A conceptual technique to mathematically quantify the trajectory of flyrock

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Synopsis

Flyrock remains a significant threat to the health and safety of mine employees and integrity of infrastructure, as well as to the safety of the neighbouring communities and their property. This investigation was motivated by the general lack of fundamental research and mathematically quantifiable data in the literature regarding the relationship between blast design parameters and their impact on flyrock. The focus was to develop a concept that can be used to mathematically quantify the trajectory of flyrock resulting from a blast, which can be used for future research. The ultimate goal for this technique, once it has been fully developed, is to:

- ➤ **Enable mining operations to generate a database with accurate historical flyrock measurements resulting from their blasting operations**
- ➤ **Allow research teams to conduct scientific investigations into flyrock and the impact of various blast design parameters**
- ➤ **Generate point-cloud data to visualize blasts and flyrock in a virtual reality environment for training and education purposes.**

This paper summarizes a conceptual technique and preliminary fieldwork that was carried out to determine the technique's feasibility and motivate further development. The results show conclusively that a modified photogrammetric technique is capable of capturing flyrock data for further processing and analysis. The data acquisition procedure can, at this point, be used to meet the first aim of the project, namely to gather a field database of historical flyrock generation. Further development of the technique is ongoing and it is envisioned that the scientific-based technique will provide a method whereby future flyrock studies will be comparable and that assumptions will be limited.

Keywords

flyrock, prediction, trajectory, measurement, environmental blasting, blast analysis, blast damage.

Introduction and project background

Drilling and blasting of a rock mass remain essential phases in the production cycles of most mining operations and continue to be the preferred method of rock breaking in the South African mining industry. Rock fragments projected beyond the planned or expected throw distance are often a product of this almost instantaneous release of explosive energy required to fracture a rock mass to the desired fragmentation and yield the desired muckpile profile. These fragments are known as flyrock.

In the past, flyrock has seriously, and sometimes fatally, injured people in the vicinity of the blast and has, otherwise, caused substantial damage to mine assets such as equipment and infrastructure (Bajpayee *et al.*, 2003). Injury to mine employees as well as injury to residents, livestock, structures, and/or equipment in in surrounding communities can result in high penalties for the mine. These penalties may be legislative, financial, or reputational, or possibly a combination thereof.

An initial literature review concluded that existing predictive models may not be sufficient to constitute a global technique that can be considered during the blast design process (van der Walt and Spiteri, 2020). The multiple studies reviewed and analysed concluded that 'there are major research gaps into the phenomena of flyrock and that this concept is not well understood' (Raina, Murthy, and Soni, 2015). The biggest concern is the inconsistent parameters used in various prediction models and the estimated impact of these parameters on the model's output. Using the data presented by Raina, Murthy, and Soni (2015), the theoretically causative factors of flyrock are compared to the factors taken into account in the predictive models and equations (Figure 1).

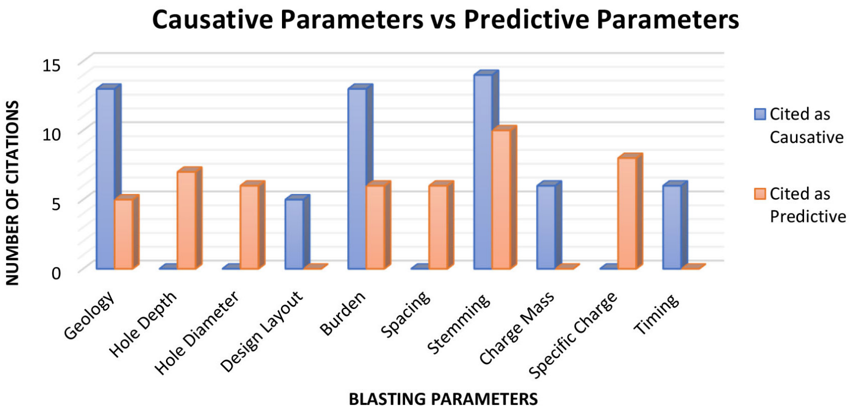

Figure 1—Flyrock causative parameters *versus* predictive parameters considered in existing prediction models (data from Raina, Murthy, and Soni, 2015)

As it stands, the effect of the causative factors on the travel distances of flyrock must be investigated, and this should be supported by actual quantitative field data that has been collected scientifically. Only once the effect of blast parameters on flyrock can be accurately determined and the relationship between flyrock and these parameters is incorporated into prediction models will it be possible to develop a new or revised model to increase the precision of the predicted flyrock distances calculated for different environments. The ideal would be to have one globally applicable flyrock prediction model where site-specific conditions can be compensated for through site-specific constants.

