Development of a Specialised UAV (Unmanned Aerial Vehicle) for Remote Coal Mine Exploration

By Stephen Tonegato –State Operations Manager NSW Mines Rescue – Australia

Introduction

This provides an update on the research project regarding the development of a specialised Unmanned Aerial Vehicle (UAV) for Mines Rescue deep penetration exploration post explosion. An early stage report was provided in Germany in 2015.

All current UAVs are designed to fly in a surface environment. Hence they are designed to operate in an atmosphere, that whilst it may have varying wind speeds, and where the pilot relies on direct visual contact or on a visual feed from a UAV mounted camera, with little impedance to transmission of two way communications, or where the flight path can be programmed utilizing spatial coordinates that the UAV can self-reference from orbiting satellites.

Developing a UAV that is designed for use in an underground coal mining environment, with associated obstacles and varying wind velocities and where direct visual observation is not possible, signal propagation from an onboard camera is severely limited and with no spatial coordinates, is extremely difficult.

NSW Mines Rescue, using funding from the NSW coal industry, embarked in 2014, on developing a UAV ('quad-copter' or drone), suitable for use in hostile underground environments. The technology aiming to have the ability to search multiple mine roadways, not only in the horizontal plane but also vertically, by having the ability to navigate ventilation shafts giving the rescue team full three dimensional remote search capabilities.

Acknowledgements

Mines Rescue wishes to acknowledge the research and development delivered in this project by the 2 contributing organizations and individuals:

<u>Paul Martin</u>
Manager - Chief Pilot Australia
Aerial Photography Specialists (APS)
ApplusRTD

<u>Kumudu Munasinghe PhD</u>
Assistant Professor in Network Engineering
Faculty of Education Science Technology and Mathematics
The University of Canberra (UOC)

Benefit

The primary benefit of this development is to increase the industry's ability to effectively manage an emergency in underground coal mines via the deployment of a "Self Aware" Unmanned Aerial Vehicle (UAV).

Such a UAV overcomes the current industry limitations regarding the adequacy, resilience and effectiveness of current post explosion data gathering, communication devices and systems. Having the capability of entering a mine to determine atmospheric conditions and searching for survivors, without the traditional distance and environmental barriers to active Mines Rescue teams, needs to become a viable option.

A fit for purpose UAV would have enabled exploration of the post explosion environment at Pike River). The human and financial cost from Pike River has been massive and is ongoing, with other mines and miners likely face similar situations. There are many examples both in Australia and overseas where the deployment of such a UAV would have major tangible benefits, for e.g. Sago, Blakefield South, and Moura.

Summary
The project was completed successfully in delivering a flying UAV platform capable of traversing down a mine roadway regardless of the condition of the terrain on the floor of the mine (avoiding the problems that ground-based robots encounter when a mine roadway collapses), being piloted remotely by an operator external to the mine utilising a live video feed in real time with the capability to monitor, record and relay gas levels alongside visual and thermal images.

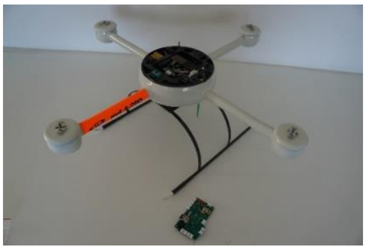
Underground flights were carried out at Wollongong's Coal's Russell Vale Mine with the UAV being flown remotely over 170 metres on the 30th of March 2017. It was able to do this via the transmission of live video and flight control commands transmitted over a wireless mesh node network.

Development History
The project was successful by the individual development of 2 separate components whch were then integrated into one platform, which was in itself quite challenging.
The UAV Platform was developed by APS, whilst the Communication nodes and associated integration was developed by UOC.

