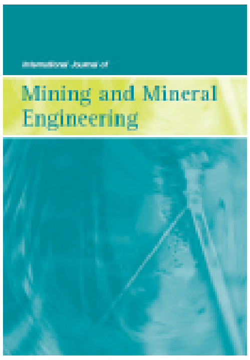

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Ilpo Niskanen, Santeri Lampinen, Matti Immonen, Lauri Hallman, Martti Mikkonen, Jarno Karvinen, Juha Kostamovaara, Jouni Mattila, Rauno Heikkilä

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3D-imaging of boulders using a solid-state 2D profilometer: case study for autonomous robotic rock breaker

Ilpo Niskanen*

Faculty of Technology,
Civil Engineering Research,
University of Oulu,
P.O. Box 4000, FI-90014 Oulu, Finland
Email: ilpo.niskanen@oulu.fi
*Corresponding author

Santeri Lampinen

Rambooms Oy,
Yrittäjänkatu 10,
FI-15170 Lahti, Finland
Email: santeri.lampinen@rambooms.com

Matti Immonen

Faculty of Technology,
Civil Engineering Research,
University of Oulu,
P.O. Box 4000, FI-90014 Oulu, Finland
Email: matti.immonen@oulu.fi

Lauri Hallman

Faculty of Information Technology and Electrical Engineering,
Circuits and Systems Research Unit,
University of Oulu,
P.O. Box 7300, FI-90014 Oulu, Finland
Email: lauri.hallman@oulu.fi

Martti Mikkonen

A-Perustus Oy,
Linnunrata 14,
90440 Kempele Finland
Email: martti.mikkonen@a-perustus.com

Jarno Karvinen

Faculty of Technology,
Fibre and Particle Engineering,
University of Oulu,
P.O. Box 4300, FI-90014, Oulu, Finland
Email: jarno.karvinen@oulu.fi

Juha Kostamovaara

Faculty of Information Technology and Electrical Engineering,
Circuits and Systems Research Unit,
University of Oulu,
P.O. Box 7300, FI-90014 Oulu, Finland
Email: juha.kostamovaara@oulu.fi

Jouni Mattila

Tampere University,
ATME FI-33101, Tampere, Finland
Email: jouni.mattila@tuni.fi

Rauno Heikkilä

Faculty of Technology,
Civil Engineering Research,
University of Oulu,
P.O. Box 4000, FI-90014 Oulu, Finland
Email: rauno.heikkila@oulu.fi

Abstract: Measurements of a boulder's fundamental physical properties like volume and shape can offer valuable insights for secondary breaking of boulders by a robotic rock breaker. This study analysed boulder shapes using a pulsed time-of-flight (TOF) solid-state laser profilometer. The 3D surface of boulders was reconstructed creating triangular meshes from point clouds provided by the profilometer. The main advantages of the 2D profilometer are the good measurement precision and accuracy, high speed, small size, real-time measurement capability, low weight, eye-safety, and lack of moving parts. The results indicate that a 3D map facilitates boulder diagnostics, aids in decision making, and represents a step towards a fully integrated autonomous robotic rock breaker in the mining industry. The present procedure is not only restricted to boulders, but it has also potential for other targets in industries that require precise determination of shapes for decision making.

Keywords: time-of-flight profilometer; stereo camera; boulder; robotic rock breaker; point cloud; shape.

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Biographical notes: Ilpo Niskanen received his MSc degree in Electrical Engineering from the University of Oulu, Finland in 2000, and PhD in Physics (Applied Optics) from the University of Joensuu, Finland in 2008. Since 2018, he has been an Adjunct Professor of Particle Characterization Techniques and Imaging Technologies in Autonomies Work Machines at the University of Oulu, Faculty of Technology. He has authored 44 peer-reviewed papers in journals. His current research interests include sensor technology, optical, spectroscopy, optical properties of materials, calculation algorithms, and image analysis.

Santeri Lampinen received his BSc and MSc degrees in Machine Automation from Tampere University of Technology, Tampere, Finland in 2017 and 2018, respectively, and PhD from Tampere University in 2021. From 2017 to 2021, he worked with the Department of Intelligent Hydraulics and Automation, Tampere University. In 2021, he joined Rambooms Oy, where he currently works as a Research Engineer. His research interests include mining automation, control of teleoperation systems, control of hydraulic systems, and nonlinear-model-based control.