To successfully investigate the realistic effect of blast parameters on flyrock and develop such a globally applicable prediction model, a significantly large data-set is required which must be interpreted mathematically. However, during a literature review of recent work in the field of flyrock and flyrock prediction, no specific method of quantitatively measuring flyrock could be identified (van der Walt and Spiteri, 2020). For this reason, this study was aimed at investigating and developing a concept to mathematically quantify the trajectory (*i.e.* describe the flight path by means of an equation) of random flyrock fragments resulting from a surface blast and be able to calculate the final landing positions of the fragments relative to the blast as well as their positional origins on the bench. Once flyrock, its origins, and contributing factors can be accurately measured and mathematically quantified, it will be possible to develop a globally applicable predictive model for the international mining industry.

The purpose of this exercise is to gather data on individual fragments in mid-flight in an attempt to eliminate the need for launch velocity and launch angle as required in traditional ballistic equations. In other words, the mid-flight data (Δx, Δy, Δz, Δt) along with drag considerations will be used to calculate the trajectory equation for each fragment, which can then be used to calculate the origin (coordinate) and landing position (coordinate) of each fragment.

It is important to note that the proposed concept is not linked or limited to a specific technology (such as unmanned aerial vehicles or UAVs), thereforethe use of new and emerging technologies was not eliminated for future integration with the proposed technique.

Literature review

Several recent (*i.e.* since 2010) publications were identified that focused on flyrock and flyrock prediction. The authors of these publications proposed a variety of approaches and techniques that were used to either predict or investigate flyrock events. The approaches used to develop the various models can be grouped according to one of the following five categories:

1. Artificial neural network (ANN)
2. Adaptive neuro-fuzzy inference system (ANFIS)
3. Rock engineering system (RES)
4. Empirical and statistical analysis
5. Forensic or ballistics approach.

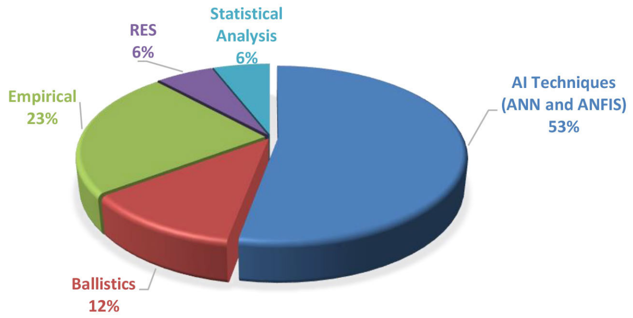

Figure 2—Approaches or techniques used in recent flyrock prediction studies (van der Walt and Spiteri, 2020)

The approaches or techniques implemented in the recent studies are summarized in Figure 2 and were comprehensively analysed by van der Walt and Spiteri (2020).

These various studies proposed viable models for predicting and analyszing flyrock based on presumed causative parameters as inputs and their estimated impact on flyrock as weights assigned to each input. However, all of these papers concluded that the respective models were site-specific and could not be applied to other environments (van der Walt and Spiteri, 2020).

Based on the analysis of these publications, the following conclusions were made (van der Walt and Spiteri, 2020):

Empirical and statistical approaches can only be used to produce site-specific models and cannot be implemented as universal solutions or models.

- Artificial Intelligence (AI) principles may be implemented in an attempt to minimize uncertainties; however, these models are highly dependent on the input parameters and the assumed relationship between these inputs and the desired output.

- The application of ballistics principles for flyrock prediction may not be ideal. However, using ballistics principles to analyse flyrock events presents exciting new opportunities.
- An investigation of the various parameters considered to be causative or most influential in the proposed models supports the argument that the flyrock causative blast parameters and their effect on flyrock distance are not fully known or understood.

The biggest knowledge gap seems to be the uncertainties associated with which blast and environmental parameters contribute to flyrock and to what degree (van der Walt and Spiteri, 2020). These uncertainties create the opportunity for developing new concepts or techniques for analysing the flyrock after it has been generated, rather than predicting it, to gain a better understanding of the factors leading up to actual flyrock events.

The techniques used to collect field data and measure the actual distance travelled by the flyrock fragments in these studies were found to be subjective and highly dependent on the judgement of the researcher. This implies that there is an opportunity for some degree of subjectivity that may influence the field data collected (van der Walt and Spiteri, 2020). Collecting and recording objective data is a critical component of any scientific investigation.

