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Smartstones: a small e-compass, accelerometer and gyroscope embedded in stones

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Pebbles or rock fragments influence soil erosion processes in various ways: they can protect the soil but also enhance the erosion as soon as they are moved by water and impact onto soil. So far, stone-embedded devices to measure the movements have been quite big, up to several decimetres, which does not allow for the analysis of pebbles from medium and coarse gravel classes. In this study, we used a novel device called Smartstones, which is significantly smaller.

The Smartstone device's dimensions are 55 mm in length, 8 mm in diameter and an approximately 70 mm long flexible antenna (device developer: SMART-RFID solutions Rheinberg, Germany). It is powered by two button cells, contains an own data storage and is able to wait inactive for longer times until it is activated by movement. It communicates via active RFID (radio frequency identification) technology to a Linux gateway, which stores the sensor data in a database after transmission and is able to handle several devices simultaneously. The device contains a Bosch sensor that measures magnetic flux density, acceleration and rotation, in each case for / around three axes.

In our study, the device has been used in a laboratory flume (270 cm in length, 5° to 10° slope, approx. 2 cm water level, mean flow velocities between 0.66 and 1 ms^{-1}) in combination with a high speed camera to capture the movement of the pebbles. The simultaneous usage of two capture devices allows for a comparison of the results: movement patterns derived from image analysis and sensor data analysis.

In the device's first software version, all three sensors – acceleration, compass, and gyroscope – were active. The acquisition of all values resulted in a sampling rate of 10 Hz. After the experiments using this setup, the data analysis of the high speed images and the device's data showed that the pebble reached rotation velocities beyond 5 rotations per second, even on the relatively short flume and low water levels. Thus, the device produced only sub-Nyquist sampling values and the rotation velocity of the pebble could not be derived correctly using solely the device's data.

Consequently, the device's software was adapted by the developers: the second (and current) version of the device only acquires acceleration and compass, as the acquisition of the gyroscope's value does not allow for higher sampling rates. The second version samples every 12 ms. All aforementioned experiments have been repeated using the adapted device. For data analysis, the high-speed camera images were merged with the device data using a MATLAB script. Furthermore, the derived relative pebble orientation – yaw, pitch and roll – is illustrated using a rotated CAD model of the pebble. The pebble's orientation is derived from compass and accelerometer data using sensor fusion and algorithms for tilt compensated compasses.

The results show that the device is perfectly able to capture the movement of the pebble such as rotation (including the rotation axis), sliding or saltation. The interacting forces between the pebble and the underground can be calculated from the acceleration data. However, the accelerometer data also showed that the range of the sensor is not sufficiently large: clipping of values occurred. According to present instrument specifications, the sensor is able to capture up to 4 g for each axis but the resulting vectors for acceleration along all three axes showed values greater than 4 g, even up to the theoretical maximum of approximately 6.9 g. Thus, an impact of this strength that only stresses one axis cannot be measured. As a result of this clipping, the derivation of the pebble's absolute position using double integration of acceleration values is associated with flaws. Besides this clipping, the derived position will deviate from the true position for larger distances or longer experiment durations as the noise of the data will be integrated, too.

Several requirements for the next device version were formulated:

- The range of the accelerometer will be set to the sensor's maximum of 16 g.
- The device will be water proof.
- Data analysis will include further methods like Hidden Markov Models or Kalman Filtering as the tilt-compensation is actually not intended for irregular moving devices. These techniques are well-established for other devices and purposes like navigation using GPS.

In near future, the Smartstone device will be used outside the laboratory in natural rills and rill experiments. In these experiments, the water is turbid and the pebble will not be visible at all, which does not allow for the usage of the high speed camera. However, the present results showed that the movement of the pebble in addition to the applied forces to the underground and the rill's sidewalls can be captured solely by the Smartstone.