of IMUs in geomorphological applications from the end of 2019 until the submission of this commentary¹. The applications range from fluvial environments (Gimbert et al., 2019, Al-Obaidi et al., 2020, Maniatis et al., 2020, Pretzlav et al., 2020, Pretzlav et al., 2021) to landslides (Dost et al., 2020, Dini et al., 2021) and to eco-morphological applications (Carley et al., 2021). Those works differ in scope, IMU specification and level of detail in the presentation, particularly when it comes to the reporting of IMU measurements. However, they signify an important change in the use of IMUs since they all either involve field deployments or use laboratory regimes to demonstrate how field deployments can work.

It is not easy to list all the pros and cons of deploying IMUs for monitoring geomorphic processes, mainly because we still are at the "trial and error" stage of this effort. The IMU sensors we deploy are developed to be used within a very well-defined parameter space. This is also true for the fully custom sensors, since they comprise of components (MEMS) developed for electronics (phones, tablets, smart wearables etc). As a result, most of the advantages of the technology come with their "dark side" when we try to capture the complexity of natural systems not only because the sensors are not perfect but because we need to understand more about the underline concepts.

¹ The author is also sure that there are more deployments that he is not aware of.

For example, there is a general agreement that IMUs “solve” the force balance equations for sediment grains (Maniatis et al., 2020) in a quite unambiguous and timely manner which can lead to a robust motion detection (Al-Obaidi et al., 2020, Pretzlav et al., 2020, Pretzlav et al., 2020, Dost et al., 2020). On top of the practical application (Dini et al., 2021), the question of “when sediment grains move?” has been in the minds of legends of the field such as Bagnold, Shields, Einstein and Yalin, it is very close to the heart of all the geomorphologists and it is an application where IMUs should be an extremely promising solution. However, satisfying the condition of Net force ≥ 0 does not mean that the grains are fully dislodged. Therefore, we are still left with the difficult exercise of parametrising the thresholds of motion probabilistically.

In this context, this commentary highlights issues that complicate the reading of IMU measurements and can restrict their future applications in geomorphology. The intention is not to provide guidance or define a specific protocol for reporting those measurements but to start a dialog that will lead to such a protocol.

Discussion points

- **Accelerometers and gravity compensation:** One interesting characteristic of inertial accelerometers is that they don’t measure applied force directly (like a load cell for example), but they capture it as a difference from the gravitational field. If we place a 3D accelerometer still on a flat surface that is perfectly aligned with the gravitational field, one of the accelerometer axes will measure +1g. When this balance is disturbed in a static manner, with the accelerometer rotating without translating for example, then all the axes will begin to pick up a component of the

gravitational field and no axis will measure +1g (or -1). This characteristic makes accelerometers good orientation sensors for well restricted applications. The complexity increases when the accelerometer rotates and translates because then the accelerometers measure both the gravitational and the applied force. The decoupling of the applied force by removing gravity from the raw acceleration measurement is often discussed in the literature as gravity compensation (Kok et al., 2017). The 3D treatment of gravity compensation requires constant orientation tracking of the IMU. In the geomorphological literature, there is a mix of reporting both compensated and non-compensated accelerometer values and it is not always clear if acceleration is used in the context of orientation change detection or to derive linear forces/dynamics. One of the few absolutely definitive statements we can make is that compensated accelerations must be used for the calculation of translational accelerations and displacement estimates². All the other presentations can be adapted to the application, but a clear discussion is needed.

Displacement and position estimates: This issue emerges from the application of Newtonian equations to accelerometer measurements; the idea that we can track the position of particles by integrating the measured accelerations twice (firstly for velocity and secondly for position). The existing literature here is unanimous: this calculation is not appropriate for low cost, consumer grade³ standalone IMU measurements (e.g. Woodman, 2007, Groves, 2014). Displacement information can be derived for very

² Imagine integrating an acceleration of +1g when the sensor is static (hence the linear acceleration is 0).

