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Slope monitoring using sensor fusion

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Abstract

Geotechnical monitoring of slopes has improved dramatically over the last 20 years due to the onset of new sensor technologies and improved computing resources. Each sensor type has its strengths and weaknesses and, although an array of different sensors is now typically deployed at large surface mines, the data and downstream analysis is not typically 'fused' in a signal processing sense.

In this paper, we present technologies that are being developed using a fused sensor approach. The first fuses vision and radar to improve monitoring of three-dimensional (3D) deformation of slopes. The second fuses vision, radar, and microseismics to support 3D rockfall trajectory estimation. The third fuses vision and prior knowledge of the 3D topography for fast 3D surface reconstruction for slope characterisation.

This paper presents ongoing industry funded research and field trials into the feasibility of using these technologies in surface mines.

Keywords: *vision, radar, deformation, rockfall*

1 Introduction

Mining operations are increasingly using sophisticated technologies for geotechnical monitoring of their slopes (Sharon & Eberhardt 2020). Although systems integrators are increasingly supporting the visualisation and analysis of data from these sensors within a single software package, the information provided by the sensors is still largely treated as distinct and separate.

Sensor fusion techniques used in aeronautical and military applications offer the possibility to jointly interpret information as well as mitigate the weaknesses of any single sensor modality. Of particular relevance to work described in this paper, sensor fusion can provide improved noise characteristics than any single sensor can provide, as well as provide monitoring of more degrees of freedom than the sensors can when used individually.

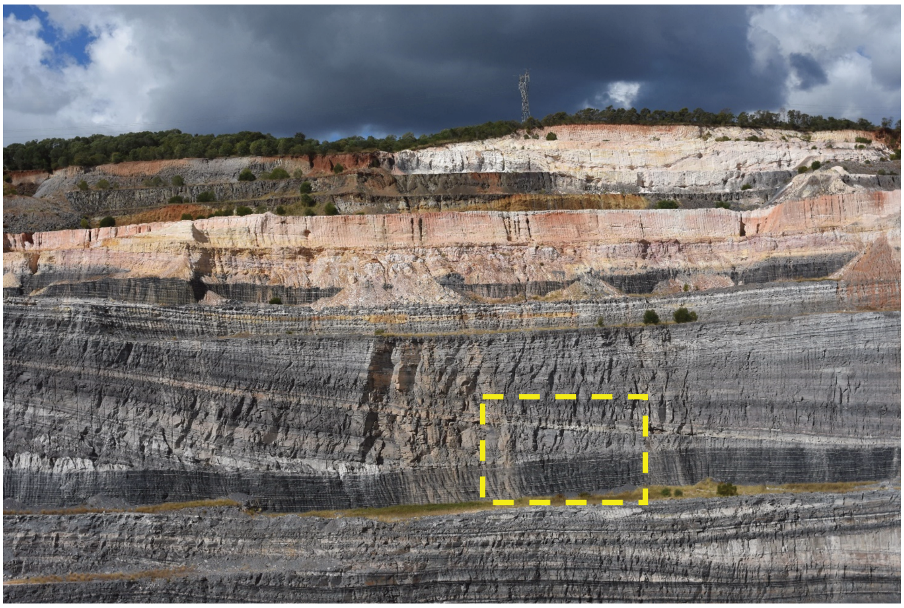
This paper presents current research by the authors in fused sensor monitoring technologies. Section 2 discusses the use of vision and radar for the reliable measurement of 3D deformation of mining slopes. Section 3 discusses the use of vision, radar, and microseismics for the monitoring and analysis of rockfalls. Finally, Section 4 presents the use of prior 3D geometric knowledge to guide more efficient and precise stereo-photogrammetry for 3D change detection applications in surface mining.

2 Slope deformation monitoring

2.1 Background

Slope stability radar suffers from line-of-sight bias, which can lead to inaccurate assumptions about the failure mechanics and deformation vector. An array of multiple slope monitors can be used to observe the same region and mitigate this issue (Severin et al. 2014), but it is cost-prohibitive for most mining operations. The authors have been undertaking research and development into a patented technology for integrating a vision-based system with a deformation monitor to allow estimation of the 3D deformation vector (Elmouttie et al. 2020a; Elmouttie & Poropat 2015). Figure 1 gives an indication of the imaging quality that can be achieved at range using low cost, commercial, off-the-shelf camera systems.

The algorithm involves acquisition of video frames from a vision system. Feature tracking is performed on these frames and is combined with line-of-sight slope deformation data provided by the radar. These two data streams are combined, taking due consideration of the differing pose and noise parameters associated with each sensor, to resolve the 3D components of the deformation. The vision system may comprise multiple units in an array and due to their low unit cost, such a configuration would not be prohibitive. The field trials and simulations described in this paper assume only one vision sensor is available and located at the same position as the radar.



