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NOVO SLEDILO ZA MONITORING DINAMIKE PREMEŠČANJA PLAVIN V TURBULENTNIH TOKOVIH
A NEW TRACER FOR MONITORING DYNAMICS OF SEDIMENT TRANSPORT IN TURBULENT FLOWS

Mojca SPAZZAPAN, Janko PETROVČIČ, Matjaž MIKOŠ

Za sodobne študije premeščanja rečnih sedimentov smo razvili in testirali novo instrumentizirano sledilo, imenovano prodnik vohun (SPY – kratica v angleščini pomeni "dinamika posameznih delcev"). Ta nova vrsta sledila je kroglasti instrumentizirani prodnik premera 99 mm in mase 994,6 g ter ima vgrajena tri tipala za merjenje pospeška. Sledilo je razvito za prepoznavanje in merjenje različnih kinematičnih in dinamičnih elementov (predvsem trčnih in trenjskih sil), ko se giblje po rečnem dnu skupaj z rinjenimi plavinami ali ko miruje na površini rečnega dna.

Ključne besede: *premeščanje plavin, rečna hidravlika, merilni instrumenti, sledila, laboratorijski poskusi, pospeškometri, tipala*

We have developed and tested a new instrumented tracer for advanced sediment transport studies, called SPY-Cobble, where the acronym SPY stands for "Single Particle dYnamics". This new type of tracers with three internal acceleration sensors is an instrumented spherical cobble of 99 mm in diameter and a mass of 994.6 g. It was developed for detection and measurements of different elements of kinematics and dynamics (especially contact impact and friction forces) when moving at river bottom together with bedload or when resting on riverbed bottom surface.

Key words: *sediment transport, fluvial hydraulics, measuring instruments, tracers, laboratory experiments, accelerometers, sensors*

1. UVOD

Pri določanju stabilnosti in dinamike premeščanja plavin v prodonosnih vodotokih ter manjših in strmih gorskih vodotokih in hudournikih je zelo pomemben element soodvisnost med turbulentnim tokom in posameznimi zrni plavin (rečnega in hudourniškega sedimenta), ki tvorijo dno in brežine teh vodotokov. Zato je bilo v preteklosti opravljenega veliko laboratorijskega in terenskega raziskovalnega dela o premeščanju plavin in stabilnosti vodotokov.

Zmogljivost računalnikov se podvoji prej kakor v dveh letih, kar nam omogoča, da uporabljamo vse bolj popolne modele premeščanja plavin, tj. povezane modele namesto nepovezanih modelov in dvodimenzijske ali celo tridimenzijske modele namesto zgolj enodimenzijskih modelov. Trend prehoda v večdimenzijski prostor je bil v preteklosti predvsem v hidrodinamičnem

1. INTRODUCTION

Interactions between turbulent flow and sediment particles conforming a riverbed and its banks are of paramount importance when defining stability or dynamics of gravel-bed rivers and smaller and steeper cobble and boulder streams and torrents. That is why a lot of field and laboratory research work has been done on sediment transport and stability of riverbeds.

Computer power being doubled every less than two years, gives us the opportunity to use more and more sophisticated models of sediment transport, e.g. coupled ones instead of de-coupled ones, or two-dimensional and three-dimensional models instead of one-dimensional models only. This trend to go into more-dimensional space was in the past more obvious for the hydrodynamic part of the sediment transport problem, but not so obvious delu opisa problema premeščanja plavin ter manj očiten pri njegovem sedimentološkem delu. Razlog za to je bil verjetno v dejstvu, da znanja o premeščanju plavin v treh dimenzijah primanjkuje. Večina študij o premeščanju plavin je bila izvedena ob dobro kontroliranih hidravličnih pogojih in ob prevladujoči eni smeri gibanja plavin, tako da so obstoječe enačbe premeščanja plavin v svoji zasnovi v bistvu enodimenzijske enačbe.

Za razvoj naprednih modelov premeščanja plavin moramo uporabiti nove smeri opisa tega pojava. Tako lahko uporabimo na primer Lagrangeov model sledenja delcev ter bolj realistične fizikalne procesne parametre namesto le regresijskih koeficientov. Za tak model premeščanja plavin je posebnega pomena znanje o temeljnih fizikalnih zakonih, ki opisujejo soodvisnosti med tekočo in trdno fazo kakor tudi trke med posameznimi trdimi delci. V prihodnosti bo to znanje vgrajeno v nove napredne matematične modele premeščanja plavin.

Gibanje rinjenih plavin in prodonosnost lahko merimo s pomočjo različnih mehanskih naprav, kot so lovilci proda ali vzorčevalniki proda, vizualno s pomočjo videonaprav, zvočno, uporabljajoč različne vrste hidrofonov, ali s pomočjo sledil. V praksi je pogosta uporaba kemičnih, radioaktivnih ali fizikalnih sledil. Pasivna sledila, ki jih izdelamo iz umetnega ali naravnega rečnega materiala, lahko obarvamo, dodamo magnet ali pa jim sledimo z opazovanjem njihovega naravnega magnetizma.

Zgodnji terenski poskusi z grobimi sledili so bili izvedeni s pomočjo pobarvanih prodnikov. Ti imajo na terenu slabo stopnjo odkrivanja (običajno manj kot 50 % že po nekaj poplavnih valovih), saj jih lahko najdemo le na površini rečnega dna. Magnetna sledila omogočajo opazovanja, kako se v času poplavnega vala gibljejo sedimentni delci. Prav tako jih je mogoče najti po poplavnem valu na površini ali pod njo s pomočjo detektorjev kovin (Barsch *et al*., 1994).

Zakaj bi potrebovali novo vrsto sedimentnega sledila? Vemo, da se značilno večji sedimentni delci premikajo prekinjajoče, pri čemer so obdobja premikanja prekinjena z daljšimi obdobji mirovanja. Med poplavnimi dogodki so sedimentni delci v naravi v gibanju le nekaj odstotkov trajanja dogodka. Vsakemu

for the sedimentological part. A reason for that may quite well be that there is lack of knowledge how sediment transport looks like in three dimensions. The majority of hydraulically well controlled sediment transport studies was simply performed under prevailing one-dimensional conditions. Therefore, the existing sediment transport equations are in their concept basically one-dimensional.

For development of advanced sediment transport models, we should use new ways for its description. We may use for example the Lagrangian particle tracking model and more realistic physical descriptors or parameters of the processes involved instead of using only regression coefficients. For such a sediment transport model, the knowledge on basic physical laws governing interactions between the fluid and solid phase as well as between solid bodies in contact is of essential importance. In future, this knowledge will be incorporated into new advanced mathematical models of sediment transport

Bedload movement and rates can be measured by means of various mechanical devices like sediment traps or samplers, visually using video devices, acoustically using different types of hydrophones, or by tracers. Chemical, radioactive and physical tagging of material being transported in a river is readily used in practice. Passive tracers are placed in a channel, which are built from artificial material or natural bed material, and marked using paint, artificial magnet or baked for total magnetism.