Since the results of the proposed models were evaluated by comparing the predicted and *measured* (or *actual*) data, some margin of error can be expected from the findings based on the transferred error from the testing methodology (van der Walt and Spiteri, 2020).

To present results that are objective and uncriticizable; an accurate, quantitative, and objective method of measuring the *actual* travel distance of flyrock is required. This conclusion emphasizes the need to investigate the potential for developing such a measuring technique that will yield unbiased field data, which can be used to evaluate the results from existing and future flyrock prediction models.

Potential techniques or technologies

Various techniques and technologies are available to monitor processes and measure performance or deterioration within the process. Since this investigation was aimed at developing a concept that can be used to mathematically quantify the trajectories of multiple 'random' flyrock pieces, it can be assumed that a non-contact technique would need to form the basis of the final model. The reason for this assumption is the inherent danger associated with blasting activities.

Initially, the use of drones was considered for recording pre- and post-blast survey data by flying over the blast area and scanning the topographical surface, either photographically or using LiDAR, in an attempt to identify new fragments on the ground. This would have been done by overlaying the point data generated from the image data or scans and identifying the topographical differences. Control points would have been placed within this area to ensure that the acquired data could be georeferenced.

However, some critical problems became apparent while exploring this option further:

➤ The blast area must be cleaned of all loose materials on the ground before the fly-over. This is not feasible at an operational mine.
➤ The blast area can be very large and would require the drone to fly at a high altitude to timeously acquire the necessary data. An increase in altitude will result in lower resolution scans or image data.
➤ Equipment cannot move within the area before the drone has completed the data acquisition, as this may result in loose rocks or material on the ground that was not a result of the blast.
➤ Highly vegetated areas within the blast area could result in missed rocks or targets within or below the vegetation.
➤ Finally, if successful, the data acquired with this technique could only be used to determine the final landing positions and overall travelling distances of rock fragments, *i.e.* including rolling distance. No other information can be deduced from the data.

The technique can still potentially produce useful data; however, it will not produce the data-sets required for this study and was not pursued further.

The following techniques were investigated further with the outcome of this study in mind:

- High-speed photography
- Photogrammetry;\
- Radar;
- LiDAR;
- ViDAR
- Other systems, including:
  - Hawk-eyeTM Innovations' ball tracking technology
  - Visual or optical detection and tracking
  - Active infrared systems.

These techniques were evaluated in a comparative analysis to identify which could form the optimal foundation for the development of the proposed technique.

Comparative analysis for technology selection

Each technique or technology was evaluated against the following criteria:

1) *Non-contact or remote method*

Due to the safety risk associated with blasting activities, the proposed method should be able to acquire data from a safe distance. Therefore, a non-contact or remote approach or sensor system is a necessity.

2) *Passive system*

The flight path and physical properties of flyrock are typically very random. Therefore, a passive system is essential to minimize the consequence of varying physical properties since a passive system records the existing, natural electromagnetic energy.

3) *Remote triggering*

Similar to the motivation for a non-contact system, initiating the proposed method should be possible from a safe distance. This means that the operator should not be required to be near the equipment.

4) *Multiple projectile detection*

Multiple fragments are thrown simultaneously from a blast, each with the potential of causing significant damage or harm. It is, therefore, essential that the proposed method is capable of recording the data from multiple fragments concurrently.

5) *Flexible system*

The proposed method should be flexible enough to easily adapt to the different topographies and layouts of mining operations.

6) *Independent of the physical properties of the target*

The physical properties of flyrock fragments are often unknown before the blast and cannot be accurately estimated or predicted. The system should, therefore, not be reliant on physical properties such as surface characteristics or reflectance.

Table I

Weighting matrix used to evaluate the trade-off criteria

Criterion	Rating				
	1	2	3	4	5
-Non-contact	Full contact is required	Contact is not required but advised for accurate data	Non-contact	Non-contact, short range (<50 m)	Non-contact, long range (>100 m)
Passive system	Active	N/A	N/A	N/A	Passive
Remote triggering possible	Not available	Remote triggering is not possible	Remote triggering is possible	Short-range triggering (<50 m) or continuous recording	Long-range triggering (>100 m)
Multiple projectile detection	Not possible	Unlikely	Neutral	Possible	Multiple projectiles can be detected
Flexibility	Not flexible	Less flexible	Neutral	Flexible	Very flexible
Independent of physical properties of target	Highly dependent	Dependent	Neutral	Fairly independent	Completely independent
Quantitative data	Not possible	Unlikely	N/A	Possible	Definitive

7) *Quantitative data*

The purpose of the study is to mathematically quantify the flight path of flyrock. Therefore, the proposed concept must include a technique for obtaining quantitative measurements from the acquired field data.