(a)

(b)

Figure 1 NIKON D7200 at around 500 m range: (a) 35 mm; (b) 180 mm. The yellow dashed rectangle in the top 35 mm image delineates the 180 mm field of view

2.2 Field trials

Field trials have been undertaken at two sites: Site A using a GroundProbe radar and vision system and Site B using an IDS Georadar and Vision system. For brevity, we present Site B results in this paper but note that Site A results were also very encouraging.

An IDS IBIS-FM radar is the primary monitoring system used at an overseas gold mine. IDS and the mine site set up an IDS Georadar Eagle Vision camera system. The camera was mounted on the door of a shipping container that housed the IBIS-FM (Figure 2). This door was anchored during the image acquisition programme. Table 1 shows the system parameters used in this study.

Figure 2 IBIS-FM monitoring station and with Eagle Vision camera mounted on container

Table 1 Sensor parameters used in the field trial

Parameter	Value
Sensor resolution	36 mm @ 1 km or 0.037 milli-radians
Radar resolution	<4 m @ 1 km or 4 milli-radians
Radar deformation sensitivity	Sub-millimetre

Simultaneous monitoring of the failure zone with both vision and radar systems was undertaken with the region of interest comprising a bull-nose geometry located approximately 500 m away from the monitor and obliquely positioned relative to the radar. Around 20 mm of deformation was measured by the radar during the 28-day observation period. Figure 3 shows this zone being observed.

The sensor fusion algorithm described in Section 2.1 was applied to this data and Figure 4 shows the results. The solid black line (vectors) indicates the final solution of the fusion algorithm. The observed deformation is dominated by that detected by the vision system with a magnitude over 10 times greater than that observed with the radar.

Figure 3 Wide field view of the region of interest from the monitoring pad

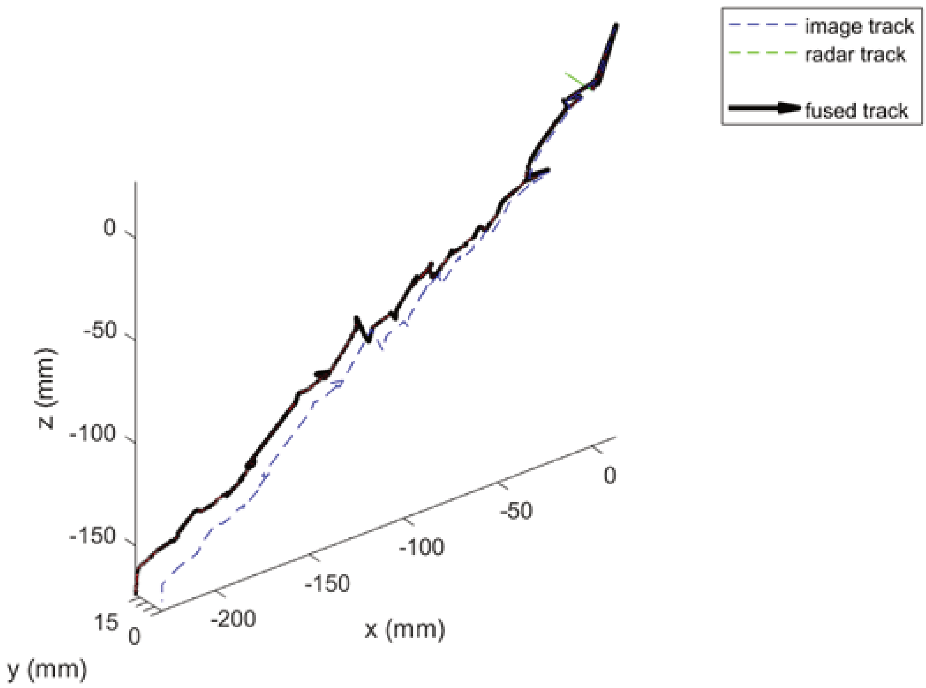


Figure 4 3D deformations based on fusion of image and radar data for deformation vectors. Note the green line indicating raw radar track at the top of the figure

A plan view is shown in Figure 5, which more clearly highlights this. The green line indicating the radar line-of-sight measurement is also shown. The deformation magnitude predicted in this result has been validated qualitatively with the mine staff and was somewhat expected, given the location of the radar and the oblique angle to the deforming bullnose that was being monitored. The direction of deformation (3D vector) predicted in this result has been quantitatively validated against previous measurements undertaken by the mine of the same slope sector using a dual-radar system. For the purposes of this field trial, the algorithm was run offline. However, an assessment of the computational performance indicates it can support real-time processing in an integrated vision-radar system.