Early coarse sediment tracing experiments consisted of simple painted clasts. These, however, have poor recovery rates (usually less than 50% already after few floodings) in the field, as they are found only on the bed surface. Magnetically tagged clasts allow sediment particles to be monitored as they move (during a flood event), or when recovered on the bed surface or buried under the surface using metal detectors (Barsch *et al*., 1994).

Why would we need another type of a sediment tracer? We know that typically coarse bedload grains move intermittently where movement phases are interrupted by obdobju gibanja (značilna dolžina je nekaj sekund ali nekaj 10 sekund) sledi obdobje mirovanja (Busskamp, 1993). Za statistični opis obdobij gibanja in mirovanja so bile predlagane različne porazdelitve, npr. Poissonova porazdelitev ali gama porazdelitev (Troutman, 1980).

Manj raziskan je način gibanja v posameznem obdobju gibanja, čeprav vemo, da se sedimentni delci kotalijo in drsijo po dnu vodotoka, kakor da tudi poskakujejo v vodni tok ali celo v njem lebdijo. Med temi vrstami gibanja ni ostrih mej. Laboratorijske raziskave so pokazale, da je način gibanja odvisen od lokalnih in trenutnih hidravličnih razmer (Hu & Hui, 1992).

V tem smislu smo razvili in preizkusili novo instrumentizirano sledilo za napredne študije premeščanja plavin, imenovano “prodnik vohun” po njegovi kratici v angleškem jeziku (kratica SPY označuje “dinamiko posameznih delcev” – single particle dynamics v izvirniku). Tako razvito instrumentizirano sledilo lahko razumemo kot novo vrsto sledil. Taka vrsta sledila ni le sposobna pokazati svoje pozicije ali povprečne hitrosti, kakor je to pri magnetnih ali radijskih sledilih, temveč gre za zapleten instrument za monitoring, ki se uporabi z namenom pridobiti podroben vpogled v dinamiko gibanja posameznih večjih sedimentnih delcev, ki se premeščajo v turbulentnem toku.

Na kratko, prodnik vohun je umetni instrumentizirani kroglasti prodnik, ki se lahko uporabi za zaznavanje in merjenje elementov kinematike in dinamike (posebno sil) posameznega večjega sedimentnega delca, ki se premešča po dnu s kotaljenjem ali drsenjem oziroma poskakovanjem ali pa miruje na dnu in v njega občasno trkajo drugi premikajoči se delci.

2. MERILNI KONCEPT

Prvi prototip prodnika vohuna je bil narejen leta 1996 v obliki medeninaste krogle s premerom 6 cm (Mikoš *et al.*, 1996; 1997). Medeninasta krogla je bila prevlečena s polimernim materialom, da bi bila čim bolj podobna naravnemu sedimentnemu (kamninskemu) delcu. Krogla je imela v svoji

long resting phases. During flood events, sediment grains are typically in movement only for several percentage of the total time of event. Each phase of movement (typically few seconds to some 10 seconds) is followed by longer resting phase (Busskamp, 1993). For a statistical description of moving and resting periods or phases different distributions have been proposed, e.g. Poisson or Gamma distribution (Troutman, 1980).

Less known is the way of movement within each moving phase, eventhough we know that sediment particles roll or slide on the bottom of the riverbed, and they may also advance by saltation or in suspension. There is no strict line between one way and the other, and laboratory studies have shown that the way of movement depends on local and current hydraulic conditions (Hu & Hui, 1992).

Having these facts in mind, we have developed and tested a new instrumented tracer for advanced sediment transport studies, called SPY-Cobble, where the acronym SPY stands for Single Particle dYnamics. Such developed tracer can be seen as a new type of tracers. They are not only capable of giving its position or average velocity like passive tracers such as a magnet or a radio tracer. They are sophisticated monitoring instruments that are used for getting a more precise insight into the dynamics of single coarse sediment particles, being transported in turbulent flows.

In short, the new tracer with internal sensors called SPY-Cobble is an artificial and instrumented spherical cobble, which may be used for detection and measurements of different elements of kinematics and dynamics (especially forces) of single coarse sediment particles either moving as bed load or resting on the bed surface.

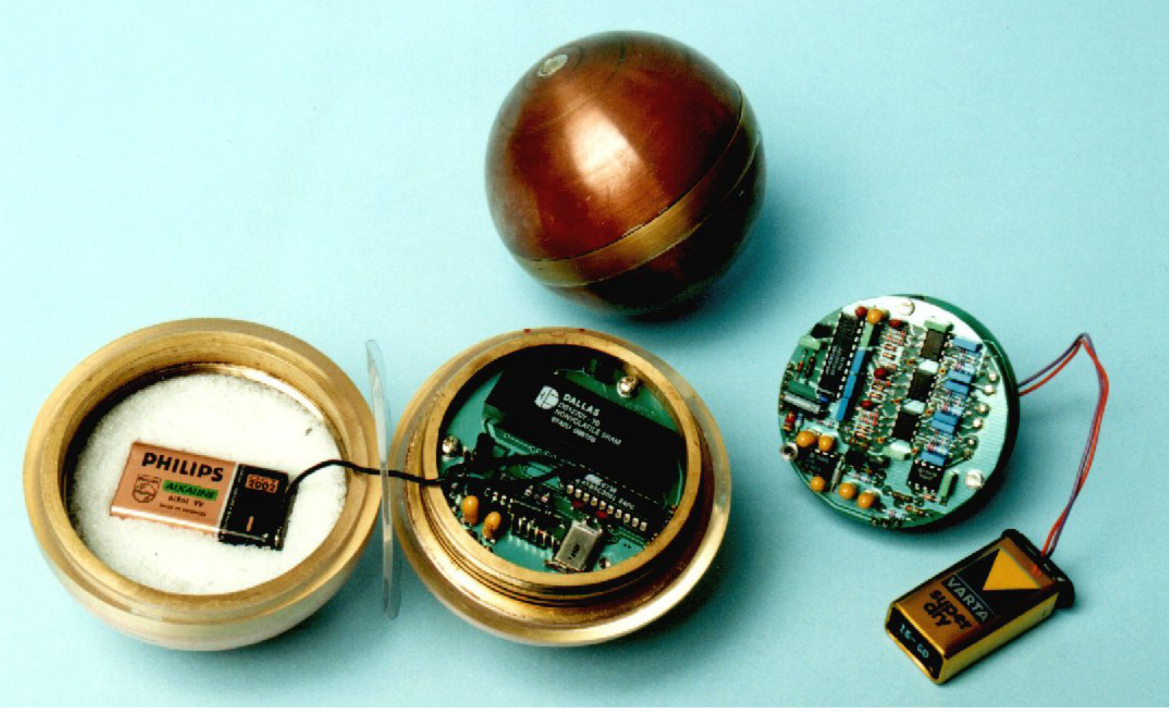
2. MEASURING CONCEPT

The first prototype of the SPY-Cobble was built in 1996 as a brass sphere of 6 cm in diameter (Mikoš *et al.*, 1996; 1997). The brass cobble was coated with a polymeric material to mimic a natural sediment (rock) particle. It had in its centre one miniature triaxial accelerometer (KISTLER Piezotron© Miniature Triaxial Accelerometer). The sensor sredini vgrajen mini triosni pospeškometer (KISTLER Piezotron© Miniature Triaxial Accelerometer). Tipalo je imelo kabel za napajanje in prenos signalov ter je bilo povezano z napajalnikom in osebnim računalnikom s kartico za zajemanje podatkov.