³ There is a classification between aviation grade, tactical grade and consumer/automotive grade IMUs. The only ones relevant to geomorphic applications at the moment, in terms of both cost and size, are the latter.

small time periods (usually $< 2\text{sec}$), but it is definitely not possible to do long term tracking. Thus, for the geomorphological applications, it is very important to clarify the reported displacement and position values, particularly when the IMUs are deployed in conjunction with independent telemetry systems.

- **Orientation estimates:** This is probably the most technical of all the issues discussed here. An estimate of the orientation of the IMU is needed for both general motion tracking (e.g. mobility/non-mobility states) but also for estimating the direction of the applied forces. There are a lot of mathematical representations for orientations and some of them, like Euler angles, suffer from singularities which makes them inappropriate for tracking the orientation a particle that can rotate freely (see Gimbal Lock, Hemingway and O'Reilly, 2018). Those representations are readily used in electronics (Pedley, 2013) as they perform well for well restricted motions. The non-restrictive representation (quaternions) is mathematically steeper and more difficult to code, but it is probably the most suitable to use for geomorphic applications. This is an open debate; the author's opinion is that we need to agree on the use of an open source quaternion library and train ourselves and the community to its application.

- **Calibration of IMU sensors (and particularly of accelerometers):** Full spec IMU calibration is very expensive and perhaps impossible in the facilities that are usually available to geomorphologists (e.g. multi-axes positioning tables). We have resorted to the use of shaking tables and simple rolling and pendulum experiments that calibrate the axes of the IMU

separately. Unfortunately, the IMU errors are not independent which needs to be considered in future IMU applications. In addition, some of the calibration setups that have been used are difficult to link with the physics of the sensors. For example, it is difficult to measure impact after the free fall of the accelerometer because physically the sensor will measure 0 acceleration during the fall⁴. Finally, it is important to recognise clearly the effect of the sensor's shape on the measurements and the calibration. Changing the overall shape of the sensor using different enclosures, for example placing the same unit in a spherical case, an ellipsoid or even natural stone, means that an initial calibration is useful only if the IMU is placed exactly at the centre of mass of all the enclosures. That is both technically challenging and very difficult to assess, particularly for natural stones. If the sensor cannot be placed exactly at the centre of mass, then a correction for the Coriolis and the centrifugal acceleration needs to take place which, in practice, means a new calibration. For calculated kinematics (such as kinetic energy), the rotational component depends on the moment of inertia of the whole enclosure, which is again different between different enclosures/ shapes.

- **Sensor fusion, motion detection and use of proprietary code:**

Scientists and engineers from a range of disciplines have tried to correct the orientation and the position estimates from IMUs, by combining the measurements from all the sensors (accelerometer, gyroscope and

⁴ Many accelerometers are programmed to detect a "free fall" state. Without out good access to the low-level operational code of the sensor it is not possible to know when the sensor "wakes up" form this state. Also, the impact measurement is not a sole function of the height of the free fall but requires understanding of the mechanical properties of the sensor and the impact surface.

magnetometer). The methods vary, but a good part of those works uses a version of Kalman filtering to cross-check the measurements and adapt the estimate according to the measured variance. Because this application becomes common, providers of proprietary computational software (e.g. MATLAB) have coded libraries that apply different Kalman or Complementary filters for IMU measurements in a quite user-friendly manner. However, those estimates are highly sensitive to initial conditions, come with a set of assumptions and are very sensor specific. They are also impossible to read without the full list of the parameters used. More generally, this type of sensor fusion (for standalone low-cost IMUs) is difficult to assess at this stage, as it has only been verified fully for electronics and simple robotic applications (see the works that reference Sabatelli et al., 2012 and other similar works). Similarly, geomorphologists have used code for motion detection based on IMU measurements that is not fully documented or verified in a manner that relates to the targeted natural processes. The author's opinion is, again, that we need to agree on the use of open source tools for this type of analysis, which we will curate as a community, so our results become comparable and reproducible.

