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MiCas: FROM PRESSURE SIGNALS TO COUNTING BEDLOAD PARTICLES

BY RUI ALEIXO, LUÍS MENDES, FEDERICA ANTICO & RUI M.L. FERREIRA

A new device to measure bedload transport, MiCas, is presented. It analyzes pressure time series by recognizing the imprints of impacts of individual particles as they hit pressurized membranes. A pattern analysis algorithm is used to identify the impact events. The implementation of this principle in a dedicated microprocessor allows for real-time measurements of particle hits and cumulative particle count. MiCas particle counts correlate well with the results of image analysis. MiCas provides hardware-based measurements, hence its key advantages of minimal needs of data storage and low processing times to retrieve bedload discharge rates.

To characterize the morphological evolution of loose bed channels it is necessary to develop a deep understanding of bedload transport processes at several scales. Despite the advancements made in the last 60 years, driven by the improvements in measurement techniques, research efforts on grain-scale mechanics of bedload are still required, especially to clarify the intermittent nature of bedload, its stochastic structure and its scale dependence.

Several types of instrumentation have been employed to pursue this research. Existing instrumentation can be grouped into:
i) **weighing methods**, that measure the cumulative weight of the sediments,
ii) **impact methods**, that count the impacts of particles on a sensitive plate and
iii) **digital image processing methods**, that rely on image acquisition and processing to identify and count the particles.

For bedload discharge purposes, most of the existing devices, independently of the method group that belong to, are not designed to work in recirculating flumes (in the application of weighing methods), and/or do not have the capability to resolve individual particles and particle flow rates in a time resolved manner (in the application of weighing methods and some impact methods), or are too expensive in terms of data storage requirements and processing times (for the use of image processing methods).

The MiCas device, used in a new pressure-based impact method, is intended to overcome those limitations. It has been initially developed by researchers of the Fluid Mechanics for the Built and Natural Environment (FMBNE) Group of the Civil Engineering Research and Innovation for Sustainability (CERIS) Center and is currently installed in the Hydraulics Laboratory of Instituto Superior Técnico of the University of Lisbon. It was designed to meet the following key requirements: simple data output composed of time instant and location of impacts; no need for post-processing – impacts determined through hardware and firmware; capable of computing simple statistics in real time such as cumulative particle counting and discrete lateral distribution of cumulative particle counts; able to run for very large periods (days, weeks); ability to detect particle impacts of large size fractions that are separated by a few milliseconds; composed of robust and relatively cheap components.

These characteristics allow the collection of very long time series of particle impacts since the output data are provided in a file with positions and instants of particle hits, which is relatively small (order of kb or a few Mb), compared to the size of the high-speed video footage needed to extract similar information (order of hundreds of Mb or Gb). Data can be collected with very high temporal resolution since successive impacts distanced about 12 ms in time can be identified. Characterization of intermittency (Ancey et al. 2008) and discussion of scale effects in the definition of bedload rates (Ballio et al. 2014) can be based on the data

Figure 1. Schematic of the key mechanical features of the MiCas system

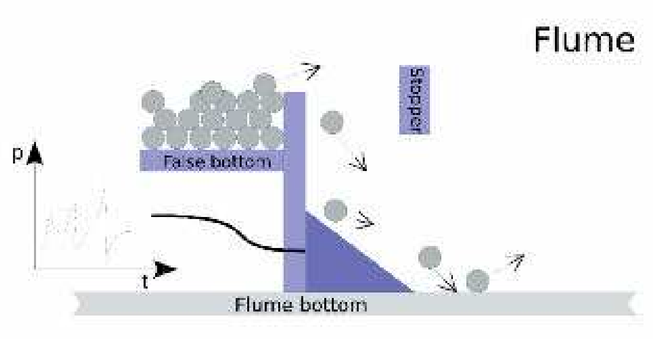


Figure 2. Overall view of MiCas system from downstream with membrane boxes installed in the flume visible in blue. Each membrane box constitutes a bin

provided by this system. Further details about the design process and applications can be consulted in the website of FMBNE (http://www.fluidmechenv.tk/). Preliminary results and detailed description of the key features of the system have been published in Mendes et al. (2016).