Drugi prototip prodnika vohuna smo nato razvili med letoma 1997 in 1999. Rezultat razvoja in laboratorijskega testiranja je bil delujoč prototip merskega inštrumenta – instrumentizirani prodnik. Ta prototip je namenjen raziskavam dinamike posameznih grobih sedimentnih delcev v turbulentnih tokovih.

had a cable that allowed both its powering and reading of signals. The cable connected the sensor to a coupler device, which was then connected to a personal computer with a data acquisition card.

In the period 1997–1999, we developed the second version of the SPY-Cobble. As a result of this development and laboratory testing, a functional prototype of a measuring instrument – instrumented sphere – was developed. This prototype was intended to investigate dynamics of single but coarse sediment particles in turbulent flows.



Slika 1. Prodnik vohun in njegovi sestavni deli.
Spodaj levo: odprt instrument. Zgoraj: Zaprta medeninasta krogla brez epoksidne zaščitne plasti.
Spodaj desno: elektronski tiskanini in vir napajanja.
Figure 1. SPY-Cobble and its parts.
Left bottom: Opened tracer. Top: The closed brass sphere with no epoxy coating.
Right bottom: The two electronic boards and a battery.

Vodilo pri delu je bilo oblikovati in zgraditi merilno napravo, zasnovano na novem konceptu merjenja dinamike posameznih sedimentnih delcev. Končni cilj je merjenje dejanskih trčnih in trenjskih sil, ki delujejo na posamezni sedimentni delec rinjenih plavin v naravnih vodotokih. Prodnik vohun kot rezultat teh naporov lahko opišemo kot sistem za merjenje, zajemanje, hranjenje in obdelavo

The main aim of this work is to design and build a measuring device based on a new concept of measuring dynamics of single sediment particles. The ultimate goal is to evaluate real impact and friction forces acting upon a single sediment particle of bed load in natural watercourses. The SPY-Cobble as a result of these efforts can be defined as a system for measuring, acquisition, storing and signalov, ki jih povzročijo trčne in trenjske sile, ki dejujejo nanj v turbulentnem toku.

Do današnje oblike je prototip prešel skozi več razvojnih obdobij. V sedanji obliki je sledilo sestavljeno iz kroglaste kovinske konstrukcije, oblečene v epoksidno zaščitno plast, dveh elektronskih tiskanin, ki sta nameščeni vzporedno v njegovem središču, zamenljivega vira energije (9 V baterija), vgrajenega v eni polovici kovinske kroglaste konstrukcije, in 3 enoosnih pospeškometrov, pritrjenih na kovinsko konstrukcijo na drugi strani (slika 1). Prodnik vohun je v taki izvedbi krogla s premerom 99 mm in z maso 994,6 g. Metoda in izvedba naprave je v Sloveniji patentirana (Mikoš *et al.*, 2001), oboje je tudi v svetovnih razmerah patentibilno.

Vsak pospeškometer je pritrjen na notranjo stran kovinske kroglaste površine. Na eni strani merijo globalno in v splošnem pospešeno ali pojemajoče gibanje naprave ter na drugi strani trčne in trenjske sile ob dotiku naprave z drugimi delci v turbulentnem toku, in sicer posredno s pomočjo zvočne emisije. V času meritev je prodnik vohun samostojen merilni inštrument brez kakršnih koli povezav z zunanjo opremo, saj se izmerjeni signali shranijo v notranjem spominu. Za sporazumevanje z uporabnikom po opravljeni meritvi ima naprava vgrajeno stikalo. Ta se uporablja za prenos nastavitev naprave pred vsako meritvijo in za prenos izmerjenih pospeškov iz notranje spominske enote za nadaljnjo obdelavo signalov po vsaki opravljeni meritvi.

Po analogni obdelavi so trije izmerjeni signali preoblikovani v digitalne signale v 12-bitnem analogno-digitalnem pretvorniku in nato shranjeni v 2 MB statičnem pomnilniku z naključnim dostopom (SRAM). Podatki se zajemajo z vzorčevalno frekvenco 2665 vzorcev na kanal in sekundo. To daje uporabniku možnost meriti z vsemi tremi pospeškometri do 130 sekund, preden je statični spomin zapolnjen. Signali so za nadaljnjo obdelavo po vsaki meritvi preneseni v osebni računalnik prek serijskega vmesnika (9600 b/s). Merilno območje naprave je ± 427 g, kadar ne uporabimo analognega ojačanja signala. Pri uporabi 10-kratnega ojačanja merilno območje naprave pade na ± 42,7 g.

signal processing of impact and friction forces acting upon it in turbulent flow.

Up to its present form, it has undergone several phases of development. At present, it consists of a spherical metal construction coated by epoxy resin, two built-in electronic boards, which are mounted horizontally in its centre, a replaceable power source, which is a standard 9V battery, built-in on one side of the metal construction, and three one-axis accelerometers attached to the metal construction on the other side (Figure 1). The SPY-Cobble in this composition is 99 mm in diameter and has a mass of 994.6 g. The method and the apparatus are patented in Slovenia (Mikoš *et al.*, 2001) and are patentable worldwide.

Each accelerometer is mounted on the inside of the metal spherical surface. On one hand, they measure global and generally accelerated or decelerated movement of the instrument. On the other hand, they measure contact forces due to impacts and friction of the instrument with the surrounding particles in a turbulent flow indirectly via acoustic emission. During measurements, the SPY-Cobble is standalone (autonomous) and has no connection to any external equipment, as the measured signals are stored internally. For the communication with the user after each measurement, there is a built-in connector. This is used for setting the configuration before the measurements, and for downloading the measured accelerations for further signal processing after the end of the measurements.

