IOSI PROJECT FINAL REPORT

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DISCLAIMERS

EXECUTIVE SUMMARY

In 2019, the Centre for Innovation and Research in Unmanned Systems (CIRUS) at SAIT participated in a study which investigated the use of Unmanned Aerial Systems (UAS) for mapping of active mine faces at Imperial Oil's Kearl mine. This project was instigated by Imperial Oil, who wished to investigate whether the use of UAS mapping could assist with mapping of mine face geology and interpretation of subsurface bitumen ore deposits.

The project was divided into two main phases. Phase 1 took place in the Spring of 2019, and was focused on reconnaissance and planning. During this time personnel from CIRUS visited the Kearl mine on three separate occasions. Site reconnaissance was carried out, all CIRUS personnel involved in the project received mandatory site orientations and safety certifications, project logistical requirements were determined, and working relationships were developed with key on-site Imperial personnel. During Phase 1 several UAS surveys were carried out over inactive sections of the mine, and the imagery captured from these surveys was used to generate a number of 3D models and to test different image acquisition strategies. Completion of Phase 1 meant that the CIRUS crew were ready to address the more complex challenge of surveying active mine faces.

Phase 2 was the operational phase of the project, which ran from the beginning of July to the end of October 2019. During this time CIRUS personnel made a total of six visits to the Kearl mine. During each of these visits, several surveys were carried out over active mine faces. Over the duration of Phase 2, image acquisition and processing of data collected became considerably more efficient, with surveys being carried out in half the original time, and processing and model generation taking place on site. Phase 2 culminated in a ten-day visit to Kearl in October, during which two CIRUS teams operated continuously and were able to carry out multiple data collections for actively-mined areas, under the guidance of the Imperial geoscience team.

Overall, the project was able to generate highly-detailed models of active mine faces at the Kearl mine. The ability to map ore deposits at centimetre-level resolution was found to be very useful by Imperial's Geoscience team, as was the ability to pan and zoom through an active model in 3D. Potential cost savings that could be achieved through reducing the amount of exploratory drilling required in advance of mining operations are significant, and provide justification for continued research in this area.

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1 INTRODUCTION

The Centre for Innovation and Research in Unmanned Systems (CIRUS) at SAIT is an NSERC-funded centre of excellence which focusses on the use of aerial and ground-based unmanned systems, and has a particular focus on the applications of Unmanned Aerial Systems (UASs). During 2019, CIRUS personnel worked closely with Imperial Oil on a project which investigated the use of UASs for 3D modelling and mapping of vertical mine faces at Imperial's Kearl mine, which is located approximately 50 km NE of Fort Mackay in northern Alberta. Imperial also wanted to know whether accurate mapping of active mine faces using UASs could be used to estimate the location of sub-surface bitumen ore ahead of the active mine face. This is currently done by obtaining a series of cores, spaced at 150 m intervals behind the mine face, a very expensive and time-consuming process.

The project began in early 2019, and from its initial stages was envisaged as being the first stage of a long-term collaboration between CIRUS and Imperial, aimed at introducing UASs into mine operations at Kearl in a variety of different roles. The work supported by IOSI in 2019 focused on 3D modelling and mapping of vertical mine faces, and was divided into two phases. Phase 1 ran from mid-April until the end of June 2019, and comprised three field visits, during which CIRUS staff were on site for a total of 13 days. This phase of the project was conceived as a reconnaissance and knowledge-gathering phase, and was designed to pave the way for operational data collection flights in Phase 2.

The broad goal for Phase 1 was to provide the CIRUS team with an introduction to the mine and to enable the development of Standard Operating Procedures (SOPs) to allow for UAS operation at Kearl. This phase of the project also included carrying out trial UAS surveys for inactive sections of the mine where operational risk could be minimized, as well as experimenting with different procedures for data acquisition and processing in order to work out efficient procedures for operational data collection during Phase 2.

The first reconnaissance visit took place in mid-April, when four CIRUS personnel spent three days on site establishing key contacts, becoming familiar with the mine layout, and assessing the scale of the challenge. Two more site visits took place over the course of Phase 1, in May and June, during which the majority of CIRUS staff involved in the project completed site orientation and safety training. During the second of these visits, several successful UAS flights were carried out in an inactive part of the mine. On return to Calgary, photos collected during these flights were processed to generate 3D terrain models of exposed vertical faces.

The goal of Phase 2 was to carry out regular data collection missions over active mine faces, using techniques developed during Phase 1. Phase 2 was designed to demonstrate that regular UAS surveys of active mine faces could be carried out safely and with minimal impact on mining operations. Phase 2 objectives included refining field and office procedures over time and producing a manual of procedures for UAS surveys at Kearl. A detailed list of objectives for both Phase 1 and Phase 2 is provided in the Background section of this report.