MiCas – THE PRESSURE-BASED IMPACT PARTICLE COUNTER

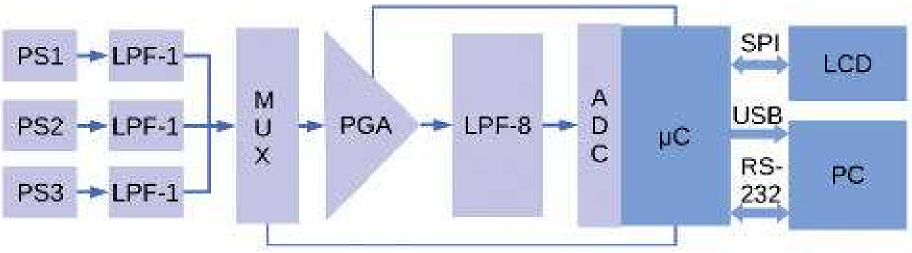
MiCas stands for **M**edidor **i**ntegrado de **Ca**udais **s**ólidos, in Portuguese, or integrated system for solid discharge measurement in English. This device counts impacts on a sensitive surface and was conceived to be installed at the downstream end of a mobile bed reach of a laboratory recirculation flume, as sketched in Figure 1. It is divided in two subsystems: mechanical and electronic. The mechanical system includes the sensitive element (blue surface in Figure 2), composed of a hollow box filled with air at a certain pressure, P, connected to a pressure transducer through silicon tubes (the tubes passing near the flume lateral glass walls, as depicted in Figure 2). The upward face of this prism is made of a rubber membrane. Each pair of boxes is separated by a plastic surface that extends upward and downstream in relation to the actual box dimensions. It is placed in such a way as to avoid propagation of pressure waves to adjacent boxes, thus reducing sources of possible false impact detections (white vertical surfaces in Figure 2). For the experimental installation at FMBNE 10 membrane boxes were made and identified from 1 to 10. Each membrane box is considered a bin. This allows characterizing the lateral distribution of bedload with a spatial resolution equal to the membrane box width.

Sediment particles hitting the rubber surface cause a pressure variation that is measured by the pressure transducers. A sequence of particles impacting the membrane boxes is shown in Figure 3.

The pressure transducers are part of the electronic subsystem that convert the pressure signal into an electrical signal, which is then sampled and analysed with Digital Signal Processing and Patten Recognition (DSP) techniques to be validated as a particle impact. A simplified block diagram of the MiCas system is depicted in Figure 4. The Pressure Sensors (PS1,PS2,PS3) convert the corresponding pressure signal variations into a voltage signal, which is then filtered by the respective 1st order Low Pass Filters units (LPF-1) for noise removal.

Figure 3. Sequence of 5 mm glass beads hitting the membrane boxes. Hydraulic test with Fr = 0.756, $\theta = 0.014$ and $\Phi = 0.001$ (where Fr, θ and Φ stand for Froude number, Shields parameter and non-dimensional bedload rate). All frames are 0.25 seconds apart except frames 2 and 3 that are 0.10 seconds apart

Figure 4. Simplified block diagram of the MICAS system. PS1 to PS3 are the pressure transducers. LPF represents the low pass filter unit. MUX is the MiCas Multiplexer and PGA is the programmable gain amplifier. LPF 8 is an 8th order anti-aliasing Butterworth filter block. The ADC is the analog-to-digital converter that converts the analog signal into a digital form to be then processed by a microcontroller. This microcontroller has outputs for an LCD screen and a PC