Matti Immonen received his MSc degree in Mechanical Engineering from University of Oulu, Finland in 2014. He is currently working as a Project Researcher in Structures and Construction Technology Research Unit. His current research interests include autonomous machines, construction automation and robotics.

Lauri Hallman received his MSc and DrTech degrees in Electrical Engineering from the University of Oulu, Oulu, Finland in 2006 and 2015, respectively. He has done research in areas of laser transmitter development and 3D range imaging. Since 2016, he has been a Postdoctoral Researcher with the Circuits and Systems Research Unit, Faculty of Information Technology and Electrical Engineering, University of Oulu.

Martti Mikkonen received his BSc degree in Land Surveying from Mikkeli University of Applied Sciences, Finland in 1990. He has been working for private owned surveying company Mitta Oy since 1990. He has specialised in laser scanning, mobile mapping, 3D-data and UAV image processing, 3D-machine control systems. He is assisting part time for University of Oulu in the Structures and Construction Technology Research Unit taking part in research projects and teaching.

Jarno Karvinen graduated as a Laboratory Technician from Tampere University of Applied Sciences in 1992. He is currently working as a Laboratory Technician in Fibre and Particle Engineering Unit University of Oulu. His tasks include grinding materials and particle size analyses.

Juha Kostamovaara received his DrEng (Electrical Engineering) degree from the University of Oulu, Oulu, Finland in 1987. He has hold the Academy Professorship Position nominated by the Academy of Finland during 2006–2011 and then for the second time during 2012–2017. Currently, he holds a Professorship in Electronics at the University of Oulu (Circuits and Systems Research Unit). His main research interest is in the development of pulsed time-of-flight devices, circuits and systems for electronic and optoelectronic measurements.

Jouni Mattila received his MSc (Eng.) in 1995 and DrTech in 2000, both from Tampere University of Technology (TUT), Tampere, Finland. He is currently a Professor of Machine Automation with the Unit of Automation Technology and Mechanical Engineering, Tampere University. His research interests include machine automation, nonlinear model-based control of robotic manipulators and energy-efficient control of heavy-duty mobile manipulators.

Rauno Heikkilä is a Professor of Digitalized Construction and Mining Operations in the Faculty of Technology at University of Oulu, Finland. He is the Head of the Structures and Construction Technology Research Unit. He received his DrTech in 1996 from the University of Oulu. His major research interests cover structures and construction technology, engineering mechanics, information modelling (BIM in construction) automation and robotics in the construction of roads, railways, fairways, bridges and buildings as well as in mining. His current research interests include digitalised construction and mining operations, building information modelling (BIM), construction automation and robotics, mining automation and robotic, autonomous machines and vehicles.

1 Introduction

The World Economic Forum and Accenture have estimated that digitalisation could provide more than $425 billion in value to the mining industry, customers, society, and the environment over the next ten years (to 2025) (Schneider Electric, 2018). Because of the magnitude and complexity of its operations, as well as the harsh circumstances and high integration costs that come with change, the mining industry has been slow to adopt new technology in the past. Mining companies use less than one percent of the data collected from their equipment (Schneider Electric, 2018). Digitisation, automation, and electrification play a particularly significant role in today's mining industries. Digital technology can alter the fundamental processes of mining by making operations safer and more remote, transparent, and autonomous (Young and Rogers, 2019). For autonomous systems, this value comes from the fact that small decisions can be made automatically (Young and Rogers, 2019).

Secondary breaking is a key process of ore extraction in mining, where over-sized boulders are broken into smaller pieces prior to the primary breaking process. The conventional method of breaking over-sized boulders is by a manually operated hydraulic manipulator equipped with a hydraulic breaker boom. The manually operated hydraulic manipulator provides hazardous conditions for operators, as a lot of noise and dust is generated during boulders breaking. Therefore, an autonomous robotic rock breaker is needed to increase process efficiency, productivity and to improve the operator's safety and wellness. The ongoing trend of automating manual processes has progressed to secondary boulder breaking, and initial commercial applications are projected to start emerging. Key implementation issues include visual identification of boulders, as well as the pose and shape estimation of over-sized boulders. It is important that over-sized boulders are broken up in order to avoid jamming the primary crusher, possibly halting the mine's entire production, causing additional costs. Moreover, the operator often has a poor view of the boulders, especially when using an assistance remote control system. Therefore, modern measurement techniques that may prevent such unexpected stoppages are extremely favourable and necessary.