UAV development was managed in a number of stages:

1. *Construction of the platform, and build of equipment*

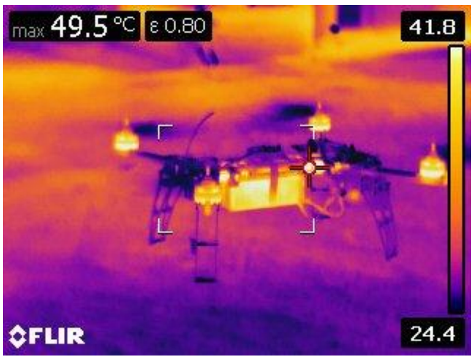
2. *Assessment alternate UAV designs*



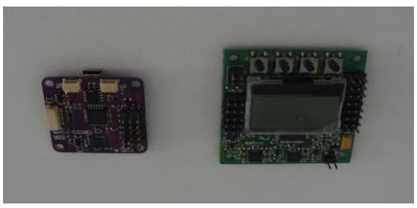
Tested were the alternate options of low rpm and low eight and assessment to determine if this design resulting in reduction in downwash and air turbulence would improve stability and reduce airborne particles / vision loss.

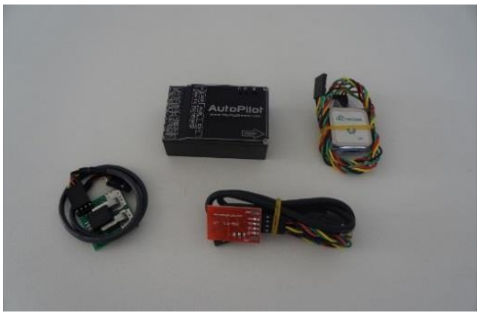
3. *Thermal testing*

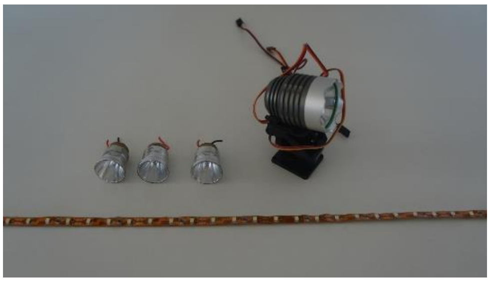
A series of prolonged flights of over 30 minutes were performed to test the thermal capacity of different motor controllers and motors. This allowed selection of electronics that are capable of running only a few degrees above ambiant air temprature as they are running at about 25 % of their full power capacity.



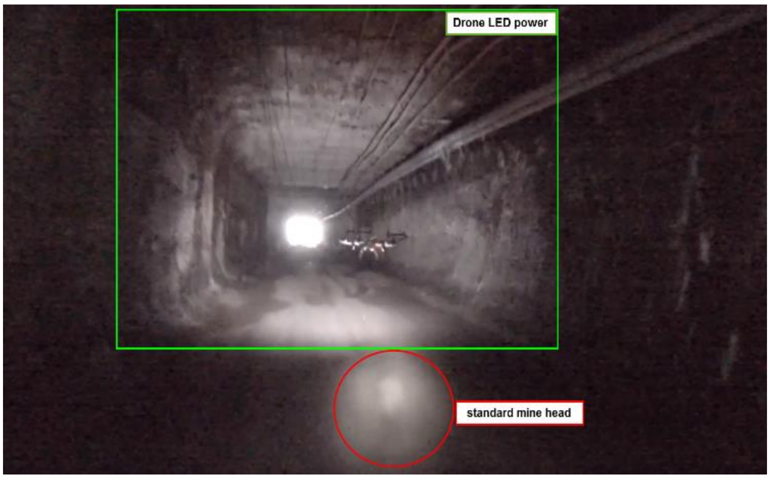
4. *Individual Component testing*







Many different flight controllers and sensors were tested to see what was the most suitable. Many different LED lights and ways of distributing the light were tested. We were able to produce about 1000 % more light than a standard head torch for only 36 grams of LEDs.

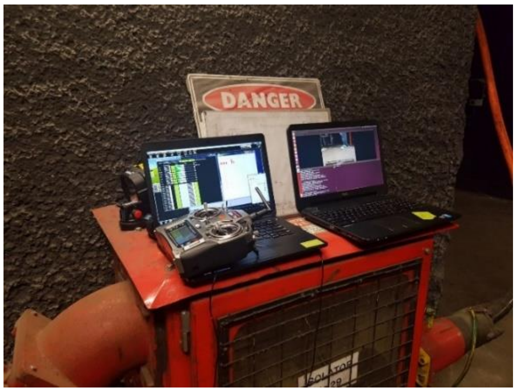


5. <u>Underground flight testing at SMRS March 18, 2015</u>

In this trial APS used its own dedicated video transmitter and receiver system that had only 50 milliseconds of video feed delays. We were able to demonstrate how a skilled pilot could easily fly through the mine with total ease and navigate with great precision.