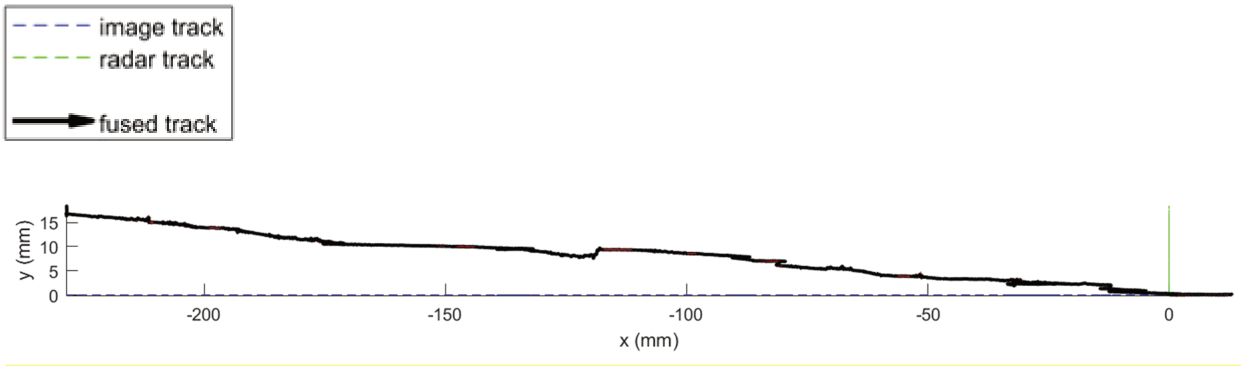


Figure 5 Plan view of 3D deformation vectors

This result clearly demonstrates the benefits of fusing vision systems with radar for deformation monitoring. In certain scenarios, such as the one studied in this paper, the line-of-sight bias introduces gross underestimation of deformation and lack of understanding of failure mechanism geometry.

3 Rockfall monitoring

3.1 Background

Systems to detect, monitor, and analyse rockfalls in open pit mining operations have the potential to improve decision-making, for example, for operational safety, improve calibration of rockfall simulators (restitution coefficients), and importantly provide quantitative data to justify current standoff designs. Although several technologies have potential to assist in the monitoring and analysis of rockfalls and their trajectories, to date, no effective systems exist. Figure 6 shows the characteristics of a typical rockfall event needing to be observed by such a rockfall monitoring system.

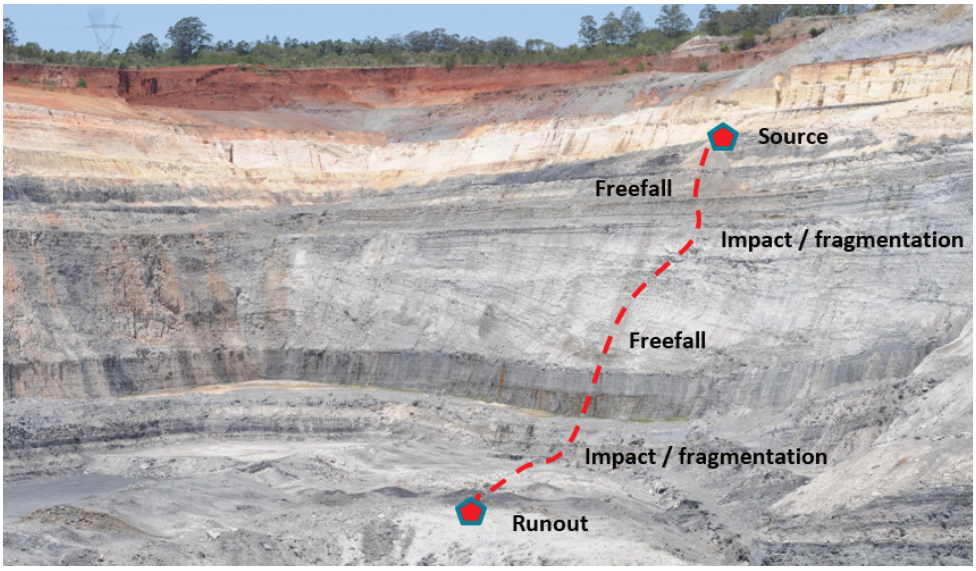


Figure 6 Example rockfall event

The authors have designed a monitoring system that can accumulate a large database of rockfall events across the full strike length of highwalls. The use of existing monitoring systems (radar, vision, lidar), as well as knowledge of the wall geometry, geology (rock mass types), and structural characteristics (defect orientations and intensities) has the potential to support detection of events and detect rockfall movements accurately enough for determination of trajectories (bounce kinematics), impact locations and final resting positions.

To achieve this goal, the authors undertook a scoping study to define the technical requirements, specifications and system design for a fused sensor system to support the analysis of rockfalls on slopes (Elmouttie et al. 2020b). The technologies required include computer vision in combination with new rockfall-specific radar systems, and acoustic (seismic) monitoring. The study also involved benchtop analyses and initial field-based feasibility studies.

3.2 Simulations and field trials

As outlined in Section 2, vision systems have great potential for slope monitoring applications. Unlike long-term monitoring, rockfall monitoring relaxes constraints associated with consistency of lighting and atmospheric transparency. Only sufficiently constant illumination (and object contrast) is required for the short duration of the rockfall event (order of seconds). Indicative images, as shown in Figure 7, provided to CSIRO from a coal mine and acquired at a range of between 100 and 200 m, using 720p video and captured at 25 fps using a low-quality, compact camera. Sufficient contrast is present for detection of the small (in the order of 10–20 cm) rockfall circled in the frames. Clearly, vision systems operating in the visible spectrum will be unable to provide input to the monitoring system outside of daylight hours.