In the past, measuring the volume and shape of boulders has often been based on vision techniques. Vision-based boulder detection for autonomous rock breaker was first proposed in (Corke et al., 1998; Takahashi and Sano, 1998). Both studies proposed the use of a single CCD camera that is complemented with either a laser pointer or articulated 2D lidar. Stereo cameras were used to identify larger boulders autonomously

(Niu et al., 2019). The automatic identification of large boulders has also been studied with a time-of-flight (TOF) camera (McKinnon and Marshall, 2014). Mining conditions are often poorly lit, and dust and moisture levels can vary significantly. Unfortunately, the vision-based techniques' image quality depends on good viewing angles and lighting. The choice of the most appropriate technique depends on the dimension of the boulders, robustness, accuracy, and real-time requirements.

In our previous work, we studied the measuring of soil surface shapes and construction of roadways with a single sweep movement of an excavator arm with a solid-state 2D line profiler to acquire 4D point clouds (Niskanen et al., 2020, 2021). These preliminary studies revealed the potential of the suggested technology to identify objects' locations and physical properties accurately at construction sites. The present study aims to evaluate the suitability of a robust 2D solid-state profilometer for measuring the 3D surface profile of boulders via a robotic rock breaker that is able to predict target properties of the rock in order to perform at the optimal impact force. By integrating the profilometer position vector into the breaker boom's system it is possible to collect 3D point cloud data to be displayed in the breaker boom's coordinate system, increasing situational awareness. The profilometer system provides a direct view of the real world shows prominence in the properties of boulders. The 3D point cloud data can be used to identify individual boulders, which is important for an efficient and autonomous robotic rock breaker. Being able to present point cloud data in the breaker boom's coordinate system opens new possibilities for automating breaker boom movements, including the use of the point cloud data to detect appropriate breakage points on a boulder. When an appropriate point is detected, a breaker boom's hammer can be self-driven into that point for breaking. In comparison, the coordinate transformation method for a stereo camera is significantly more complicated. The problem is that the location and orientation of the stereo camera with regards to the breaker boom are not precisely known. Furthermore, the performance of the stereo vision camera depends on the image quality and is worse in dark and in extreme weather conditions, such as when the sun directly blinds the camera sensor.

2 Material and methods

2.1 Stereo vision camera

A ZED stereo vision camera from Stereolabs was used to create a comparative point cloud. The stereo camera could produce up to a 2.2K image and had the same depth resolution. The depth of each pixel was calculated with a triangulation method, and the depth accuracy calculation varied between 1–9% of the measurement range, decreasing quadratically as a function of distance. The maximum range of the camera was 20 m.

Depth calculation from the stereo images was done via a disparity triangulation method, in which the cameras' focal lengths (*f*) of the parallel optical axes, as well as the distance between cameras, must be known. Then, depth (*z*) can be calculated as follows:

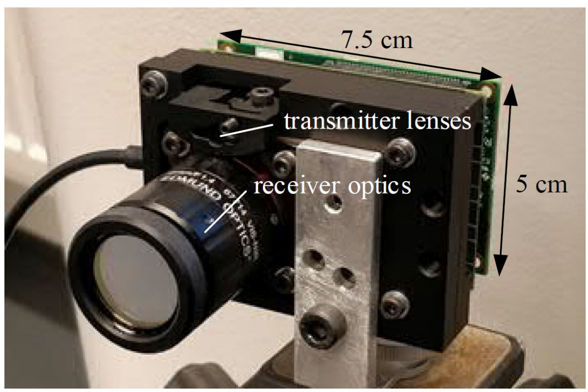
$$z = f * b/d, \tag{1}$$

where b is the baseline distance between cameras and d is the disparity (i.e., the difference between the corresponding 3D point in the images projected to the different cameras) (Jain et al., 1995).