After analogue conditioning, the three measured signals are internally converted to digital signals in a 12-bit analogue to digital converter and they are stored in a 2 MBytes static random access memory (SRAM). The data is sampled by sampling frequency of 2665 samples per channel per second. This gives the user the possibility to measure about 130 seconds with all three accelerometers before the SRAM is full. The signals are transferred after the measurement to a personal computer via serial communication (9600 b/s) for further analyses. The measurement range of the device is ± 427 g when there is no analogue amplification. Using an amplification by a factor of 10, the range drops to ± 42.7 g.

3. OPIS STROJNE OPREME

Naprava deluje kot zapisovalec podatkov in ima zato glavne sestavne dele, prikazane na sliki 2. Na izhodu 3 tipal nastaja električni naboj, ki ga pretvorimo v električno napetost z ojačevalnikom naboja. Analogno električno napetost nato z analogno-digitalnim pretvornikom prevedemo v digitalno vrednost. Digitalne vrednosti, izmerjene na senzorjih, se shranijo v SRAM.

Po vklopu napajalne napetosti mikrokrmilnik preveri, ali je konektor serijskega vodila na svojem mestu. Če je, mikrokrmilnik vzpostavi povezavo z osebnim računalnikom prek serijskega vodila. Drugače se začne izvajati meritev, ko instrument zapusti magnetno polje. Shranjevanje merjenih vrednosti poteka tako, da mikrokrmilnik sprejme digitalizirano vrednost iz analogno-digitalnega pretvornika in jo shrani v SRAM na tekoči naslov. Ta naslov se vsakič poveča in pripravi za shranitev naslednje vrednosti. Ko je meritve konec, torej ko je doseženo prednastavljeno število vzorcev ali ko je pomnilnik napolnjen, se instrument avtomatsko izključi.

Vsak element ima svojo značilno tokovno porabo, ki je poda proizvajalec. Te vrednosti so za vsak element podane na sliki 2. Današnja izvedba naprave porabi 120 mA v stanju delovanja, kar smo ugotovili z meritvijo. Ker ima običajno 9 V alkalna baterija zmogljivost do 500 mAh, bi taka baterija zadostovala za okoli 4 ure neprekinjenih meritev. Za prenos izmerjenih podatkov v osebni računalnik se raje uporabi zunanji vir napajanja.

Elektronski del naprave sestavljata dve elektronski tiskanini, tj. analogna in digitalna. Velikost teh dveh elementov in njuno mesto v merilni napravi prikazujeta sliki 3 in 4.

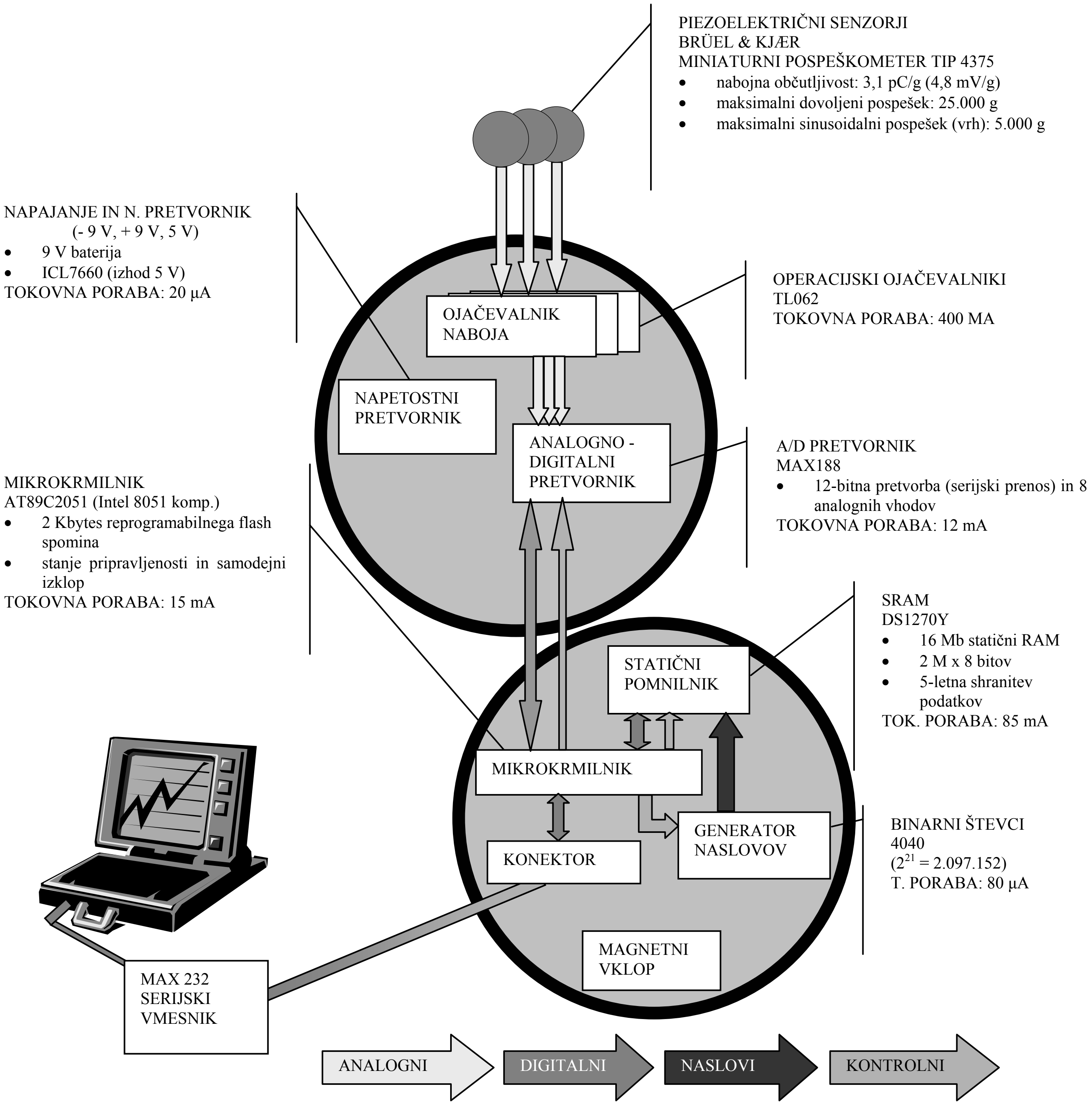
3. HARDWARE DESCRIPTION

This device works as a data logger and its main units are shown in Figure 2. The outputs of 3 sensors need to be charge amplified, and then these analogue values are converted to digital values using an A/D converter. The digital values measured on sensors are stored in SRAM.

After switching on the voltage the microcontroller checks whether the connector of the serial bus is in place. If it is, the microcontroller starts communication with a personal computer via the serial bus. Otherwise, the measurement starts when the device leaves the magnetic field. The storing process of measured values starts with the microcontroller obtaining a digital value of one sensor from the A/D converter, and then storing it to the SRAM at the certain address. This address is then increased to store the next value. When the measurement is over, i.e. when the preset number of values is reached or when the memory is full, the device shuts down automatically.