Figure 7 Consecutive video frames of a rockfall (circled) on a highwall

Computer vision software developed by the authors to perform change detection was applied to the video to test the potential of such algorithms for rockfall detection. Figure 8 indicates that the results are very encouraging with both small (of the order of 10 cm) and larger rockfalls being detected before the eventual wall failure.

(a) (b)

Figure 8 Change detection being performed on the video sequence, with detections shown as white. (a) Small rockfall detection; (b) Detection of larger mass movements

Microseismic monitoring is considered to be a crucial sensing modality to support this fused sensor approach. Studies were undertaken to determine the efficacy of potentially dense networks of geophones for impact point localisation. Figure 9 shows the results of one such simulation using software developed by the authors. It indicates that localisation errors of the order of a few metres should certainly be achievable even with moderately dense networks.

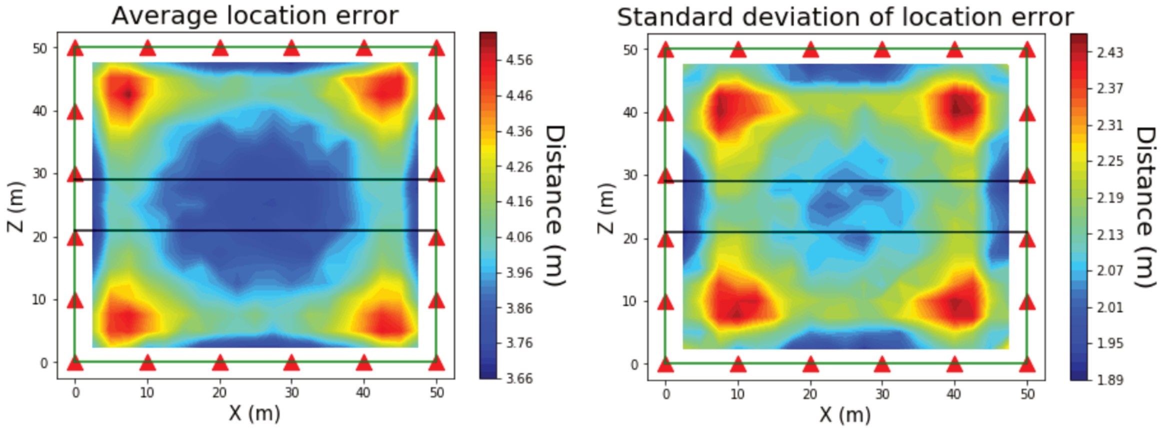


Figure 9 Mapping the average and standard deviations of location error for network layout 1. The red triangles indicate the geophones

Experiments were also conducted at CSIRO's Pullenvale site to establish proof-of-concept for surface impact detection and localisation of small rocks using a shallow array. Several rock types and samples, as shown in Figure 10, were used in the testing, with masses from around 500 g to 4,700 g.

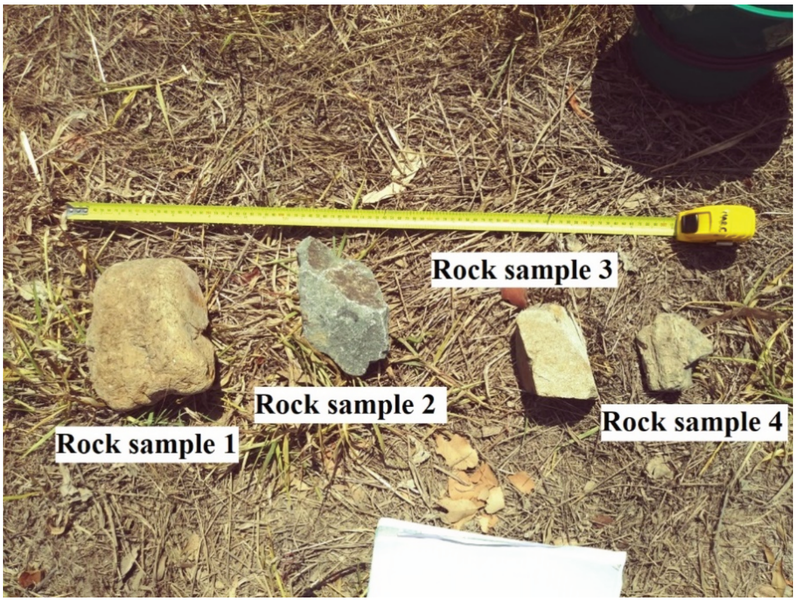


Figure 10 Rock samples used for this experiment. They were dropped from the largest (left) to the smallest (right)

The samples were dropped and rolled from the top of the slope with the site geometry, geophones locations, and dropping zones, as shown in Figure 11.