2.2 2D pulsed TOF profilometer

In this paper, the stereo camera described above was compared against a line profiling laser radar (Keränen and Kostamovaara, 2019a). This custom-developed compact device with no moving parts does pulsed laser TOF distance measurements in 256 directions simultaneously within a linear field-of-view of ±19 degrees (uses stripe-like illumination). Measurements were gathered by illuminating a laser fan on the boulders with a pulsed laser diode output spread with simple optics while laser pulse flight times back and forth to the boulders in 256 individual directions were measured with a linear CMOS single-photon avalanche diode (SPAD) and time-to-digital converter (TDC) array on an integrated circuit.

Figure 1 Solid-state 2D time-of-flight (TOF) profilometer (see online version for colours)



The distance to each direction was calculated based on the measured laser pulse flight times and the known speed of light. In worst-case conditions of full sunlight, the distance measurements worked to at least 5 m with a frame rate of 30 frames/s, and a few tens of metres in lower ambient illumination levels (Keränen and Kostamovaara, 2019b).

Because of the high measurement accuracy and precision of the custom-designed photon flight time sensor, the distance measurement accuracy and precision were greater than 1 cm. The use of a custom- designed laser diode that emits brief 200 ps laser pulses helped achieve great measurement precision as well. 3D measurements of the rock surface were possible, for example, by tilting the 2D lidar on a moving platform. Figure 1 shows a photograph of the solid-state line profiler system used.

2.3 Hydraulic breaker boom

The Hydraulic breaker boom used to conduct the experiment was from the X8 line-up of Finnish original equipment manufacturer Rambooms (RamBooms, 2018). The manipulator was a medium-sized three- link boulder breaker, weighing roughly 10,000 kg. The manipulator's horizontal reach was approximately 5.4 m, while the vertical reach was 3.7 m. The hydraulic hammer located in the last link was nominally kept in a vertical position during operation; this positioning was also considered to be the case for the previously stated reach figures. The boom could rotate around its base 135 degrees in both directions from the nominal position. Figure 2 depicts the manipulator and compares its size to a human for reference.

Figure 2 Hydraulic breaker boom (see online version for colours)

Source: RamBooms (2018)

For accurate pose measurement during the experiment, the manipulator was retrofitted with SIKO WV58MR 14-bit absolute rotary encoders for each joint. Control of the manipulator was done using a dSPACE MicroAutoBox 2 real-time computer.

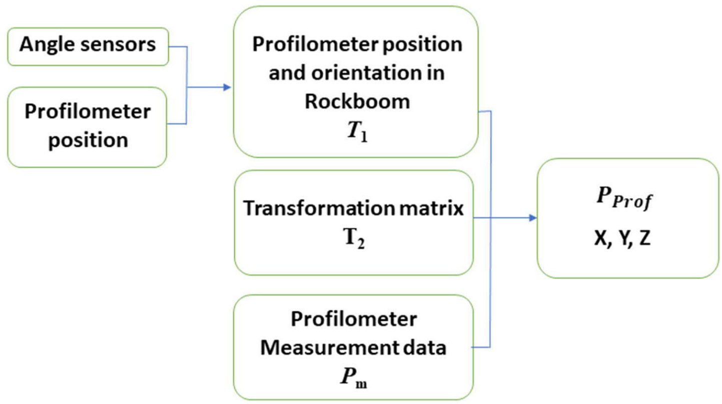
The proposed system attaches the profilometer to a robotic rock breaker boom. The profilometer itself produced two-dimensional scans, and the natural motion of the robotic rock breaker boom during the work was utilised to produce a three-dimensional image of the objects. Our approach is a Euler's formula solution. The whole mathematical procedure is illustrated in Figure 3. Coordinates for each frame of the profilometer are obtained by including its orientation, coordinates, and distances. The positions in the coordinate system of the profilometers (P_{prof}) each 256 measurement results can be expressed as

$$P_{prof} = T_1 \times T_2 \times P_m = \begin{bmatrix} R_{ORI} & A_P \\ 000 & 1 \end{bmatrix} \begin{bmatrix} R_{prof} & 0 \\ 000 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ me \\ 0 \end{bmatrix} \tag{2}$$

where T_1 and T_2 are the transformation matrices. The transformation matrix is implemented using quaternion algebra. Vector P_m is a measurement result of the profilometer and vector A_P expresses the scanner position in the workspace coordinate system, R_{ORI} expresses the orientation of the profilometer, R_{prof} is the rotation matrix of

T_2, and *me* is the Z-component of vector P_m. More detail on the calculation method can be found in Ref. (Niskanen et al., 2020).