Every element has its typical current consumption, defined in its data sheet. These values are also presented in Figure 2. The present device uses 120 mA while functioning. Since 9V alkaline batteries have usually about 500 mAh of capacity, it would do for more than 4 hours of continuous measurements. For downloading the stored data to a personal computer external power source is rather used instead.

There are two electronic boards, an analogue one and a digital one, which form the electronics of the device. Positioning and size of the elements on each board can be seen on Figures 3 and 4.



PIEZOELEKTRIČNI SENZORJI
BRÜEL & KJÆR
MINIATURNI POSPEŠKOMETER TIP 4375
- nabojna občutljivost: 3,1 pC/g (4,8 mV/g)
- maksimalni dovoljeni pospešek: 25.000 g
- maksimalni sinusoidalni pospešek (vrh): 5.000 g

NAPAJANJE IN N. PRETVORNIK
(- 9 V, + 9 V, 5 V)
- 9 V baterija
- ICL7660 (izhod 5 V)

TOKOVNA PORABA: 20 µA

OPERACIJSKI OJAČEVALNIKI
TL062
TOKOVNA PORABA: 400 MA

A/D PRETVORNIK
MAX188
- 12-bitna pretvorba (serijski prenos) in 8 analognih vhodov

TOKOVNA PORABA: 12 mA

MIKROKRMILNIK
AT89C2051 (Intel 8051 komp.)
- 2 Kbytes reprogramabilnega flash spomina
- stanje pripravljenosti in samodejni izklop

TOKOVNA PORABA: 15 mA

SRAM
DS1270Y
- 16 Mb statični RAM
- 2 M x 8 bitov
- 5-letna shranitev podatkov

TOK. PORABA: 85 mA

BINARNI ŠTEVCI
4040
(2^{21} = 2.097.152)
T. PORABA: 80 µA

Slika 2. Shematski prikaz naprave (komponent in signalov).

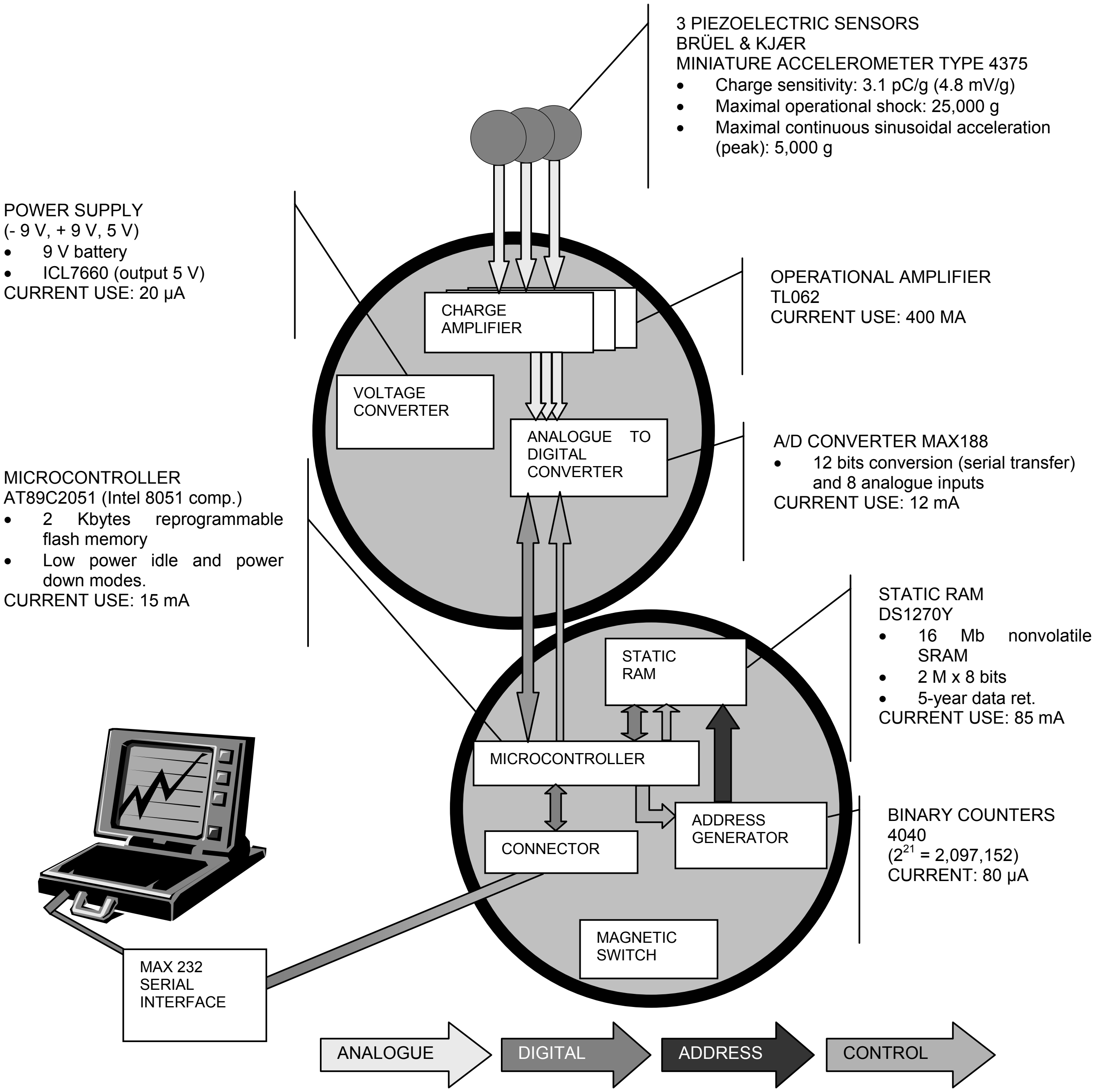
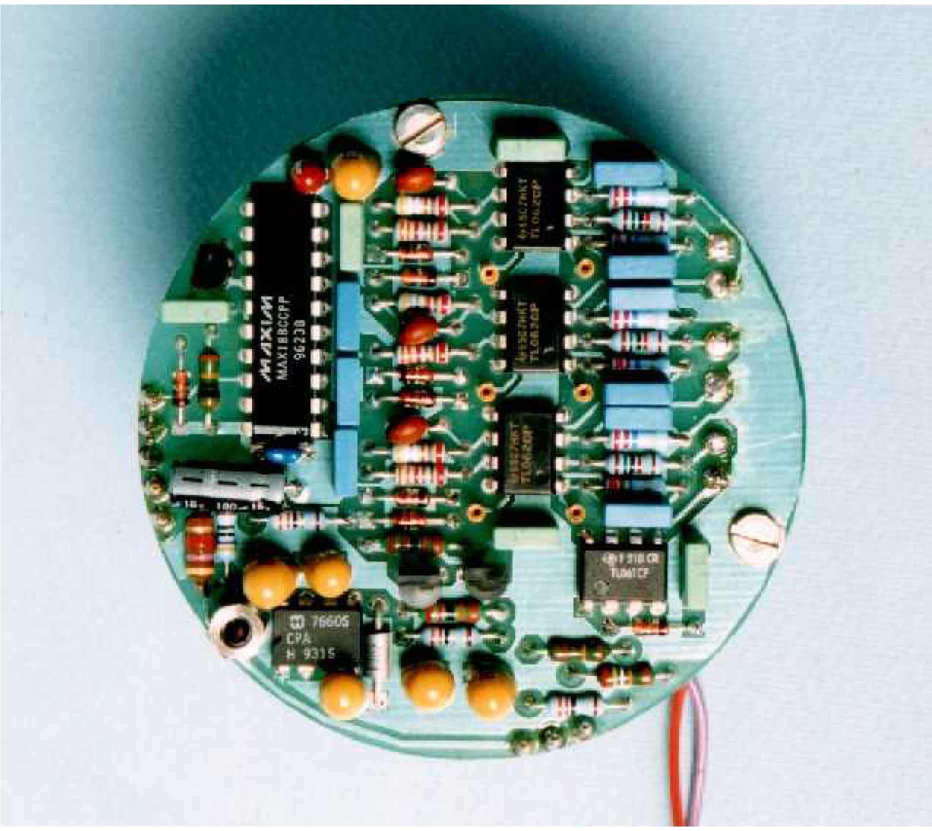
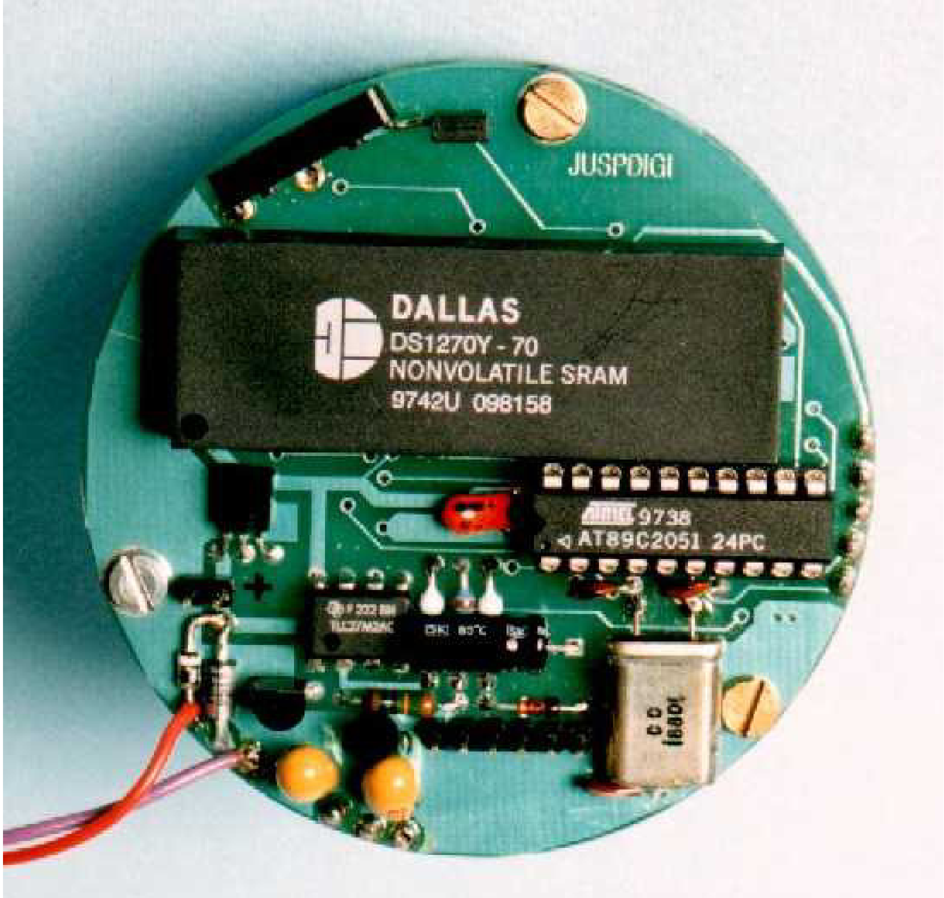