During Phase 2, it was decided that the team should carry out fewer, but longer field visits than originally planned in order to align with the ten-day rotation of Christopher Wall, the Imperial site minder for the CIRUS group. Six visits were made to Kearl, with an average separation of two weeks between visits. During this phase of the project, CIRUS staff were on site for 32 days, spread over six field visits between mid-July and the end of October 2019. The final visit occurred in the middle of October, after which all CIRUS equipment was packed up and shipped back to Calgary. During Phase 2, photographic surveys were carried out over a number of active mine faces on each visit, under a range of different weather conditions including bright sunshine, rain, and snow. All images collected were processed and used to generate 3D models of the different mine faces.

Training of Highly Qualified Personnel (HQP) was a key objective of the project. In total 17 CIRUS personnel were involved in the project, with a total of 219 person days spent on site between the two phases, excluding travel days. An additional 83 person days were spent in the development of optimal processing techniques, and in processing of the data collected on site. Of the people involved in the project, 12 were research assistants within CIRUS, of whom five were current or recently-graduated SAIT students. This project provided many training opportunities for these personnel, and the experience of working at a major oil sands production facility provided them with valuable skills which will help them to advance their future careers.

In terms of project results, the project can be considered a success. On each of the Phase 2 field visits, multiple imagery sets were collected, and 3D models were produced for several of the active mine faces. Over the course of several visits, different approaches to image collection were tested, before settling on the optimal approach for capturing detail on active mine faces. Image collection and data processing methodologies were therefore refined continuously over the course of the project. The project resulted in a series of highly-detailed 3D models, showing the changing mine faces over time. These models were critically analyzed by members of the Imperial Oil geoscience team and were found to have considerable potential for the mapping and prediction of ore deposits.

The project and the associated results provide validation of the use of UASs for the mapping of active mine faces. While the techniques involved were developed specifically for use at Kearl, there is no reason why these techniques cannot be adapted for general use by other oil sands operators. This project therefore has the potential to provide value to all oil sands operators, allowing them to model resources and develop more efficient extraction plans. It also aligns well with IOSI's extraction research theme, as the primary aim was to improve the efficiency of resource extraction through improved mapping of ore deposits.

2 BACKGROUND

The adoption of UAS technology is experiencing rapid growth across multiple industry sectors. A recent report by Goldman Sachs predicts that by the end of 2020, the global market opportunity for this technology will be worth 100 billion dollars[1]. Many companies were initially wary of this technology, but now that the UAS industry has become well established, they are seeing that a solid business case can be made for integrating UASs into their workflow. One area which offers considerable scope for UAS integration is in mining[2]. This industry has a disproportionately large number of tasks which are dirty, dangerous, and repetitive. UASs offer a potential means to reduce the number of such tasks, while also improving production efficiencies[3]. Canadian Mining Magazine identified three ways UASs are starting to change the mining industry: 1) allowing more reliable and frequent surveys; 2) providing improved data for making strategic decisions; and 3) improving safety and reducing risk.[4] To this can be added, provision of entirely new forms of data, which can lead to the development of new workflows and new data products.

After watching the growth of Unmanned Systems for a number of years, Imperial Oil made a strategic decision to trial the use of UASs in their Kearl mine. Since each mining operation is different, and since companies have their own operating conditions and safety procedures, implementation of a drone program cannot follow a cookie-cutter approach, but must be uniquely tailored to the specific conditions encountered at the mine. Imperial decided to start by implementing drones for basic tasks, and to gradually increase the complexity of the program over time. The complexity of operating in an active mine environment, while at the same time complying with all safety requirements imposed by Imperial, as well as regulatory requirements imposed by Transport Canada (TC) for UAS operations justify this incremental approach.

The IOSI-supported project at Imperial's Kearl mine involved carrying out repeat UAS surveys of several active mine faces over a number of months, with a view to providing Imperial's geologists with information to better interpret ore bodies, thereby helping them to make improved predictions of the position of the subsurface ore bed relative to the active mine face. Traditionally this has been done by drilling boreholes every 150 m behind the active face, which is an extremely time-consuming and expensive process. The project was designed to test whether repeat UAS surveys of the active mine face made it possible to generate multiple 3D models, thereby allowing both for improved estimation of the amount of ore extracted and improved predictions of the ore bed location.

The main challenges and gaps in knowledge associated with this project related to the size and the complexity of the Kearl mine site. Safety is an extremely high priority for Imperial, and risk mitigation was therefore a key element of the project. While small-scale UAS operations can be carried out relatively simply at many other sites, the scale of the Kearl site necessitates a higher level of organization. One of the key deliverables from the project was a manual of operational procedures for conducting UAS operations in the specific environment of the Kearl mine. Thus, while the techniques for UAS survey may be similar to those used in other environments, the key difference is that these techniques had to be customized for the unique operating and environmental conditions associated with the Kearl mine.

2.1 Detailed Objectives

The following are the detailed project objectives developed for Phase 1. These were drawn up by CIRUS personnel in consultation with Imperial, and were designed to ensure that all pieces were in place, prior to operational data collection during Phase 2.