Figure 3 Representation of 3D point clouds process (see online version for colours)



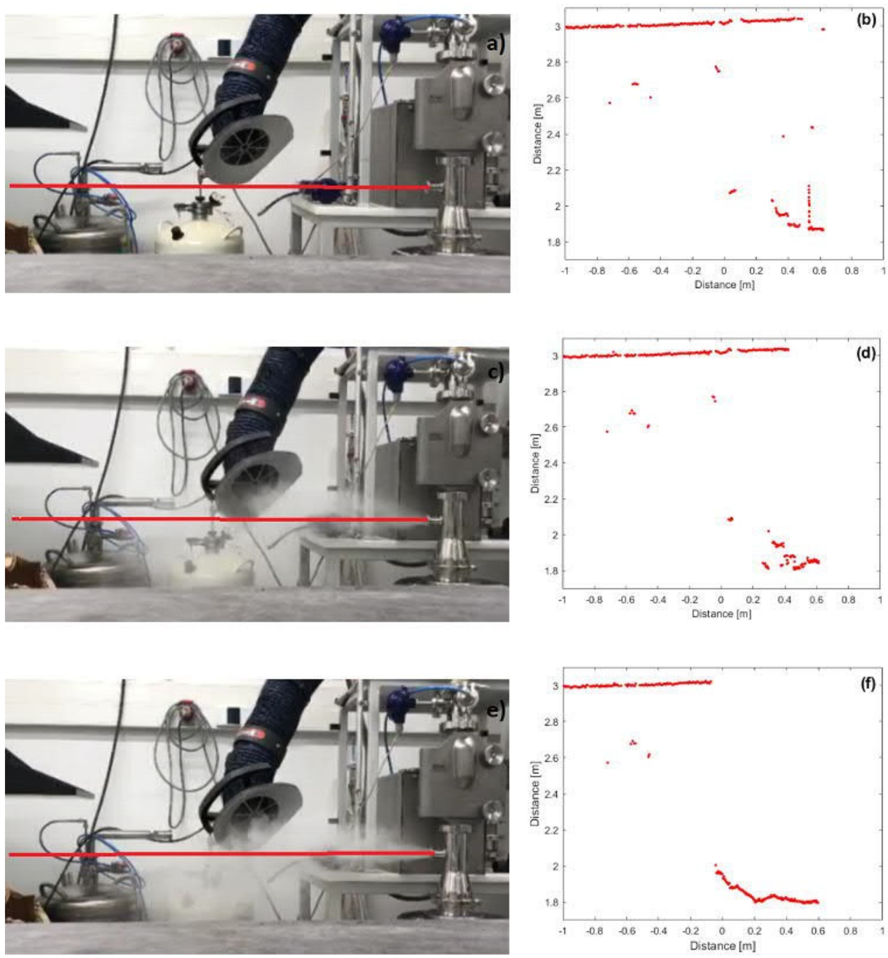
3 Experiments and results

3.1 The effect of boulder dust on visibility

Where mineral ore is transferred mechanically, abrasion and impaction occur leading to the release of fine particulates (Silvester et al., 2007). The fine dust adversely affects the visibility of boulders to the secondary rock breaker system when using monitoring techniques. The effect of rock dust on optical transmittance was studied by observing the change in the profilometer's signals from the back wall of the room during the grinding process as a function of time. Some of the incident laser pulses passed through the dust particles and recovered the depth information of objects through the dust.