The different techniques and technologies were evaluated using a weighting assigned for each criterion. The detailed decision matrix is given in Table I.

Following the comparative analysis, the top three available technologies were identified as:

i. Photogrammetry
ii. ViDAR
iii. Optical detection and tracking.

Based on this analysis, it is apparent that a visual or optical approach is the best option to acquire flyrock flight data that can be analysed and quantified mathematically. An essential criterion is, therefore, to obtain quantitative data or measurements from the field data collected. Photogrammetry is a technology that has a well-established quantitative element is, and data processing using photogrammetry is also relatively manual compared to automated detection and tracking technologies. This is so as to enable the operator to measure and control any measurement or calculation errors throughout the process, and not only at the end of the process. The main drawback is that photogrammetry may not be very flexible in terms of commercially available software.

The purpose of this comparative study was to identify a technique or technology that can establish a foundation only. Photogrammetry was, therefore, chosen as the base technology that will, most likely, produce a successful outcome in terms of the objectives of this study.

Concept development

Photogrammetry integrates the data captured in multiple still images, taken in a stereo configuration, to represent or model the data as a stereo model (three-dimensional representation). This means that the environment captured in still images can be transformed into a three-dimensional environment, relative to the surveyed control points.

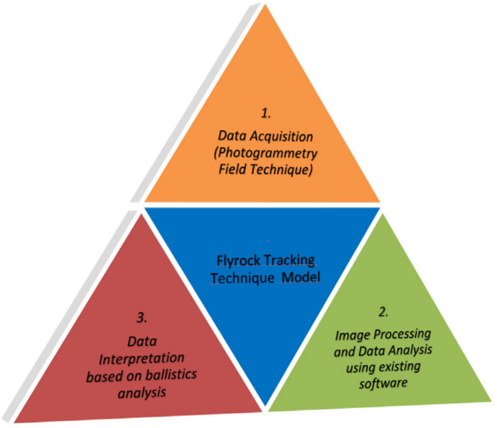

Figure 3—Concept model

Based on the previous studies, it was concluded that empirical approaches have generally not produced reliable prediction results and these prediction models were only applicable as site-specific solutions. However, the laws of physics and principles of ballistics remain true and relevant for objects moving through a medium. For this reason, a ballistic and projectile physics approach was determined to be the best in terms of mathematically quantifying the trajectory of flyrock (*i.e.* a projectile) based on the image data (field data) acquired.

The proposed concept model is given in Figure 3.

The model consists of three main components or phases and is designed to incorporate both photogrammetric techniques and ballistics principles.

Phase 1

The field data acquisition methodology was designed using a modified photogrammetric technique.

Traditional photogrammetry, specifically for mine surveying purposes, involves a series of overlapping high-quality images taken of a specific stationary structure, feature, or terrain. The sensor (camera) is, therefore, the mobile component moving over or around the target object or area to capture as many overlapping still images as necessary. By overlapping multiple images, the photogrammetric software is able to combine the image data and the surveyed control points in these images to create a three-dimensional representation of the target, from which specific measurements can be taken and the required calculations made.

Due to the environment and process of blasting on a mine site, this traditional photogrammetric approach is not possible. A modified photogrammetric approach was therefore developed and used. The main modification, in this case, was to essentially reverse the data acquisition process of traditional photogrammetry. Instead of moving a single mobile sensor over or around a stationary target, multiple stationary sensors (cameras) were used to capture and record an event in motion. However, to be able to use existing software and obtain reliable results from the process, the foundation principles and considerations of photogrammetry still had to be adhered to.

To maintain the accuracy of traditional photogrammetry, high-quality still images are required. Since a blast is an event of relatively short duration, high-speed video, commonly used to record and analyse blasts, was considered for acquiring field data. However, high-speed video footage cannot be converted into the required high-quality still images. According to photography experts, even a 4K HD video will only produce approximately 6 MP still images or frames. Consequently, it was decided that the necessary still images should be acquired using standard DSLR cameras, such as the 24.2 MP Canon 77D. The high-speed burst shot function in these cameras enables the maximum number of still images to be captured at the full quality available from the camera and lens.