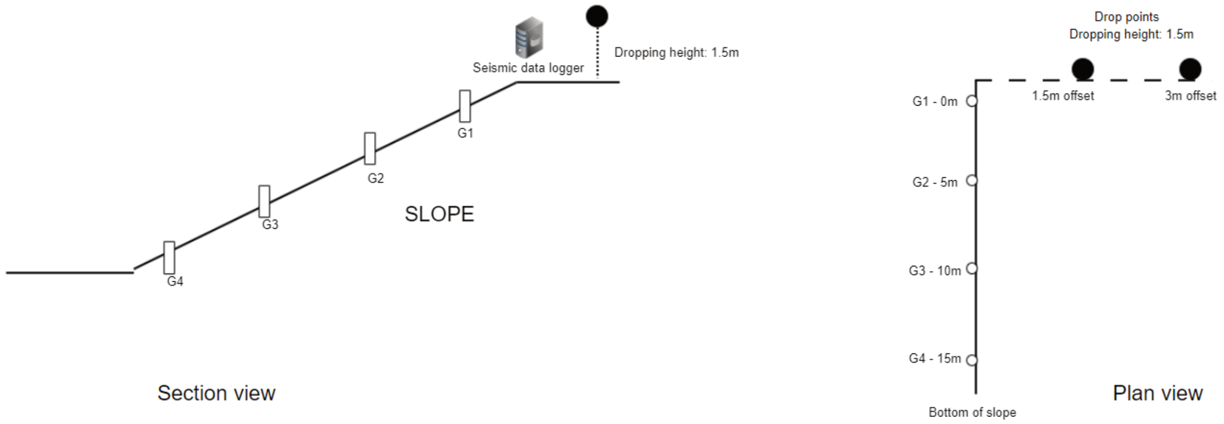


Figure 11 Locations of the geophones and dropping points

The results of these trials were very encouraging, with all rocks clearly detected by the network and with great potential for accurate localisation. Figure 12 shows that, assuming impact conditions similar to those tested, the seismic energy attenuation implies rock-dropping events should be detected between 25 to 35 m away from a microseismic geophone. This is very encouraging as it indicates network designs for mine wall monitoring should be feasible, particularly as alternative technologies (such as fibre optic based seismic monitoring) becomes more common.

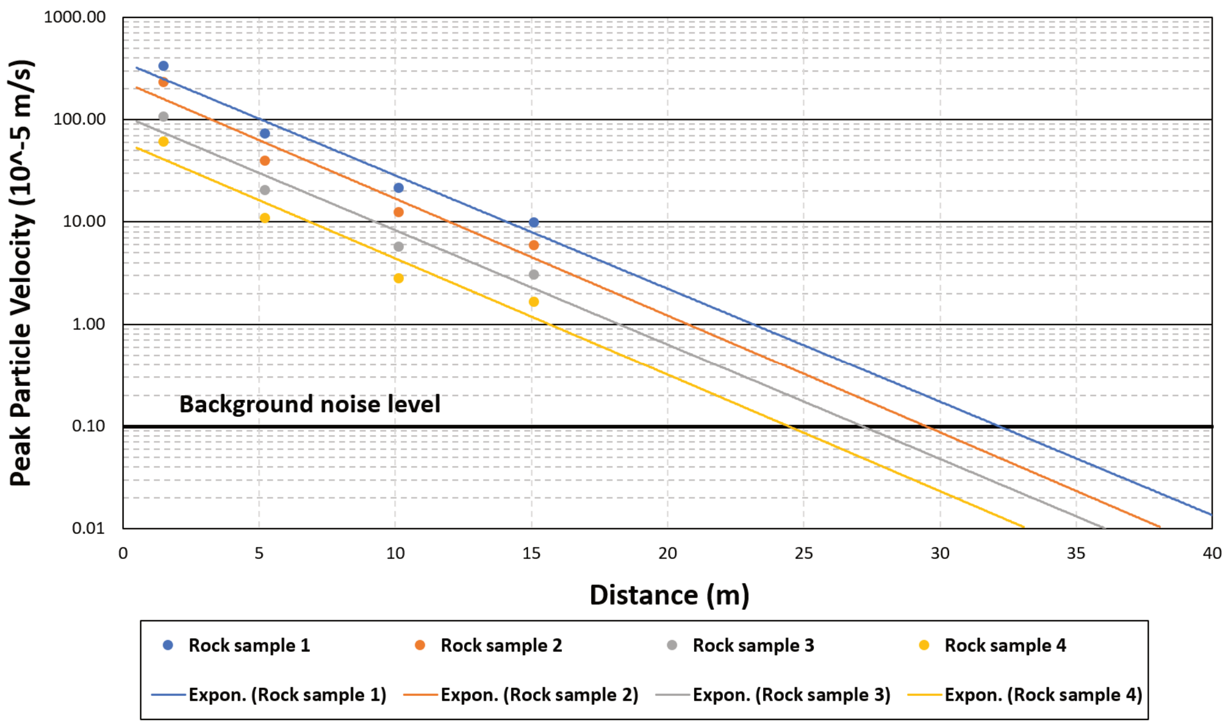


Figure 12 Relationship between peak particle velocity and the travel distance of seismic wave