- CIRUS personnel to make a preliminary site visit to assess facility, and to become familiar with safety and operational procedures.
- Development of working relationships with key Imperial personnel on site.
- Mobilization of survey crew personnel plus required equipment, and completion of all associated safety training and other considerations required to operate an appropriate UAS at the Kearl facility.
- Set up and operate the UAS at the mine site, demonstrating the functionality of the system, while staying away from the most active mine areas.
- Thoroughly test the capabilities of the system in the field.
- Test and analyze the functionality and efficacy of different UAS platforms and mission planning software to map the vertical face of the mine.
- Determine practicality and procedures required to operate the UAS around heavy equipment (i.e. timing, safety, etc.).
- Work with Imperial Oil geoscience & GIS personnel to provide a documented methodology for processing and interpreting the geological features using agreed upon software tools.
- Gather an initial data set based on a list of priorities to be developed by Imperial Oil Geoscience team.
- Familiarize the site personnel with UAS operational requirements, data acquisition protocols and quality assurance, and how these are applied.

For Phase 2, the objectives focused on operational data collection in active and high-traffic areas. The objectives were also aimed at continuous refinement of both field collection procedures and processing techniques throughout the lifespan of the project. Detailed Phase 2 objectives were as follows:

- Carry out a series of regular data collection missions over active mine faces over a four-month period between July and October 2019.
- Demonstrate practicality of application of UAS for mine surveys under a wide variety of weather conditions.
- Develop a time-sequenced dataset and animated quantitative model for geological interpretation.
- Develop processes for data management (i.e. post processing requirements, data storage, organization and access).
- Provide further recommendations on factors related to UAS operation and associated field operations on site.
- Demonstrate the value of the information gathered and investigate the utility of daily vs. weekly frequency for data gathering.
- Process the geospatial data, and deliver a series of digitized 3D geological models to Imperial's geoscience team.
- Integrate the 3D models of the mine into GIS platforms and algorithms in ERSI and some open source GIS platforms.
- Refine the processes further with the other project members and create a working manual describing the practical aspects of this project, to facilitate future projects.
- Provide training to site personnel for UAS operation and data acquisition.

3 DESCRIPTION OF WORK UNDERTAKEN

Rather than being experimental in nature, the project focus was on applied research, with the overall objective of demonstrating the feasibility of UAS technology for mapping and 3D modelling of ore deposits in an active mine environment. This also required that procedures conformed with Transport Canada regulations, as well as complying with safety requirements for operations on site by external contractors at Kearl. As such, the project emphasized the development of technical and operational procedures for mine face mapping in a complex operating environment, rather than scientific objectives.

The first phase of the project was designed around reconnaissance, developing familiarity with the mine environment at Kearl, and the development of preliminary methodologies for mapping of mine faces. The second phase focused on operational collection of data, with progressive refinement of data collection and data processing techniques over the project duration.

3.1 Equipment

For work carried out during 2019, all technical equipment was provided by CIRUS. Much of the work was carried out using DJI Phantom 4 Pro V2 UASs. The Phantom Series provides an easy to use, reliable solution but is limited to above-zero Celsius operation. The CIRUS team also used a DJI M210 RTK with a Zenmuse X4S camera. The M210 is a more robust, industrial-grade platform with a larger heated battery allowing it to fly in temperatures down to -20°C, winds gusting up to 12m/s and in light snow or drizzle. The M210, however, requires the use of an external camera (in this case the Zenmuse X4S), so the Phantom 4 was used where conditions allowed. The DJI Mavic 2 Pro was also tested on site but due to its size and camera type it is not the best suited machine for the task. The Mavic camera has a rolling shutter, which can cause distortion in the imagery, especially at higher speeds. Basic specifications of all UASs used in the project are provided in
Table 1 below:

Table 1 UAS platforms used during project

Platform	Takeoff Weight	Diagonal Distance	Max Flight (mins)	Max Wind (m/s)	Temperature Range (Celsius)	Operating Frequency
Mavic 2 Pro	907g	354 mm	31	10	-10 to +40	2.400-2.483 GHz and 5.725-5.850 GHz
Phantom 4 Pro V2	1375g	350 mm	30	10	0 to +40	2.400-2.483 GHz and 5.725-5.850 GHz
M210 RTK	6140g (max)	643 mm	33	12	-20 to +50	2.400-2.483 GHz and 5.725-5.850 GHz

One limitation imposed for work at Kearl is that the commonly-used 2.4 GHz frequency is restricted. While both the Phantom 4 and the M210 are able to work at 5.8 GHz, this frequency is also restricted at Kearl, although an exception was made for the CIRUS flight crews. The operating frequency of UAS platforms is an important consideration when working in the mine environment, and for future years, Imperial have requested that CIRUS make use of other UAS platforms which are able to operate on alternative frequencies, such as the Aeryon R60 and R70 series.

Work in 2019 was focused on carrying out photogrammetric surveys for mine mapping. This meant that most of the images at Kearl were acquired using the DJI Zenmuse X4S camera, which is designed for photogrammetric mapping. This camera is integrated into the Phantom 4 Pro V2 and was also used as an external add on camera for the DJI M210, RTK. The DJI Mavic 2 Pro contains a Hasselblad L1D-20c integrated camera. Details of the cameras used are included in Table 2 below.