We used tailings [77% SiO_2 (77%), Al_2O_3 (14%) and Na_2O+K_2O (8%)] with an average particle size of 204 µm in the dust test. The tailings were ground in a Hosokawa Alpine fine impact mill (100 UPZ) equipped with a pin disc grinding unit. During grinding, the mill speed was 18,000 rpm and the material flow rate through the equipment was 394 g/min. The ground material was divided into two parts, approximately 74% of the ground material went to the sample tank and 26% to the side branch at a 90 ° angle in the outlet pipe. Dust was analysed from the side branch (the mass flow rate of the material was about 103 g/min) which was sucked up the suction unit. The average particle size of tailings was 46 µm as measured by a Beckman Coulter LS 13,320 laser diffraction particle size analyser (dry with DPS module) from the side branch. Figure 4 shows three video captures and simultaneous profilometer results. Initially, there was no dust at all as illustrated in Figures 4(a) and 4(b). Figure 4(b) shows that a wall is at 3 m from the profilometer and its width is 1.5 m. With dust added to the air, Figures 4(c) and 4(d), the dust attenuates laser pulses near the nozzle, giving the view of the wall a measured width of 1.4 m [Figure 4(d)]. As the dust concentration continues to increase [Figure 4(e)], only 0.9 m of the wall width is observed [Figure 4(f)]. In summary, the ability of TOF profilometer to recover the profile of the wall through the dust is roughly similar as the capability of the human eye to see the wall. Low dust content in front of the boulders does not cause problems in determining the volume of the boulders.

Figure 4 Video captures and corresponding distance data given by the profilometer (see online version for colours)



Note: The red solid line represents the illumination laser stripe.

3.2 Profilometer field testing

Field experiments were carried out at Tampere University of Technology's field site. The measuring system used was a 2D laser profilometer mounted in a plastic case on the front side of a hydraulic breaker boom, as shown in Figure 5.

Five boulders were set on a metal grid; each grid square was 60 × 60 cm, as presented in Figure 6. The total size of the metal grid was 3 × 4 m. The experiment was executed by moving the boom from –96.3° to –57.5° above the boulders. In this case, about 45 s was spent scanning the boulders on the metal grid. A total of 290,000 laser points was collected. In practice, however, the 3D range image could probably be produced by the continuous up-date of the line profile information during the normal breaker operation cycle. This measurement should be considered as a reference recording indicating the quality of the recorded 3D range image and intensity map. In actual use, the range image and intensity data are produced continuously during the normal breaker operation.

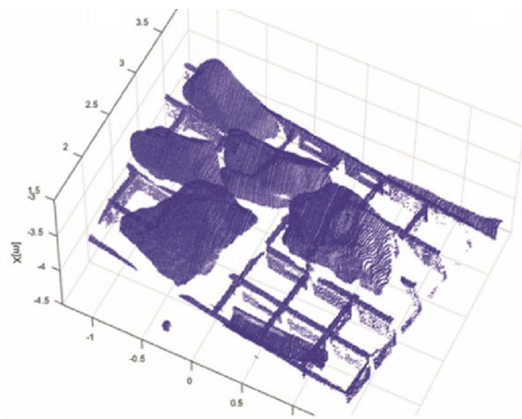
Figure 5 Profilometer installed on a hydraulic breaker boom (see online version for colours)

Figure 6 Boulders on metal grid (see online version for colours)

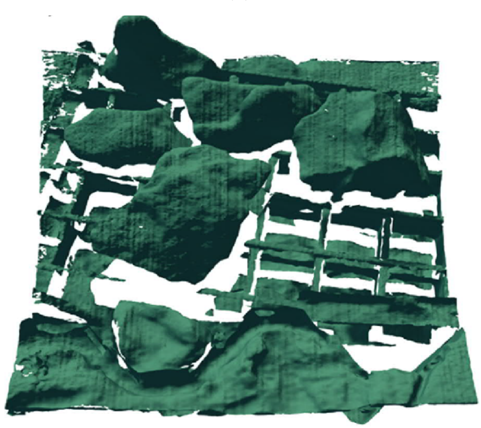
The results are shown in Figure 7. Figure 7(a) presents an intensity map of the boulders, which is substantially similar to the real images from the camera (Figure 6). This intensity map is based on the recorded pixel-wise count rate of the lidar-profilometer measurement. An intensity map can be useful in applications where materials need to be roughly identified, for example, boulders, metal, and snow. In this case, snow produced reflection values twice as high as those of boulders at near-infrared wavelengths (Singh et al., 2010; Oh et al., 2017). Figure 7(b) shows the 3D point clouds of the boulders. Lastly, a triangular mesh map was created from the 3D point cloud using the surface reconstruction Trimble Realworks program by Mesh3D algorithm (Sitnik and Karaszewski, 2008). The result is presented in Figure 7(c). Comparison measurements were carried out using a commercial stereo camera, the images of which can be seen in Figure 8, which shows that the stereo camera provided high-resolution, and density compared to the profilometer images, however, with the limitations discussed above (Zhang, 2018).