4 Surface characterisation and change detection

4.1 Background

Surface characterisation through 3D scanning technologies is becoming ubiquitous, whether via terrestrial laser scanning, photogrammetry, or aerial equivalents. Photogrammetry provides high resolution point clouds but suffers from computational burdens not present with Lidar. Prior knowledge of the 3D geometry, such as from Lidar surveys, mine plans, or even previous photogrammetric models, can be fused with stereovision systems to provide rapid, high-resolution, and more precise 3D reconstruction of the terrain. CSIRO has developed the stereo-depth fusion (SDF) algorithm and the concept is shown in Figure 13. Prior knowledge of the geometry of the pit is used to optimise the stereovision algorithm, minimising the computer time spent in the stereo-matching algorithm and improving the sensitivity of photogrammetry to small changes in 3D topography.

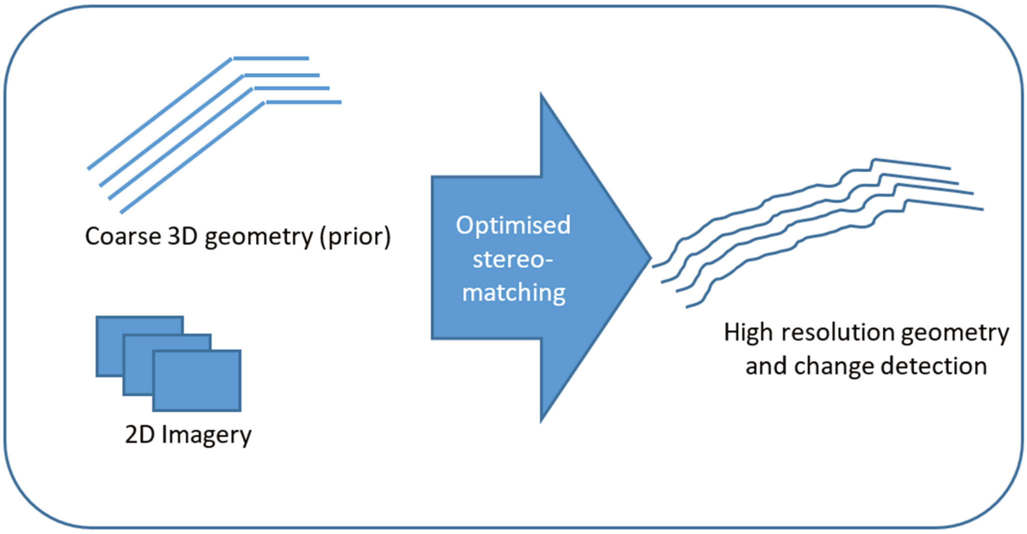


Figure 13 Stereo-depth fusion algorithm

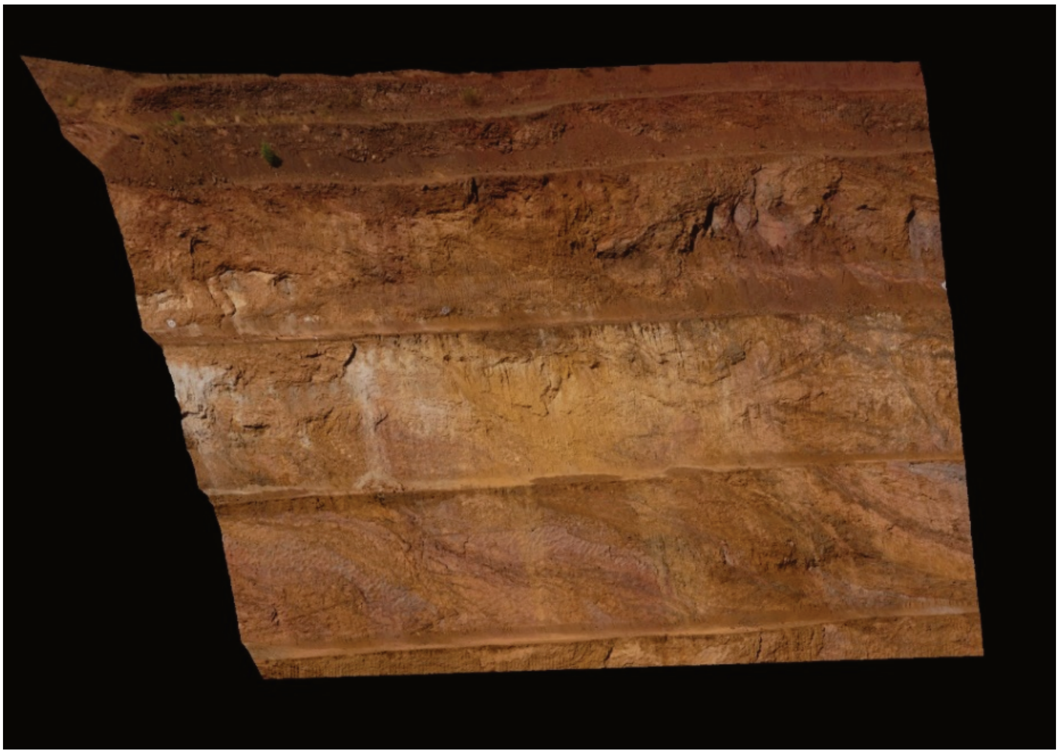
4.2 Analysis

To demonstrate the efficacy of this approach, photogrammetry data of an open pit mine acquired using traditional photogrammetry at a range of 450–500 m from the mine wall has been re-processed using the SDF algorithm. A small deformation was synthetically applied