All processing of imagery captured during the project was carried out using Pix4D. This software package was used to carry out photogrammetric processing of the raw imagery, in order to produce Digital Terrain Models (DTMs) and orthoimage mosaics, used as input for 3D modelling. Known positions of Ground Control Points (GCPs) were used to improve the accuracy of this process and to identify potential positional errors during the processing stage.

Table 2 Camera systems used during project

Camera	**Camera Sensor**	**Focal Length (35mm Equivalent)**	**Aperture**	**Lens FOV (degrees)**	**Image Size**	**Shutter**
Mavic 2 Pro	1" CMOS	28mm	f/2.8-f/11	77	5472 x 3648	Rolling/Electronic Shutter
Phantom 4 Pro V2	1" CMOS	24mm	f/2.8-f/11	84	3:2, 5472 x 3648 4:3, 4864 x 3648 16:9, 5472 x 3078	Mechanical Shutter
Zenmuse X4S	1" CMOS	24mm	f/2.8-f/11	84	3:2, 5472 x 3648 4:3, 4864 x 3648 16:9, 5472 x 3078	Mechanical Shutter

3.2 Phase 1

Phase 1 was designed to develop an understanding of Imperial's requirements at Kearl, and to test and develop potential approaches towards UAS operation and data collection at the mine. An initial reconnaissance visit was carried out by four members of the CIRUS team, who toured the mine site in April to determine the scope of the project and to assess practical and logistical challenges to meeting project objectives. During this visit, the CIRUS team were able to meet and coordinate with Christopher Wall, the Imperial site minder allocated to the project. The CIRUS team were also taken on a mine tour, during which they were able to assess the practical challenges involved in mapping active mine faces, as well as identifying lower activity areas which could potentially be used to undertake test flights and to experiment with various data acquisition techniques.

Following the reconnaissance visit, two site visits to Kearl were conducted in May and June. During the first of these visits, ten CIRUS personnel spent three days at the Kearl mine. This visit was primarily intended to acclimatise CIRUS team members to conditions at the mine, and to ensure that as many CIRUS personnel as possible were able to complete mandatory safety training and certification, prior to Phase 2 operations. During this visit, initial test flights were carried out in an inactive part of the mine, and several photographic datasets were collected of the vertical mine walls and surrounding areas. On return to Calgary, the images acquired of the mine were processed using Pix4D software, which was used to produce orthoimages and DTMs for the areas surveyed. These were then evaluated for image quality and accuracy.

For this visit most of the CIRUS personnel flew into site, but four of the CIRUS team members travelled to Kearl in the specially-converted CIRUS van, which is equipped as a mobile ground station, and which was used to carry the UASs and ancillary equipment to be used by the CIRUS team on site.

The final visit of Phase 1 took place in June and was much longer, with all team members spending seven days at Kearl. For this visit, eight CIRUS personnel were involved, with two additional members of the CIRUS team receiving site orientations and certification at this time. Once again, four team members travelled to site in the CIRUS van, to transport required equipment, and computer workstations for onsite data processing. The full record of site visits and personnel involved during Phase 1 is shown in Table 3 below.

Table 3 Project team days worked on site during Phase 1. Personnel driving to Kearl in the CIRUS van are shown in red.

Mission	Activity	SM	KW	RD	JS	WH	GW	AM	MA	FA	VS	MK	SA	SS	JF	SL	Person days			CIRUS Personnel List
Reconnaissance (15-17 April)	On site	3	3	3	3												12		SM	Shahab Moeini
																			KW	Ken Whitehead
Phase 1a fly /drive (21 - 26 May)	Travel	4						4	4	4							16		RD	Robert Davies
	Mobilization	1			1	1	1	1	1	1	1	1			1		10		JS	Jeff Samson
	On Site	3			3	3	3	3	3	3	3	3			3		30		WH	Wade Hawkins
Processing		2			2	2										2	8		GW	Gordon Wiebe
																			AM	Alireza Mardan
Phase 1b fly / drive (11-21 June)	Travel	4						4		4			4				16		MA	Mishal Arif
	Mobilization	1			1		1	1		1			1	1	1		8		FA	Fatima Auda
	On Site	7			7		7	7		7			7	7	7		56		VS	Vafa Sinaei
Processing		3			3	5										10	21		MK	Mehdi Khansari
																			SA	Sara Ashoori
Days on site		13	3	3	13	3	10	10	3	10	3	3	7	7	10		98		SS	Sepideh Safari
Travel days for van crew		8						8	4	8			4				32		JF	Janet Fleet
Processing days		5			5	7										12	29		SL	Stephanie Lapointe

The purpose of the June visit was to build on the lessons learned from the first visit, to test out different data image acquisition strategies, and to acquire multiple datasets in non-active portions of the mine. Once this was achieved and the team had acquired a high level of comfort in these areas, a test was conducted over an active mine face. This was successful, and it was found possible to create a 3D model of the active face, even while the shovel was working, and ore was being extracted. By capturing multiple images from different angles around the shovel as the shovel itself kept moving, any dead areas were avoided, allowing full 3D mapping of the mine face.