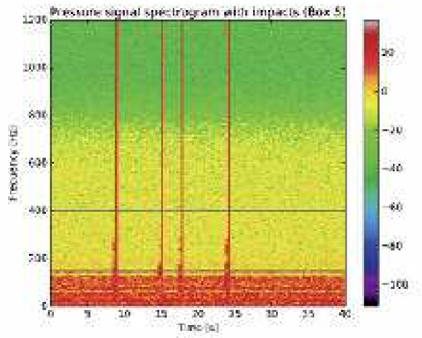


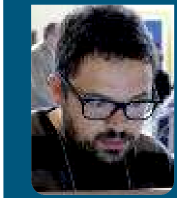
The analog Multiplexer unit (MUX) follows, connecting in round-robin fashion, one of the PS1,PS2 or PS3 sensors output signal to the input of the Programmable Gain Amplifier (PGA) unit. The PGA output is then connected to the 8th order Butterworth Low Pass Filter (LPF-8) input, unit, which contributes for the aliasing effect reduction. Following the LPF-8 unit output the signal enters the Analog to Digital Converter (ADC) to be sampled by the microcontroller (μC). The digital sampled signal is then processed with Digital Signal Processing techniques to extract the relevant signal characteristics that define a bead impact on the membrane box surface. Those characteristics are then fed to a pattern recognition algorithm to identify the presence of the impact pattern. If an impact is identified, then the instant of the impact detection is recorded and sent to the client terminal connected through the RS-232 and USB interfaces. A Liquid Crystal Display (LCD) monitor is also updated with the number of impacts detected and displays a graphic that shows the lateral bedload discharge distribution in real-time.

SIGNAL PROCESSING AND PARTICLE IDENTIFICATION

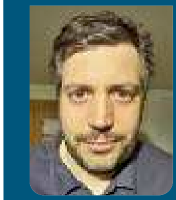
When a particle impacts the membrane, it generates a pressure signal. This pressure signal is converted into an electrical signal by means of a pressure transducer. This signal is then filtered and analysed to be confirmed as a particle impact. It is important to identify the signature of a particle impact on the membrane, being able to distinguish it from other signals' signatures like for instance, the turbulence signal. To do so, the k-Nearest Neighbour (k-NN) algorithm is used in the signal processing and analysis. The k-NN is a pattern recognition algorithm that can be fitted within the machine learning sub-area of artificial intelligence. By fitting an unknown measurement data as belonging to the class of its nearest already known classified measurement that is in the agent knowledge base, where for this case, the agent is MiCas. For this case three classes of events are considered: 1) particle impact, 2) silence (i.e. background noise) and 3) turbulence. For each class the system is trained using the MiCas only subjected to each event. For example, the training for particle impact class was made with impacts produced by dropping individual particles at random locations of the membrane in still water. After the training process, the system can identify the different events.

Figure 5. Spectrogram obtained from pressure sensor sampled signal of an operating flume with occasional bead impacts on the membrane box. The red colour in the spectrogram correspond to higher intensity signals. Vertical red lines denote a possible impact while the horizontal blue lines denote the 150Hz-400Hz range. Scale is in dB



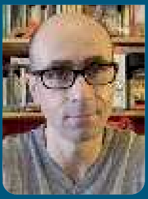


Rui Aleixo **has a PhD in Engineering Sciences from Université catholique de Louvain, Belgium. After a post-doc in the National Center for Computational Hydroscience and Engineering (USA) he joined the Fluid Mechanics for the Built and Natural Environment Group of CERIS, Instituto Superior Técnico. He is currently working in the University of Bologna. He is the IAHR Experimental Methods and Instrumentation committee (EMI) chair for the period 2015-2017. As EMI chair, he co-organized the W.A.T.E.R. Summer School and HydroSenSoft 2017 conference.**



Luís Mendes **started working as a software engineer back in 2007 following his masters in informatics and computer engineering at Instituto Superior Técnico. He worked for several companies including Nokia Siemens Networks. In early 2015 he completed a B.Sc. for the electronics and computer engineering field at Instituto Superior de Engenharia de Lisboa, complementing the previous expertise on software. Since February 2014 he joined the CERIS multidisciplinary research team at Instituto Superior Técnico.**

Federica Antico **is a Civil Engineer graduated from University of Padova, Italy, in 2013, with specialization in Hydraulic Engineering. In March 2014, she was enrolled in the project "Sediment transport in fluvial, estuarine and coastal environment" (SEDITRANS), as PhD Candidate at Instituto Superior Técnico (IST), Lisbon, Portugal. Her PhD research focuses on the experimental study of bedload mechanics at grain-scale in a granular bed subjected to a steady-uniform turbulent open-channel flow.**