to the central rectangular portion of the model to assess the algorithm's computational efficiency as well as its ability to detect said changes. The simulated deformation was around 25 mm, at the limit of the photogrammetric detection system assuming the camera parameters shown in Table 2.

Table 2 Camera parameters used for data in Figure 14

Parameter	Value
Sensor resolution	3,872 × 2,592 pixels
Pixel size	6 microns
Focal length	60 mm

The results shown in Figure 14 demonstrate the algorithm's ability to accurately and precisely reconstruct the 3D scene and support the detection of such small changes. The measure of deformation in these results is difference in disparity maps (DiD), which compares the stereo-disparity (a measure of range) before and after deformation was applied to the model. Figure 14b shows the DiD result using a naïve stereo-photogrammetric analysis without using prior geometric knowledge of the scene. Figure 14c shows the result using the SDF algorithm. The rectangular region undergoing deformation, although detectable in both data sets, is much more clearly delineated in this second DiD map.



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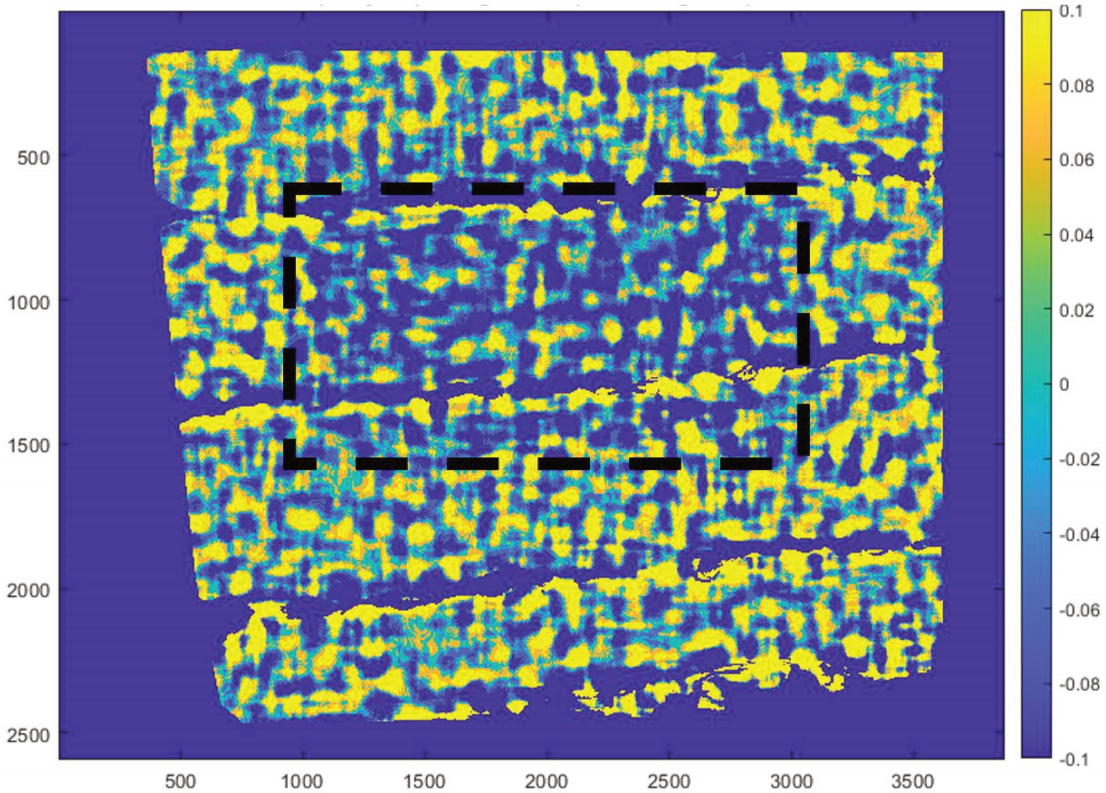
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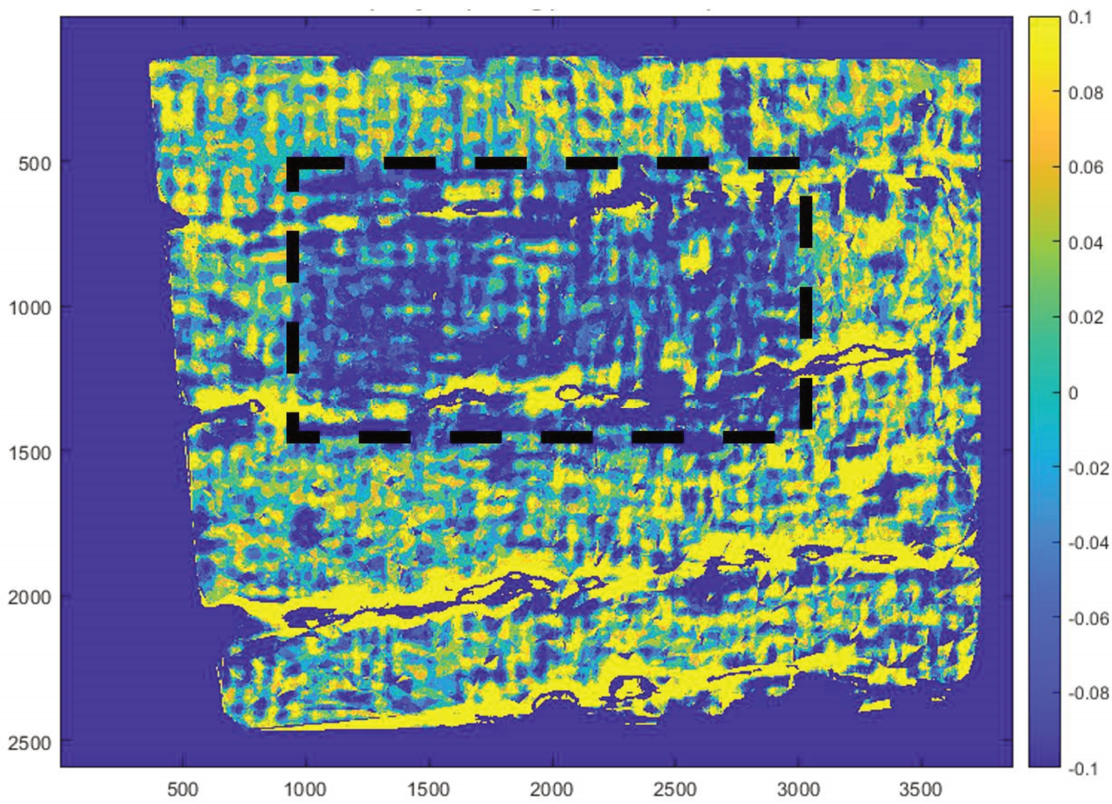