Based on previous studies (Stojadinović, Pantović, and Žikić, 2011; Stojadinović *et al.*, 2013), it was estimated that fragments between 20 cm and 35 cm in diameter will likely travel the furthest. In essence, the authors argued that smaller fragments with a smaller cross-sectional area and higher velocities will experience a larger drag force and, due to their lower mass, will not be able to overcome these drag forces, limiting the total travel distance. Larger fragments, with more mass, have the potential to overcome the drag forces and travel further. However, lower travel velocities will also limit their travel distances (Stojadinović, Pantović, and Žikić, 2011).

Considering this size range (approximately the size of a frisbee) of the fragments that will (theoretically) travel the furthest, quality DSLR cameras are fully capable of capturing the level of detail (ground resolution) required from a safe distance (approximately 300 m). The ground resolution of the images refers to the clarity of specific features at a distance – at 300 m from the blast, standard DSLR camera images can yield a ground resolution of 3 cm per pixel. This further supports the decision to use standard and commercially available cameras for the development of this conceptual technique.

The critical components within phase 1 include the following.

Placement and orientation of the cameras in the field

Since photogrammetry forms the foundation of the field technique and existing photogrammetric software is used in phase 2, the specific camera orientation and placement required by the software should be adhered to so that the image data can be successfully processed. For this study, uSmart Softcopy software from the South African company SmartTech was selected and used for phase 2 of the process.

To use existing photogrammetric software in phase 2, the following field considerations are essential:

- Images must be taken in a landscape orientation, which also allows one to capture the maximum field of view (information) in each image.
- The software also requires that the images are taken parallel to one another, *i.e.* the angle of view of the lenses was adjusted to ensure the overlap required for stereo modelling.
- A decision was made to use a minimum of three cameras to acquire the necessary image data, using fixed focal length lenses. This is essential to minimize variabilities in the system.
- Finally, to georeference the acquired images, surveyed ground control points must be placed within the fields of view of the cameras.

Calibration of the cameras' lenses in the field

To accurately georeference the image data, is it essential to calibrate each lens to eliminate the influence of slight internal and external variables on the data-set. Even if identical cameras are used, manufacturing inherently results in minor internal differences in each camera. It is essential to calibrate each lens on-site before the blast to eliminate small errors that may be magnified in subsequent phases.

Traditional photogrammetry requires calibration images to be taken perpendicular to the target surface. The target surface, whether the surface of a structure, object, or topographical area, is customarily heterogeneous which enables optical recognition within existing photogrammetric software. Once the surface captured in the image data becomes more homogenous, the software struggles to create a reliable three-dimensional representation of the site. For this study and the application of the modified photogrammetric technique, it is essential to ensure that the acquired calibration data does not contain excessive homogenous backgrounds, such as blue sky.

Triggering the cameras from a safe distance

Existing photographic remote triggers, PocketWizard PlusX, were used to initiate each camera's high-speed burst shot function. These triggers offer the fastest communication between triggers with a maximum line-of-sight range of about 80 m, based on field tests conducted to verify the manufacturer's specifications.

To initiate the triggers from a safe distance, a communication system was required to simultaneously trigger the receivers connected to each camera from a single transmitter unit. An

Figure 4—Long-range trigger system designed for this study

expert communications company was commissioned to design and develop a long-distance trigger system using the PocketWizard PlusX triggers as its foundation.

The final product, shown in Figure 4, is capable of communicating with the receiving transmitter (or transceiver) at a line-of-sight distance of over 1 km.

Synchronization between cameras to ensure the images align in terms of their timing

The synchronization between the cameras, *i.e.* the point in time when each image is taken, is a critical element of this technique. The goal is to capture the movement of each flyrock fragment through the air by creating a stereo model of each time step in this motion. Therefore, the accuracy of the measurements taken from these stereo models will significantly depend on the exact time each camera triggers.

Various time studies were conducted to determine what the actual internal delays are between identical cameras separated by a distance of 5 m to 25 m. Screens were connected to a single source, a laptop that projected a stopwatch. Any delay in the projection was determined to be negligible. While the stopwatch was activated, the three cameras were triggered. The photographed times on each screen were analysed and compared to the other screens.

A maximum variation of 2 ms was recorded between the cameras. It is important to note that this variation is not consistent throughout the image acquisition process, *i.e.* the error is not cumulative. This 2 ms average error is insignificant at this point and can be minimized by averaging the positional measurements acquired from a combination of the stereo models (created by the multiple cameras) in phase 2.