Figure 2. Schematic view of the device (of components and signals).



Slika 3. Analogno vezje.
Figure 3. Analogue board.



Slika 4. Digitalno vezje.
Figure 4. Digital board.

4. OPIS PROGRAMSKE OPREME

Merilni sistem uporablja tri vrste programske opreme:

1. Prva programska oprema je tista v mikrokontrolerju, ki upravlja merilno napravo. Program je bil napisan v programskem jeziku C51 (Keil Elektronik), kombiniran z zbirno kodo, nato preveden in shranjen v napravi. Njegova maksimalna velikost je 2 Kbyte.
   Program v mikrokontrolerju najprej preveri povezavo z osebnim računalnikom in ponudi dve izbiri: ali oblikujemo naslednjo meritev ali pridobimo oziroma zbrišemo shranjene podatke v merilni napravi.
   Oblikovanje meritve obsega določitev parametrov: čas trajanja meritve (npr. 10 s, 30 s, 60 s ali vsa dolžina SRAM ~ 130 s) in ojačitev signala (npr. 10-kratna ali 50-kratna). Ko je oblikovanje meritve končano, se shrani v statičnem spominu.
   Nato se konektor odklopi in ko naprava zapusti magnetno polje, se začne meritev, ki traja toliko, kolikor je izbrano v nastavitvi. Meritev lahko ponovimo, ne da bi morali napravo znova povezati z računalnikom, tako, da jo vrnemo v magnetno polje in spet vzamemo iz njega. Z izbrano ojačitvijo lahko merimo šibkejše ali močnejše pospeške.
   Če želimo prenesti izmerjene podatke, moramo po meritvi napravo spet povezati z računalnikom. Na zaslonu računalnika se izpiše “Press ENTER when ready”. S tipko ENTER torej merilna naprava začne pošiljati podatke v računalnik, kjer jih zapišemo v izbrano datoteko. V ta namen lahko uporabimo poljubni modemski program, ki omogoča zapis prejetih podatkov.
   Shranjevanje podatkov poteka po serijski komunikaciji – parametri nastavitve voda so naslednji: “boudrate” 9.600, “data bits” 8, “parity” none, “stop bits” 1 in “flow control” none. Za terminalske nastavitve velja: “ANSI terminal” in “local echo on”.
   Struktura zapisanih podatkov je enaka strukturi zapisa v SRAM, torej v 12-bitnem heksadecimalnem zapisu in s tremi znaki za vsako točko signala. Uporabljamo bipolarno A/D-pretvorbo in tako dobimo