Easy wins and long-term prospects

The above points pose questions to geomorphologists; "Can those sensors be used at all in the field?", "How much more sensor development is needed to get any type of useful numbers" or even, "Is the already published work any useful at all?". The answer to those questions relies solely on the scientific question under consideration. For example, there is no technical reason preventing the IMUs from capturing accurately the durations for "mobility" and "non-mobility" states for a

sediment grain. In a context of parametrising probabilistic models, this is extremely valuable information and IMUs can provide it with unprecedented accuracy and frequency in the field. Furthermore, the technical work required to achieve a very accurate synchronisation of the sensor's response is minimal, we just need to openly program and calibrate the sensors specifically for that (most probably at the cost of battery life but there is always a trade-off) and use openly tested and reproduceable code to "break down" the derived signal.

There are other questions where IMUs can be a better solution than the existing technologies in the field, but it is necessary to develop the technology in a "purpose - specific" manner. The characterisation of grain-grain or grain-substrate interactions is a good example here. Mainly because of the restricted accelerometer ranges used in most published works, collisions have not been measured with IMUs in geomorphic contexts. Also, relevant technologies (such as Particle Image Velocimetry (PIV)) yield accurate results in experimental settings, but they are not generally applicable for the solid phase of transport in the field (despite some forward-thinking efforts, e.g. Liu and Lam 2015). Interestingly, the range of commercial IMU accelerometers available to geomorphologists increases and it is now possible to design compact units that can reliably measure $\pm 200g$ of inertial acceleration. This range cannot capture impact dynamics fully (see Vatne et al, 2008 and similar work for a conservative estimation of the required range in fluvial settings), but it is very possible that this order of magnitude is enough for *characterising* those interactions. A recent example of how this is useful to geomorphologists can be found in the incorporation of static seismic measurements in the literature of bedload transport (starting from Tsai et al., 2012). Following this example, useful contextualisation of a technology comes

with building and calibrating purpose specific sensors that are cross compared in controlled laboratory transport experiments with existing reliable technologies, before they are placed in any natural regime.

And finally, there are questions that are (at the moment) out of reach for the IMUs that can be deployed in the field. For example, the measurement of the diffusive part of transport *in-situ* will be a significant step between linking theoretical and empirical approaches. Particularly for the, largely unexplored until recently, lower transport rates (e.g. Furbish et al., 2017). To achieve that, we need to measure particle trajectories at high frequency in natural settings. RFID tracers improve, but they don't generally capture the whole motion of particles during transport. Drake et al., 1988 report displacements of 15 particle diameters per second, thus suggesting a required sampling frequency of ≈ 50 Hz for capturing the trajectory of coarse particles. Theoretically IMUs can be considered here but they cannot resolve this problem. They can only be used in conjunction with external and independent telemetry systems, as demonstrated by Dini et al., 2021, and potentially enhance the position estimates as demonstrated in the vast literature of GPS- IMU localisation⁵ (e.g. Gunawan et al., 2020). There is a lot more to be done to extend such examples to fluvial applications because GPS, and more generally radio telemetry, is limited for underwater settings⁶ and Sonar is not generally feasible for small and variable water flow depths.

⁵ Another potentially useful term here is the "Inertial-aided GPS".

⁶ We have seen though successful demonstrations of radio and magneto telemetry sediment tracking in fluvial settings (Haberschack 2001, Shear et al., 2008).

By way of conclusion

There is no room in this commentary to expand the discussion on the issues of sensor noise, the sampling frequency and measuring range which pose a range of challenges to geomorphologists. At the same time, it is important to note that the above brief descriptions do not do justice to the incredible effort the geo-scientists and engineers mentioned here have put to make sense of IMU measurements. The reader should refer to relevant sources for the full picture. It is very difficult to argue though that any researcher with a background in geomorphology, environmental sciences or a relevant strand of engineering can take full responsibility for framing and clarifying the way IMU sensors should be used in geomorphic applications. We need a collective treatment of the above issues as the literature expands. We should also be open to invite people from other fields (sensor engineers, physicists and mathematicians) in order to clarify all the above points and set ourselves free to truly explore the scientific questions we set out to explore with this new technology.

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