Rui M.L. Ferreira **is Associate Professor of Instituto Superior Técnico, Universidade de Lisboa and a CERIS senior researcher. For the past 20 years, he has been involved in experimental research in fluvial, estuarine and coastal processes, development of laboratory instrumentation and mathematical modelling of free-surface flows. He is a member of the leadership teams of the Fluvial Hydraulics Committee and of the Experimental Methods and Instrumentation Committee of IAHR.**

A key feature of this system is the possibility of doing real-time measurements. In fact, the computations are made at the hardware level thus allowing fast time processing. The implemented MiCas system consisted of 10 independent membranes. The micro-controller available analog to digital converter (ADC) units were multiplexed to scan every membrane box, thus saving costs, by reducing the number of ADC units to the ones available on-chip.

Figure 5 depicts the spectrogram obtained from one of the pressure transducers of the MiCas system. The darker spots aligned along the vertical indicate possible impacts. Each of these events is analysed through the k-NN algorithm to check if it corresponds to a particle impact or not.

VALIDATION OF THE MiCas SYSTEM

To validate the results obtained by the MiCas system, its particle cumulative count was compared with the count obtained from the analysis of a high-speed video footage. Each particle impact was tagged with membrane box identification (from bin 1 to bin 10) and the respective instant.

Experiments were carried out in the 12.5 m long and 40.5 cm wide glass-sided flume of the Laboratory of Hydraulics and Environment of Instituto Superior Técnico, University of Lisbon. This flume has two independent circuits for water and sediment recirculation. A cohesionless granular bed, composed of 4 layers of 5 mm glass beads, subjected to a steady-uniform turbulent open-channel flow, was analysed. All tests featured a period of 90 s data collection. For a detailed description of the laboratory facilities and test conditions see Mendes et al, 2016.

The cumulative particle count results are depicted in Figure 6.

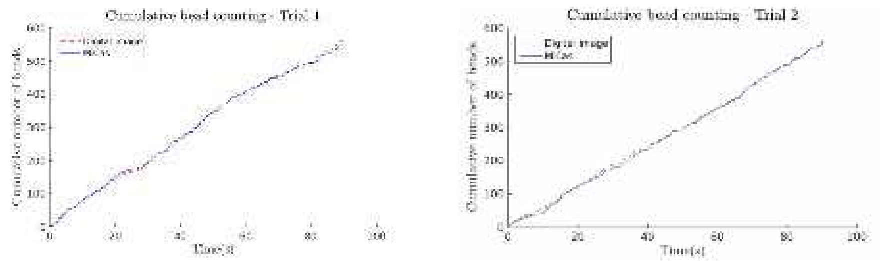


Figure 6. Cumulative bead counting for two tests performed under conditions of weak bedload transport. The main flow characteristics are: flow rate, $Q=0.0167 m^3/s$; steady-state flow depth, $h=0.067m$; slope of the flume, $i=0.0022$; Froude number, $Fr=0.756$; Reynolds number, $Re=46057$; particle Reynolds number, $Re^*=182.9$, Shields parameter, $\theta=0.014$; non-dimensional bedload discharge, $\Phi= 0.001$

The results obtained with the two techniques are in good agreement. The measurements carried out allowed to demonstrate that the MiCas system is able to track particle impacts in real-time within an error margin of 2.0%. Different tests performed under the same conditions proved the repeatability of the MiCas system measurements.

The main advantages of MiCas relatively to digital image processing methods are:

a) independence from optical access, thus avoiding problems with light intensity variations and oscillating free surfaces;
b) small volume of data associated to particle counting, which allows the acquisition of very long data series (hours, days) of particle impacts. In the cases that were tested, it would take more than two hours to generate 1 MB of data with MiCAS. For the current validation tests, 90 s acquisition time generated 25 Gb of data using the digital method, but only 11 kB of MiCas data to monitor the same experiment. On the other hand, the time necessary to process the digital images may be days, effectively limiting its usage to small time series.
c) MiCas offers the possibility of real-time measurements, allowing for detection of problems during the experiments and minimizing some post-processing steps.

On the downside, the MiCas system does not achieve sub-particle resolution nor highly resolved lateral particle distribution. However, the MiCas bins can provide a coarse but reliable lateral bedload distribution. ■

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