Phase 2

The image processing and data analysis phase includes the identification of critical projectiles in the captured images and measuring the positions (*x*-, *y*-, and *z*-coordinates) at different points in time using photogrammetric software. The positional measurements are highly dependent on the on-site calibration of the cameras' lenses on the day of the blast.

Figure 5—Marked GCPs on a calibration image from a small-scale blast test, using Pix4D

The site calibration of the lenses was based on the calibration of aerial photogrammetry cameras. These principles were rotated to a horizontal perspective and applied to this study. Calibration is done by marking each ground control point (GCP) (shown in Figure 5) in every image and linking the GCPs to their surveyed coordinates in the software (Pix4D), shown by the yellow markers in Figure 5. The key output of this process is to determine the internal and external parameters and orientation of the cameras.

Once all the GCPs are marked and referenced to the relative coordinates, the software is allowed to process the data. During processing, the software uses the marked GCPs on each image and the surveyed coordinates to create tie-points between the images. These tie-points represent specific features that the software recognizes in different images, creating a relationship between the location where the image was taken, the specific feature in the image, and the known GCPs.

The creation of these tie-points will determine the accuracy of the point-data and three-dimensional representation of the scene. This will directly influence the error applicable when taking the positional (coordinate) measurements of the highlighted fragments or projectiles.

The process of obtaining these measurements has been tested using existing stereo mapping software. Initial concept tests proved that is it possible to obtain positional coordinates of a projectile travelling through the air. This process is being refined as part of ongoing development work.

Initial concept tests

A series of concept tests was conducted from 2018 to 2019. The initial tests were tightly controlled with only a single projectile (a clay pigeon) as the target object. The layout of these tests is illustrated in Figure 6.

The purpose of these simplified tests was to prove the concept of using a modified photogrammetric technique to gain reliable data that can be used in further trajectory calculations. The focus elements and desired and actual outcomes for the initial proof of concept tests are summarized in Table II.

For the controlled proof of concept tests, the positional measurements were simply obtained by marking the centre-point of a feature within each stereo model to measure its position. Measurements were taken from a stationary feature (in this case the top of a powerline pole in the background of the images) to give an estimate of the error within the stereo model.

Following the initial proof of concept tests, two small-scale blast tests were conducted at a local quarry to determine the flexibility of the data acquisition technique and its application on an operational mine site. The quarry tests were carried out to determine the following:

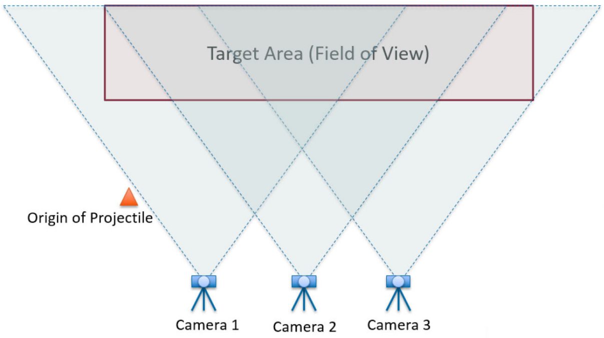

Figure 6—Initial proof of concept test set-up

Table II

The focus elements, and desired and actual outcomes for the initial proof of concept tests