3.3 Phase 2

Phase 2 was conceived as the operational phase of the project. This phase was initially planned as a series of two- or three-day visits to be made on a weekly basis to Kearl by CIRUS flight crews, to capture weekly datasets from active mine faces throughout the summer of 2019. However, in order for visits to Kearl to align with Christopher Wall's 10-day rotation cycle, the plan for Phase 2 was modified to accommodate fewer, but longer visits by CIRUS crews. In total, six visits were made by CIRUS crews between July and October, with an average two-week separation between visits. The length and timing of each field visit, along with the people involved at each stage are shown in Table 4.

Table 4 Project team days worked on site during Phase 2. Personnel driving to Kearl in the CIRUS van are shown in red.

Mission	Activity	SM	JS	WH	GW	AM	MA	FA	SA	SS	SL	AB	OO	Person days
Phase 2a fly in (24 - 28 July)	Travel													
	Mobilization		1					1	1	1				4
	On Site		5					5	5	5				20
Processing			2	2							4			8
Phase 2b drive (15th August) - cancelled	Travel	1			1				1	1				4
	Mobilization	1			1				1	1				4
	On Site													
Phase 2c fly / drive (26 - 30 August)	Travel	4				4			4	4				16
	Mobilization	1			1	1			1	1	1			6
	On Site	3			3	3			3	3	3			18
Processing		2	2								4			8
Phase 2d fly in (4 - 7 September)	Travel													
	Mobilization		1					1				1	1	4
	On Site		4					4				4	4	16
Processing		2	2								4			8
Phase 2e fly in (19 - 21 September)	Travel													
	Mobilization				1	1				1				3
	On Site				3	3				3				9
Processing		2	2								4			8
Phase 2f fly in (26 - 28 September)	Travel													
	Mobilization							1	1			1	1	4
	On Site							3	3			3	3	12
Processing		2	2								4			8
Phase 2g(1) fly / drive (5 - 11 October)	Travel	3				2			3					8
	Mobilization	1				1			1	1	1		1	6
	On Site	1				6			1	6	3		6	23
Phase 2g(2) fly / drive (11 - 18 October)	Travel	3				3	3		3					12
	Mobilization	1			1	1	1		1		1	1		7
	On Site	1			4	1	1		1		3	7	5	23
Processing											7		7	14
Days on site		5	9		10	13	1	12	13	17	9	14	18	121
Travel days for van crew		11			1	9	3		11	5				40
Processing days		8	10	2							27		7	54

	CIRUS Personnel List
SM	Shahab Moeini
JS	Jeff Samson
WH	Wade Hawkins
GW	Gordon Wiebe
AM	Alireza Mardan
MA	Mishal Arif
FA	Fatima Auda
SA	Sara Ashoori
SS	Sepideh Safari
SL	Stephanie Lapointe
AB	Adam Batchelor
OO	Oladipupo Olatunbosun

During Phase 2, Imperial provided CIRUS with a mobile office at the Kearl mine. This meant that a computer workstation could be set up on site. On-site processing of images collected in the field provided rapid feedback to field crews and considerably improved the efficiency of data collection. The first Phase 2 visit took place in late July, when a crew of four CIRUS personnel were able to acquire imagery of several active mine faces. Another five visits were conducted after the initial visit, culminating in a ten-day visit during October, during which multiple surveys were carried out of several active mine faces, on a daily basis. During this visit the CIRUS van made two round-trip visits to Kearl to collect equipment from the CIRUS mobile office and return it to Calgary.

3.3.1 Data Acquisition

During Phase 1 and at the start of Phase 2, CIRUS crews collected both vertical and oblique imagery over mine faces. This was in line with best practices suggested by Pix4D for processing imagery for mapping of vertical features. However, this approach was found to be time consuming and inefficient both during the data collection phase, where two separate flights were required, and during the processing, where vertical and oblique imagery needed to be processed separately and combined at the end. During Phase 2, CIRUS started acquiring only oblique imagery, at a downward-pointing angle of 45° over the mine faces. This meant that imagery could be collected and processed much more efficiently than previously. Figure 1 shows an active mine survey in progress.

Figure 1 UAS survey of active mine face using a DJI M210.

The process developed by CIRUS is much faster than the original process used during Phase 1. First, a short flight was carried over the area to be mapped at a height of 120 m, using a minimal 60% overlap between the photos. The photos from this flight were then processed at low resolution in the field directly on an iPad tablet using DJI Ground Station Pro to produce a low-resolution orthophoto. This orthophoto was then used for flight planning. During flight planning, the position of the mine face, as mapped in the orthophoto was used to select the optimal flight lines for image collection. Image collection then took place with the camera pointing down at an oblique angle of 45°, with flight lines perpendicular to the general orientation of the mine face, and from a height of approximately 30 m above the top of the bench. Using this method, it was possible to gather high-quality imagery of the vertical mine face and complete processing in a fraction of the time it originally took. An example of a 3D model generated using this methodology is shown in Figure 2.