4. SOFTWARE DESCRIPTION

In this measuring system, three kinds of software are used:

1. One is the microcontroller, which controls the device. It has been written in C51 programming language (Keil Elektronik), combined with assembler code, compiled and stored internally. Its maximum size is 2 Kbytes.
   The microcontroller program first checks the connection to the PC and offers two choices: either to configure the (next) measurement, or obtain or clear the data stored before in the measuring device.
   Under a measuring configuration the following parameters are to be set: time of measurement (e.g. 10, 30, 60 seconds or “FULL size of SRAM” ~ 130 s) and amplification of the signal (e.g. 10 or 50). When the configuration is selected and confirmed, it is stored in the SRAM.
   Then the connector is disconnected and when the device goes out of the magnetic field, the measurement starts and it lasts depending on the selected configuration. We can repeat the measurement without reconnection to the PC by placing the device back to the magnetic field and taking it out again. Via the selected amplification factor we can measure low or high accelerations.
   After the measurement the device needs to be reconnected to the PC in order to obtain the measured data. The message that appears is "Press ENTER when ready". That means that by pressing ENTER the device will start to send data to the PC and we have to capture it to a file that we define and create. Every modem program that has the option of storing the received data, may be used for this purpose.
   The downloading is finished via serial communication – the port settings need to be: boudrate 9,600, data bits 8, parity none, stop bits 1 and flow control none. Terminal settings are “ANSI terminal” and “local echo on”.
   The structure of the data will be as it was stored in SRAM, which means in 12 bit hexadecimal value, 3 characters per each

tudi negativne vrednosti. Na primer, če je bila v nekem trenutku vzorčenja digitalna vrednost 3523 (torej DC3 HEX), je bila to v resnici negativna vrednost –573 nivojev pretvorbe. Stopnje pretvorbe so odvisne od referenčne napetosti (v našem primeru 4,096 V), torej je ta vrednost dejansko –0,573 V. Maksimalna napetost je 2,048 V in minimalna –2,048 V.

2. Ko se prenos konča, poseben program napisan v programskem jeziku C^{++} (v. 5.01, Borland) opravi omenjeno pretvorbo in zapisani signal pripravi za nadaljnjo obdelavo. Istočasno so lahko zapisani podatki prestrukturirani in pretvorjeni iz heksadecimalnega v decimalni zapis.
3. Nadaljnja analiza signala sestoji iz različnih postopkov, zapisanih v programskem okolju Matlab® (MathWorks, 1999), kot je npr. frekvenčna analiza, analiza makro gibanja, kalibracija, analiza signalov, avtomatsko prepoznavanje vrhov signala, statistična analiza itd.

5. UMERITEV INSTRUMENTA

Merilna naprava je bila testirana na različne načine. Za umeritev merilne naprave so bili najprej opravljeni poskusi na zraku z uporabo plošče za merjenje sil in infrardečih oznak na napravi. Pot, ki jo je pri poskusu trka merilne naprave v prostem padu in plošče opisala infrardeča oznaka, je prikazana na sliki 5. Primerjava med signaloma plošče in merilne naprave je prikazana na sliki 6. Kalibracijska krivulja med merjenimi pospeški v merilni napravi in trčnimi silami, ki so povzročile te pospeške, je bila linearna.

Z uporabo te umeritvene krivulje lahko pretvorimo merjene vršne pospeške v prodniku vohunu, izražene v mnogokratniku težnostnega pospeška g (9,81 m/s^2), v vršne sile, izražene v N (kg.m/s^2). Pretvorba je linearna in odvisna od mase prodnika vohuna:

point of signal. We have bipolar A/D conversion, which is why we get also negative values. For example, if the digital value was sampled as 3523 (that is DC3 HEX), it was a negative value and it was in fact –573 levels of conversion. The levels of conversion depend on the reference voltage (in our case 4.096 V), so this value is –0.573 V. The maximum voltage is 2.048 V and the minimum is –2.048 V.

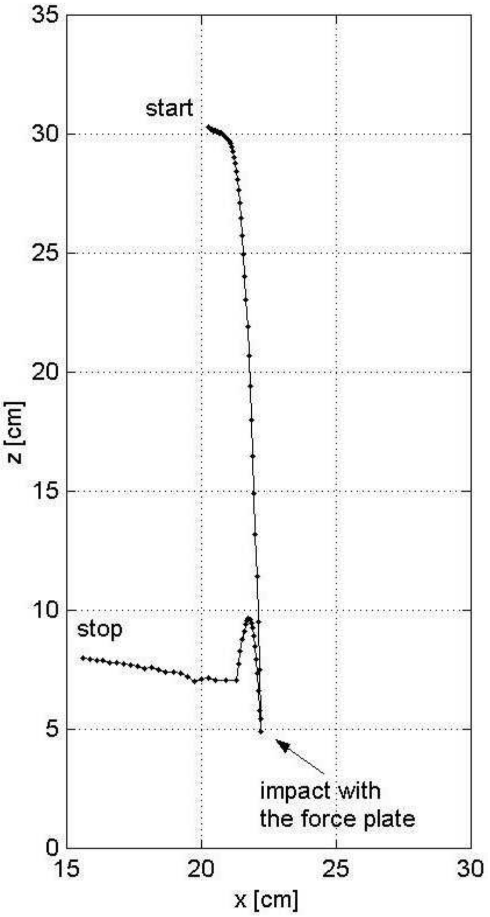
2. When the download is over, the second program written in C^{++} (Ver. 5.01, Borland) makes this conversion and it prepares the signal for further analyses. At the same time the data stored in a file can be reconstructered and converted from hexadecimal to decimal values.
3. Further signal analyses consist of various routines, written in Matlab (MathWorks, 1999), such as frequency analysis, macro movements analysis, calibration, signals analysis, automatic signal peak detection, statistical analysis, etc.