Figure 7 Imaging of boulders by 2D profilometer, (a) intensity map (b) 3D point cloud (c) 3D triangular mesh map (see online version for colours)

(a)



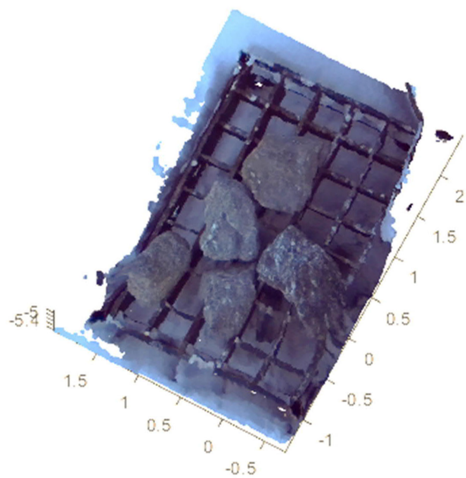
(b)



(c)

With the stereo-camera approach the spatial measurement accuracy can be very low if an object does not present rich surface texture, as boulders generally do. Measurements were done in the afternoon in March, under twilight and cloudy conditions. Therefore, the low environmental illumination affected the resolution of the stereo image. In contrast, the profilometer is not sensitive to variations in illumination conditions and can even operate even in the dark. The disadvantage of the stereo camera is that features for both images must be matched to calculate distance information (Mohan and Ram, 2015), which may result in inadequate depth information for the image area. In contrast, the profilometer allows reliable detection in challenging conditions, such as in the presence of boulder shadows. The results obtained here verified that it is possible to determine the shapes of boulders with a 2D laser profilometer. Acceptable image quality was achieved using a high scanning frequency.

Figure 8 Point cloud produced by the stereo camera (see online version for colours)



The accuracy of the proposed line profiler-based method was approximately 50 mm, based on the accuracy of the profilometer and the hydraulic breaker boom. The limiting factor for the accuracy of the overall measurement system was the hydraulic breaker boom. The accuracy of the rotary encoders of the boom was 0.38 mrad. However, due to uncertainty in the kinematics regardless of the kinematic calibration, the worst-case absolute accuracy of the tip of the hydraulic breaker boom was approximately 50 mm. The absolute error of the profilometer was not distance dependent as long as the signal-to-noise ratio [SNR] was high enough. It was measured in a calibrated track and found to be within the limits of +/–2 mm (including possible errors in the track calibration) for a range of 35 m (Keränen and Kostamovaara, 2019b). Precision decreased linearly as a function of distance at a given measurement rate and was typically at the level of 1…10 mm within a range of 35 m at a measurement rate of 28 fpsec (Keränen and Kostamovaara, 2019b).

4 Conclusions

A system recognising the shape and volume of boulders is a key technology for enabling autonomous robotic rock breaker operation in secondary breaking. This paper described an effective optical method of determining the shape of boulders using a custom-designed pulsed TOF laser radar profilometer. The profilometer's major advantages are its accuracy, lack of moving parts, low cost, low power consumption, eye-safety, high speed, and small size. These are valuable measuring device features for future autonomous robotic rock breakers. The major disadvantage of the method is the time necessary to create a 3D image due to the necessity of performing sweeping movements of the 2D profilometer across the field of interest. On the other hand, the 3D range image could probably be produced by the continuous update of the line profile information during the normal breaker operation cycle. The proposed method can enable increased autonomy of mining processes, leading to higher efficiency and improved profitability. The safety of underground mining can also be increased, as fewer people need to work in hostile underground environments.

Real-time tracking of 3D objects is possible with a stereo camera. However, the stereo camera has low depth accuracy on surfaces with low local contrast due to the difficulty of observing any disparities between images. In mining applications, the environment is usually very dusty and, thus, the suitability of a stereo camera requires further studies. Furthermore, local contrast, especially in low light environments, is often very low, which can also limit stereo camera performance. The results obtained with this study show that the line profiler can produce both the 3D range and intensity data to inspect the shape and volume of boulders. Future work should endeavour to generate more dense 3D point clouds, resulting in improved accuracy and performance.

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