3.3.2 Processing

All processing for both phases of this project was carried out using Pix4D, which is a photogrammetric package designed to work effectively with images acquired from UASs. While processing sequences varied during the project, all jobs shared a similar workflow. Once a project had been created, the software created a preliminary alignment of all the images based on coordinates obtained from the onboard GPS of the UAS. At this stage, a preliminary triangulation and bundle-block adjustment was carried out, using common points found across multiple images. After the initial triangulation had been completed, GCP coordinates were entered into the package, and GCP positions were identified across all images on which they occurred. The triangulation process was then rerun, and a coarse point cloud created. The next step was to use point cloud densification to create a dense point cloud. At this point, textured surfaces, with a nominal resolution of one centimetre, and DTMs could then be generated for the mine face.

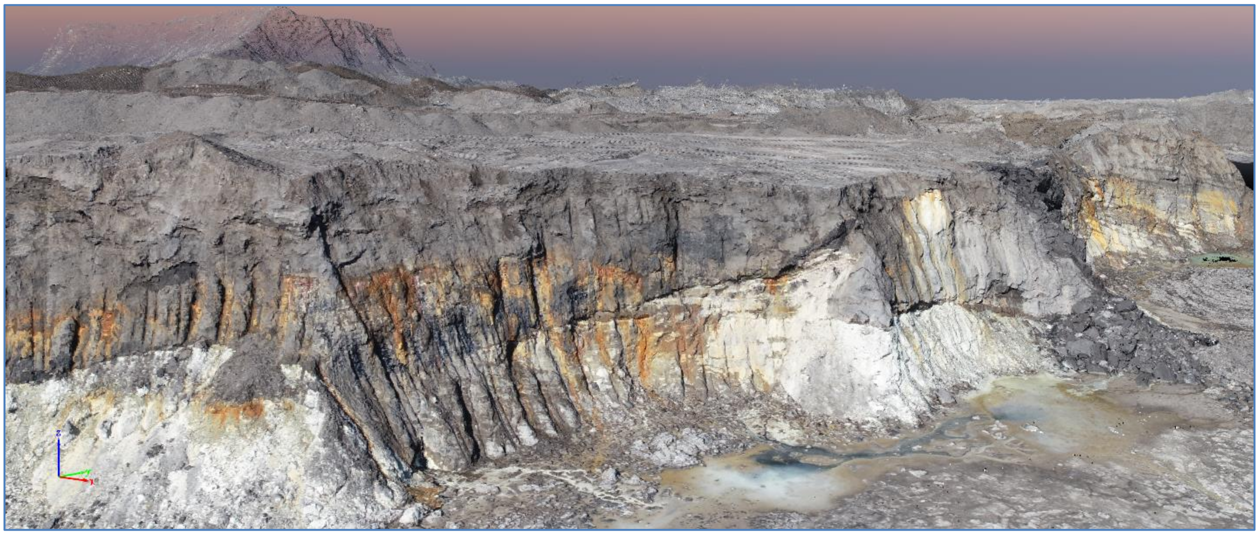

Figure 2 Example 3D model generated for an active mine face.

3.3.3 Accuracy and GCPs

For each of the Phase 2 surveys, Imperial's mine survey crew provided the CIRUS crew with a set of pre-surveyed GCPs within the area of interest. These were surveyed using RTK GPS, thus providing an extremely high level of relative accuracy (typically sub-centimetre). While the absolute accuracy of any surveyed points is dependent on the base station position and could potentially be out by several centimetres in X, Y, and Z, the relative accuracy is more important, as UAS surveys must match up with the mine coordinate system. An example of a pre-surveyed GCP is shown in Figure 3.

Figure 3 Example of a surveyed GCP

Typically, for each flight, five or six GCPs were provided. These were incorporated into the Pix4D processing to improve the accuracy of adjustment. Following processing, Pix4D provides an accuracy report.

Table 5 provides an example of a typical accuracy report for one of the Phase 2 surveys. It can be seen that in this case, the Root Mean Square (RMS) error in Z is of the order of a centimetre while

RMS X and Y errors are considerably lower. This is typical of the errors that were observed during Phase 2 surveys and shows that the 3D models produced from UAS surveys have a high level of relative accuracy.

Table 5 Sample error report from Pix4D for a Phase 2 survey with six GCPs.

Geolocation Details

Ground Control Points

GCP Name	Accuracy XY/Z [m]	Error X [m]	Error Y [m]	Error Z [m]	Projection Error [pixel]	Verified/Marked
3B (3D)	0.020/ 0.020	-0.000	-0.001	0.000	1.189	20 / 20
3C (3D)	0.020/ 0.020	0.003	-0.003	-0.010	1.265	25 / 25
1A (3D)	0.020/ 0.020	-0.003	0.002	0.009	0.286	21 / 21
1B (3D)	0.020/ 0.020	0.007	-0.004	-0.017	0.556	20 / 20
1C (3D)	0.020/ 0.020	0.000	-0.000	-0.007	0.517	17 / 17
1D (3D)	0.020/ 0.020	-0.002	0.003	0.011	0.275	27 / 27
Mean [m]		0.000971	-0.000505	-0.002236		
Sigma [m]		0.003443	0.002627	0.010139		
RMS Error [m]		0.003578	0.002675	0.010383		

Localisation accuracy per GCP and mean errors in the three coordinate directions. The last column counts the number of calibrated images where the GCP has been automatically verified vs. manually marked.