	Main element	Desired outcome	Actual outcome
1	Evaluate the horizontal (rotated aerial) calibration technique.	Internal and external camera parameters before the blast or event can be determined with the Pix4D software.	The calibration data from the Pix4D software is exported in the form of external and internal camera parameters and summarized in a .csv file that can be imported into the stereo mapping software. The calibration process was successful but very time-consuming.
2	Generation of point-cloud data of the scene.	Sufficient point-cloud data of the environment can be generated using the calibration images.	A point cloud of the environment was successfully generated. This point cloud can be used for further data processing and interpretation, as well as potential visualization of the data in virtual reality.
3	Capturing a high-quality image of a moving object.	High-quality images without significant motion blur will allow clear and accurate measurements to be taken.	This was accomplished by using good quality cameras and lenses and applying photographic principles. However, these specific camera settings will vary with each environment and are therefore not presented as results.
4	Capturing a moving object in flight and visually tracking that object's motion in successive images.	Identifying and tracking the same object in successive images. The physical characteristics of the object will assist with this.	In the proof of concept tests, it was decided to only record the motion of a single projectile, in an attempt to simplify the test methodology and limit the potential variables. Future tests will involve the motion of multiple projectiles simultaneously.
5	Creating a stereo model of an object in motion from images taken from two separate cameras.	The point cloud of the scene based on the calibration data is combined with the event data ('blast' images) to create stereo models (two cameras per model) for each camera combination.	For the proof of concept tests, it was possible to create these stereo models in the mapping software (uSMART Softcopy) to within an accuracy of a couple of centimetres. To prove the concept, this error was considered to be acceptable; however, further testing and refining of the procedure will enable the reduction of this error to an acceptable margin for actual field application.
6	Obtaining positional measurements (x-, y-, and z-coordinates) using existing stereo mapping software.	Once the stereo models are successfully generated, the coordinates of a point within the images can be acquired.	Once the stereo model has successfully been created, measurement of any feature within this model can be acquired. This is simply done by marking the centre-point of a feature to measure its position or using the Softcopy software (similar to any CAD software) to measure the distance or the circumference of an object. The process of creating an accurate stereo model is still under investigation. Further testing and investigation of the improvement of the entire phase 2 process and its accuracy is ongoing.

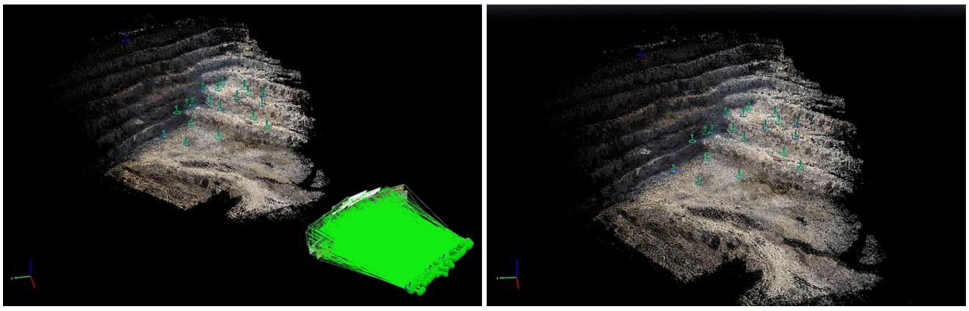

Figure 7—Point cloud generated from calibration images during a quarry test

- Whether the camera site calibrations were possible outside of a controlled environment
- Whether the cameras would capture flyrock in flight from an actual blast, considering the likelihood of a homogenous background that may increase the difficulty of visual detection of individual fragments
- Whether the synchronization between the cameras remains acceptable, *i.e.* all cameras captured the same point in time (within an acceptable tolerance).

Site calibration of the cameras at the quarry tests was done in the same way as in the controlled concept tests, *i.e.* by creating a point-cloud data-set of the site before or after the blast to determine the internal and external specifications of the cameras on the day. While taking these calibration images, special attention was given to exclude as much homogenous or 'blue sky' background as possible to facilitate the processing of these images. Figure 7 shows the point cloud generated from the calibration images, which was used to determine and export the camera specifications, which were used for the stereo model during the data analysis phase. This point-cloud data-set also forms the foundation of the VR models that can be created based on the data and analysis inherent in this technique.

Figure 8 shows that some fragments were successfully captured and could be visually identified and tracked in subsequent images taken by the cameras. This may not be ideal or the most efficient way of tracking these fragments, but it is sufficient for the purpose of proving the concept and motivating further research and development.

Figure 8—Quarry test blast image data, showing the same projectiles at different time intervals

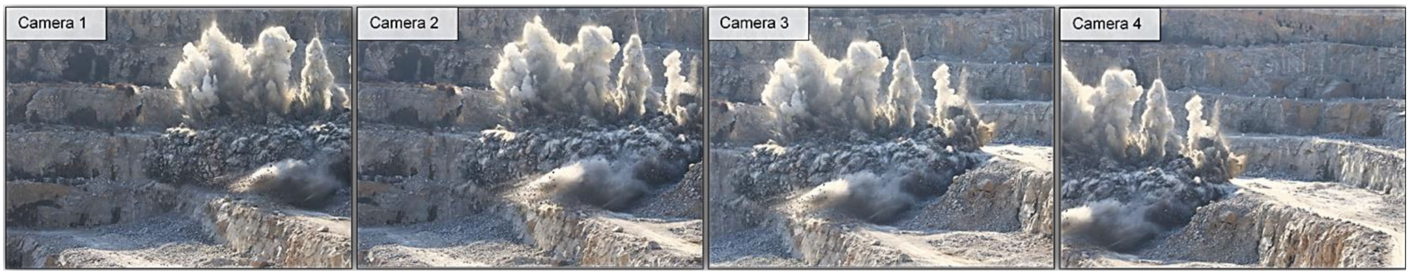

Figure 9—Quarry test blast image data, showing the synchronization between adjacent cameras