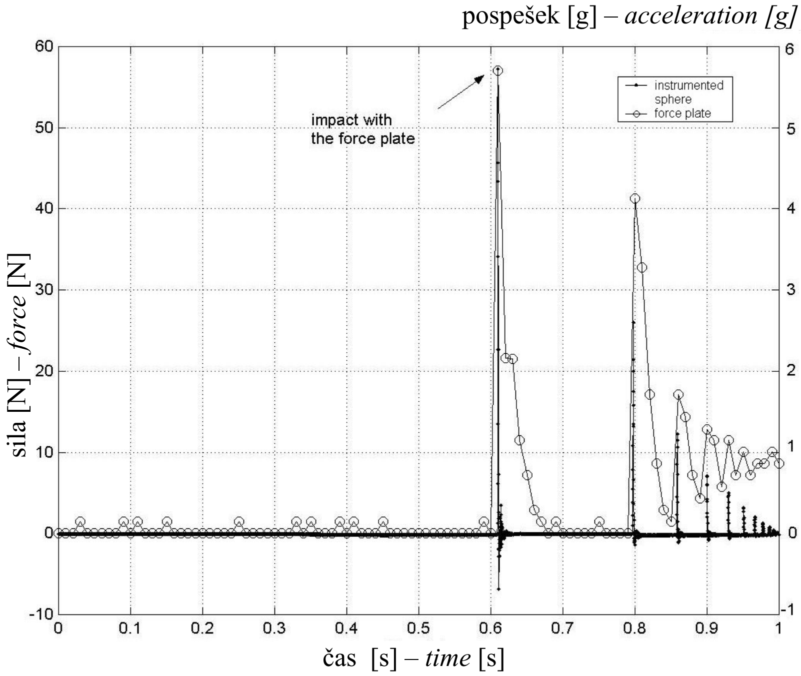
5. CALIBRATION OF THE INSTRUMENT

The device was tested in several ways. First, for the purpose of calibration, it was tested in the air using a force plate and the infrared markers placed on the device. The path obtained from an infrared marker during a drop test is presented on Figure 5. A comparison of force plate signal vs. the instrumented sphere signal is presented on Figure 6. The calibration curve between accelerations measured by the device and impact forces, causing these accelerations, proved to be linear.

Using this calibration we are in a position to convert the measured peak accelerations in the SPY-Cobble in g's (9.81 m/s^2) into peak forces in N's (kg.m/s^2). The conversion is a function of the mass of the SPY-Cobble and is defined as follows:

$$F = m\,a = 0.9946\;kg\;9.81\,\frac{m}{s^2} = 9.757\;N/g$$





Slika 6. Umeritveni poskus prostega pada na ploščo – primerjava med časovnima odvisnostma med merjeno trčno silo na plošči [N] in merjenim pospeškom [g] na sledilu.
Figure 6. Calibration drop test on a force plate – Comparison between measured impact force [N] on the force plate and measured acceleration [g] in the tracer, both given as a function of time.

Slika 5. Umeritveni poskus prostega pada na ploščo – pot infrardeče označbe na sledilu. Koordinata *z* je usmerjena navzgor od plošče in koordinata *x* je usmerjena vzdolž plošče.
Figure 5. Calibration drop test on a force plate – path of an infrared marker attached to the tracer. The z-coordinate is above the force plate and the x-coordinate is along the force plate.

6. ZAKLJUČEK

Po opravljenem umerjanju smo prodnik vohun testirali v laboratorijskih pogojih ob različnih hidravličnih razmerah. Glavni rezultati laboratorijskih testov so prikazani v spremljajočem članku (Mikoš & Spazzapan, 2005). Kontaktne sile med sledilom in dnom laboratorijskega žleba, prek katerega se je premeščalo sledilo v turbulentnem toku v hrapavem režimu, so bile uspešno merjene s pospeškometri v sledilu.

V enaki izvedbi, kot je sledilo opisano v tem članku, je bilo uporabljeno tudi v drugačnih laboratorijskih pogojih, in sicer v rotacijskem abrazijskem bobnu. Za potrebe laboratorijske analize obrabe kamnin zaradi premeščanja rečnih sedimentov se je sledilo

6. CONCLUSION

After calibrating the SPY-Cobble, we tested the tracer in a laboratory flume under different hydraulic conditions. The main results of the laboratory tests are given in the companion paper (Mikoš & Spazzapan, 2005). The contact forces between the tracer and the bottom of a laboratory flume over which the tracer was transported in turbulent flow in rough regime, were successfully measured by the acceleration sensors in the tracer.

The same tracer as described in this paper was also applied under different laboratory conditions, namely in a rotational abrasion mill. For the purposes of laboratory analysis of rock abrasion due to river sediment transport, the tracer was applied in a typical abrasion mill of the Los Angeles type (Kim, 2004). The uporabilo v tipičnem abrazijskem bobnu vrste Los Angeles (Kim, 2004). Ti laboratorijski eksperimenti so se izvedli v laboratorijih Univerze v Glasgowu. Analize signalov izmerjenih podatkov iz pospeškometrov so omogočile določiti število trkov in intenziteto trkov sledila z notranjo površino abrazijskega bobna in posameznimi sedimentnimi delci, ki so se vrteli v bobnu skupaj s sledilom. Prav tako je bilo možno iz signala pospeškometrov iz sledila ugotoviti vrsto materiala, v katerega je trčilo sledilo (Šolc *et al*., 2006).

Sledilo, opisano v tem članku, je bilo v času nastanka nedvomno edino take vrste na svetu (Mikoš *et al*., 2001). Razvoj podobnih sledil za razne namene bo v prihodnosti vsaj deloma navdahnjeno tudi s prodnikom vohunom. Kot primer navajamo razvoj t. i. cmoka (angl. Dumpling) sledila s premerom 0,3 m in vgrajenimi tridimenzijskimi pospeškometri, ki je namenjen meritvam notranjega dogajanja v drobirskih tokovih (Hanisch *et al*., 2005).

Sledilo je – glede na unikatnost izdelave (dosedaj sta bila izdelana dva prototipa) in relativno visoko ceno izdelave uporabno predvsem za monitoring gibanja plavin velikosti proda in grobejših plavin od tega v turbulentnem toku v laboratorijskih pogojih. Upoštevajoč te omejitve seveda ne more enakovredno nadomestiti bistveno cenejša sledila, kot so pobarvana ali magnetna sledila. Kljub temu je prodnik vohun polnovredno sledilo namenjeno za meritve v laboratorijskih pogojih.

experiments were performed in the laboratories of the University of Glasgow. The signal analyses of measured acceleration data have made possible the determination of the number and the intensity of the tracer impacts with the mill inner surface and the single sediment particles that were moving in the mill together with the tracer. Also, from the acceleration signals measured in the tracer, it was possible to detect the material into which the tracer had hit (Šolc *et al*., 2006).

The tracer described in this paper was at the time of its development definitely the only one of its kind in the world (Mikoš *et al*., 2001). In the future, the development of similar tracers for different purposes will be in the future at least partially inspired also by the SPY-Cobble. As an example we quote the development of a “dumpling”, a tracer with the diameter of 0.3 m and built-in 3D accelerometers for measuring internal processes in debris flows (Hanisch *et al*., 2005).

Due to its unique production (two prototypes have been produced so far) and relatively high production costs, the tracer is especially applicable for monitoring gravel-size sediment movement or (larger than gravel) in turbulent flows under laboratory conditions. Having these limitations in mind, the tracer cannot adequately replace the significantly cheaper tracers, such as painted or magnetic tracers. Nevertheless, the SPY-Cobble is a comprehensive tracer to be used for measurements under laboratory conditions.

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