3.3.4 Data handling and dissemination

Due to the confidential nature of the data, all data sharing with Imperial team members took place via Imperial's internal Sharefile drive. Once data was collected from the UAV, the images were saved to an external hard drive and shared amongst CIRUS team members who needed to process it. Backup copies of the data were also stored on the CIRUS internal server and uploaded to Imperial's Sharefile in a folder designated for raw data, ensuring the raw data was backed up and remained unaltered. Once processing was complete, the finished Pix4D models (and all associated outputs) were also uploaded to both the CIRUS internal server and Imperial's Sharefile drive in a processed file folder. Once uploaded, Imperial's team was able to access the drive and download the files to their computers for viewing.

4 RESULTS

In line with the initial objectives outlined in the Background section above, each phase of the project produced different outcomes.

4.1 Phase 1 results

Phase 1 was concerned with introducing the CIRUS team to the mine environment at Kearl, including having staff complete mandatory safety orientations and obtain any required certifications. This phase was also designed to collect information on mine operation, and to identify any potential technical or operational impediments to UAS operation in the mine. Another important part of Phase 1 was the development of SOPs for operation in the mine environment, which could then be tested and refined during a series of pre-operational tests in low-activity areas of the mine.

All Phase 1 objectives were successfully met. By the end of this phase, 12 CIRUS personnel had completed safety orientations and had been certified to operate in the mine. The team were able to assess logistical and operational challenges and develop practical solutions. A system was developed for access to the mine under the supervision of Christopher Wall, the assigned Imperial minder to the team, who accompanied the team on all visits into the mine. Several test flights were completed, culminating in a successful test flight over an active mine face. Initial data processing procedures had been established using Pix4D, and these were being used to produce 3D models from flights conducted at the mine.

4.2 Phase 2 results

Phase 2 used the basic methodology and SOPs developed for Phase 1 to carry out operational mapping of active mine faces. Over the four-month duration of Phase 2, modifications were made to both field data collection and processing procedures, resulting in significantly faster turnaround of completed 3D models. At the start of Phase 2, approximately 500 m lengths of mine face were being mapped in 2-3 hours with travel and setup. By the end of Phase 2 more than 2 km of mine face was being mapped in the same time.

Two factors helped to drive these efficiencies. The first was changing SOPs, so that the flight crew started by conducting an initial flight for the collection of low-resolution imagery of the area to be mapped. This allowed for accurate flight planning to be carried out in the field, as opposed to using pre-planned flights, based on older data. Due to the rapidly changing state of the mine, even 12 hours can result in substantial changes to the position of the mine face. The initially-acquired aerial imagery was used for in-field flight planning, making it possible to create detailed flight plans that ensured good oblique imagery of the mine face at the time of image collection. Without the updated aerial imagery and in-field flight planning, significantly longer flight times would have been required to acquire imagery over larger areas than necessary, to ensure that changes due to mine advance were accounted for.

The second factor was the optimization of the angle, distance and amount of oblique imagery required to capture the detail on the near vertical mine face, further reducing flight times. Both of these efficiencies in data capture also resulted in reduced processing times as there was less extraneous data to process to produce the desired result.

By the end of Phase 2, multiple time-sequenced datasets had been created for several active mine faces. The survey team at Kearl were able to provide GCPs for each UAS survey, and these were used during the processing stage to ensure that 3D models, orthophotos, and DEMs maintained a consistently high standard of accuracy; typically better than one centimetre in X, Y, and Z.

A detailed analysis of some of the 3D models captured during Phase 2 was carried out by Janice Allen, a geologist with the Imperial team. She was impressed with the resolution and sharpness of the 3D mine face models, and was of the opinion that they would definitely be helpful in mapping ore deposits. Imperial is still undertaking a full analysis of all data collected during Phase 2 to assess whether the value proposition justifies initiation of a long-term UAS mine face mapping program.

5 DISCUSSION AND CONCLUSIONS

The full project, including the successful completion of both phases, is a model for the introduction of UAS into mine operations at a major oil sands operation. In this case, the involvement of CIRUS personnel and students also means that this project can be seen as a successful example of an industry / academic collaboration which provided considerable benefits for both parties. A total of 17 staff and students from CIRUS were exposed to operations at Kearl, and were able to contribute constructively to meeting the project outcomes.

The separation of the project into two distinct phases made considerable sense from an organizational standpoint, with Phase 1 being focused on familiarization with the mine environment, and the development of basic operating procedures in low-traffic areas of the mine. Having most of the CIRUS team participating in Phase 1 meant that mandatory orientations and certifications could be completed during the initial phases, thereby minimizing delays during the operational phase of the project.

Having access to low-traffic, previously-mined areas was also extremely useful from the standpoint of being able to develop operational procedures, while minimizing the risks involved with working close to active mine faces. The previously-mined areas provided a very similar environment to the active mine faces, and were extremely useful in helping to assess the challenges involved in UAS operations in the mine. Phase 1 provided the CIRUS team with the necessary knowledge to work safely and effectively in high-traffic areas.