(c)

Figure 14 Assessment of the stereo-depth fusion (SDF) algorithm for surface characterisation and change detection. (a) Section from a 3D model of an open pit mine processed using traditional photogrammetry; (b) Naïve deformation analysis based on photogrammetry without using prior geometrical knowledge, with deformed zone indicated by black dashed rectangle; (c) SDF algorithm applied to use previous observation as prior knowledge, with deformed zone indicated by black dashed rectangle. The deformation is more clearly detected

5 Conclusion

Three slope monitoring technologies based on sensor fusion have been described in this paper.

The slope deformation monitor uses vision and radar to address line-of-sight bias issues associated with the radar monitor. For oblique viewing angles, this can mitigate quite dramatic underestimation of deformation magnitude and misinterpretation of deformation vector. Field trials have been undertaken to validate the approach and results are very encouraging.

The rockfall monitor uses vision, radar, and microseismics monitors to estimate 3D rockfall trajectories that no individual sensor can measure. Although full system field trials are yet to commence, trials of the vision and microseismics subsystems show great promise and potential to be coupled with commercially available rockfall radars.

The SDF algorithm provides an optimised computation pipeline to use prior 3D geometric knowledge for rapid photogrammetric reconstruction and 3D change detection. Semi-synthetic data has demonstrated that this approach supports detection of small surface deformations making photogrammetric deformation monitoring a possibility for certain applications.

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References

Elmouttie, M, Dean, P & Van de Werken, M 2020a, *Estimation of True Deformation Vector from Slope Radar Monitoring*, ACARP, Brisbane.

Elmouttie, M, Luo, X, Duan, J, Dean, P & Malos, J 2020b, *Fused Sensors for Rockfall Monitoring*, ACARP, Brisbane.

Elmouttie, M & Poropat, G 2015, *Monitoring Systems and Methods* (United States of America, Patent No. US10724861B2), United States Patent and Trademark Office.

Severin, J, Eberhardt, E, Leoni, L & Fortin, S 2014, ‘Development and application of a pseudo-3D pit slope displacement map derived from ground-based radar’, *Engineering Geology*, vol. 181, pp. 202–211.

Sharon, R & Eberhardt, E 2020, *Guidelines for Slope Performance Monitoring*, CSIRO Publishing, Clayton.