Figure 9 illustrates the synchronization between adjacent cameras actuated via the remote triggering system approximately 500 m from the cameras. By comparing the dust plumes from each image, it is evident that three of the four cameras (cameras 2, 3, and 4) are very closely aligned. Camera 1 seemed to have taken its image slightly earlier than the other cameras; however, the error produced by this can be reduced by averaging the measurements taken per stereo model (*i.e.* images of the same point in time taken by two adjacent cameras) for each point in time. If four cameras are used for a blast, a total of six stereo models can be created per point in time, from which positional measurements of key fragments can be taken.

Phase 3

The data interpretation phase consists of combining the data collected in phases 1 and 2 and incorporating it into existing ballistics equations. These equations are based on the principles of projectile physics and Newton's laws of motion, which remain valid for all moving objects.

The application of ballistics equations to the acquired positional data is an ongoing investigation. However, the significance of certain parameters within these equations that relate to specific circumstances or external factors is a key focus point.

To achieve accurate trajectory equations for the recorded fragments, it is essential to investigate the following:

- ➤ An accurate estimation of the drag coefficient of different rock types
- ➤ The effect of the shape of each rock type on its drag coefficient
- ➤ The effect of rotation or spin of the fragment on the drag force experienced.

Conclusion

The focus of this study was to develop a concept that can mathematically quantify the trajectory of flyrock from a blast, with the aim of enabling future researchers to mathematically quantify the impact of the different blast design parameters on the flyrock throw distance. After a comparative analysis of various technologies, it was decided to use photogrammetry as the foundation of the proposed technique. A modified version of traditional photogrammetry was required to fit the objective of the research.

The proposed technique consists of three main phases:

1. Data acquisition
2. Image processing and data analysis
3. Data interpretation.

Only the first phase was developed up to an implementable technique – phases 2 and 3 are conceptual only and work is ongoing to improve phase 2 to obtain accurate data to be used in phase 3.

The key outcomes of phase 1 are as follows.

- ➤ The positioning and orientation of the cameras relative to one another as well as the target area was determined using photogrammetric principles.
- ➤ The site calibration of the cameras is based on the calibration of aerial photogrammetry cameras, but the principles were rotated to a horizontal perspective for this study.
- ➤ A long-range remote trigger system was designed and manufactured to trigger the cameras from the same distance from the blast.
- ➤ The camera synchronization was found to be within acceptable ranges when using top-of-the-range triggers. Identical cameras were used to minimie this variance.

Phase 2 has been tested to the point of on-site calibration of the camera lenses and creation of point-cloud data of the environment before or after the 'blast'. Initial controlled proof-of-concept tests enabled the team to take reliable coordinate measurements of a moving projectile at different times.

To include the measurements from phase 2 in phase 3, some key variables need to be further investigated. These include the drag coefficient for each projectile (including the impact of size and shape) and the effect of the environment or weather.

The concept has been developed with the objective to record, measure, and calculate reliable trajectories for fragments thrown from a blast with few or no assumptions. Initial tests proved that this concept is capable of mathematically quantifying the motion of random projectiles that originated from a relatively unknown position. Further development of the technique is ongoing. In order to ensure that future studies on flyrock and its causative factors are based on scientific principles, it is envisaged that the technique would form a common thread between these studies – making the results comparable and limiting assumptions made in the field.

Recommendations and suggestions for further work

The ultimate goal is to develop this technique to the point where it can be used for three purposes.

- Mines will be able to generate a database containing accurate historical flyrock data (did they experience flyrock and how far did it travel?). This database can be used to assign clearance distances.
- The technique can be used to guide research into flyrock and the impact of different blast design parameters on flyrock, without the need to make assumptions that may alter field data or the interpretation thereof.
- Point-cloud data combined with ballistics calculations can be used to visualize blasts and flyrock in virtual reality environments for training and educational purposes.

The modified photogrammetric technique developed thus far can already be used to meet the first of these aims, namely data acquisition. Work on the aspects, challenges, and further development of the technique is under way.

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