During Phase 2, the focus was on operational data collection from active mine faces. In this case the priority was to keep the length of time that the team was in high-traffic areas to a minimum, and to keep crews small and flexible. This prompted the evolution of field data collection procedures over time, reducing the number of images collected during each survey and the overall flight times considerably, which in turn led to more rapid processing times.

Characterization of these operational parameters and development of revised SOPs provided an independent evaluation and understanding of the scope of work required to collect this type of geological information in the mine. This work provides foundational technical requirements and guidelines for commercial operation of UAS for operating and collecting survey and geolocation information within active mining operations.

Another factor which significantly contributed to the overall success of the project was the Imperial project team. Project manager Mark Dekaban, and technical advisor Dan Priestly, accompanied the CIRUS team on most visits to Kearl and provided guidance and support from Imperial's perspective. Christopher Wall, the site minder for the CIRUS team while at Kearl was able to coordinate logistics, arrange for a mobile office for the CIRUS team, and to arrange access and transportation into the mine itself. He was also able to arrange for the Imperial survey team to place GCPs in the area of interest prior to each UAS survey. Without their support, it would have been impossible to undertake this project.

5.1 Recommendations for Future Work

The project was successful in that it showed that regular mapping could be carried out for active mine faces using UASs, allowing a 3D time-sequenced model of mining activities to be built up for each face. Feedback received from Imperial also stressed the detail obtained from each survey, which provided geologists with a highly-effective tool for mapping of geological features at the time of the survey.

What is still to be established is whether the information provided from this project has value in predicting sub-surface ore distribution and concentrations in advance of an active face. The UAS surveys provide a highly detailed map of what has already been mined. However, in order to demonstrate substantial cost savings, it will be necessary to show that UAS mapping can significantly reduce the amount of exploratory drilling in advance of active mine faces, or that improved tracking of geological interfaces will improve extraction performance. This is still being investigated by Imperial's geoscience team. However, preliminary indications are that the unprecedentedly-high level of detail provided from UAS imagery can provide geologists with a valuable tool in the prediction of subsurface ore deposits.

Some features known to cause extraction issues, such as mud clasts, are very difficult to predict with drilling alone. It is hoped that with a larger data set of the quality demonstrated with this work, better predictive models could be established. While it is unlikely to eliminate the necessity for drilling entirely, there is a strong likelihood that the need for additional infill core sampling for complex regions can be reduced, and drilling locations can be optimized through the use of time-sequenced 3D models produced from UAS imagery.

For the future, it would be beneficial to continue carrying out UAS surveys on a regular basis, to establish a multi-year dataset of bitumen ore distribution for several active mine faces, which can be compared with predictive results obtained from core sampling in each case. By carrying this analysis out over an extended time period, the value of UAS imagery as a predictive tool can be established, and potential cost savings for widespread implementation can be estimated.

Mapping of ore deposits is just one of a number of potential applications for UAS. Plans for work to be carried out during 2020 include BVLOS testing and evaluation of survey accuracy over large distances using minimal ground control points. This would provide substantial reduction of safety risk for survey staff on site, by reducing their interaction with heavy haul vehicles and when working in remote areas. Wildlife survey and management with UAS will also be investigated to evaluate its effectiveness for conducting wildlife sweeps over large wooded areas.

6 ACKNOWLEDGEMENTS

CIRUS would like to thank the following people and organizations for their contributions to this project:

From Imperial, a number of people contributed to its success. Christopher Lin is the Team Lead for heavy oil mining research at Imperial. He was key to instigating the project, and setting up the initial meetings. Mark Dekaban was the project manager from Imperial and ensured that the project ran smoothly throughout. Dan Priestly was the Primary Technical point of contact, and provided invaluable assistance in the field and with travel arrangements for the CIRUS team. Christopher

Wall was the site minder for the CIRUS team at Kearl and was able to provide logistical support, transport the team in and out of the mine, arrange office facilities for the team, and liaise with other personnel at Kearl to ensure that the operation ran smoothly.

CIRUS would also like to acknowledge the support of the Institute for Oil Sands Innovation (IOSI) in funding the project during 2019. IOSI provided a total of $444,754 in support of the project, without which it would never have got off the ground. The work funded by IOSI in 2019 has also been key in establishing momentum towards the larger goal of introducing UASs into mining operations at Kearl.

7 REFERENCES

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APPENDIX: LIST OF PUBLICATIONS AND PATENT FILING/APPLICATION

This was an applied research project, and was not focused on scientific objectives. As such no papers have been submitted for inclusion in peer-reviewed journals. Information was disseminated via a video produced by SAIT describing the collaboration, which was posted to a number of social media channels. The video can be accessed at the following link:
https://www.youtube.com/watch?time_continue=6&v=Ib3gn5-Nv9Y&feature=emb_title

A joint presentation on the project was also given by Ken Whitehead from SAIT and Mark Dekaban from Imperial at the 2019 Flying High conference, organized by CIRUS and held on campus at SAIT on the 24th of September 2019.