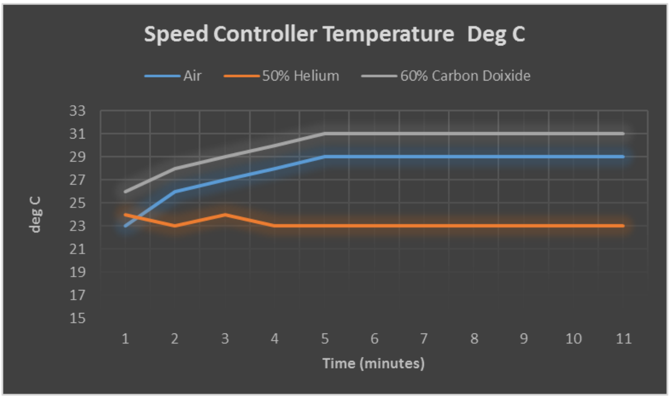
6. *Control testing*

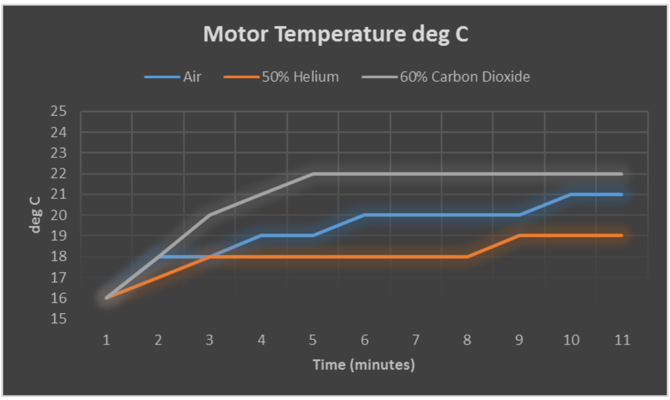
Initial control testing was done on a remote control buggy at the Mine Simulator as it is a much safer way to test and iron out the bugs in the software before trying to fly the UAV system.



7. *Temperature characteristics in alternate atmospheres*

A 1 metre cubed sealed chamber was built to test both temperature characteristics and thermal properties of the UAV in alternate atmospheres. Testing of the developed UAV in this box was limited to temperatures of speed controller and motors components. It was determined that due to the oversized motors and controllers the system generated very little heat whilst operating. This is important for prolonged flights. All components passed well below their 100 degree thermal capacity.





8. *Bump protection system*

The physical bump protection system on this system was very rudimentary but effective enough to sustain mulitiple impacts into the wall and ground. It wasn't designed to be crash proof.

9. <u>Flying ability in alternate atmospheres</u>

Flying alternate UAV in a 1 m sealed box at SMRS

Results

<u>Test 1;</u> Air density 1.0 Take off: 60% of full rpm
<u>Test 2:</u> High Density 1.41 (75 % Co2) Take off: 55% of full rpm
<u>Test 3:</u> Low Density 0.57 (50% Helium) Take off: **Unable** to lift off at 100% of full rpm

Testing of the UAV in alternate atmospheres proved challenging due to the size of the test "box" (1 metre cubed) and the inability of the developed UAV to "fly" in such a confined area. In order to be able to lift off in the small box a much smaller UAV was utilised with different flying characteristics. This had an effect as the UAV that was tested had a significantly less power to weight ratio than the specifically developed UAV.

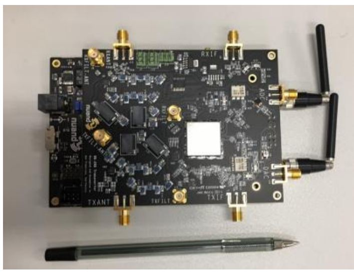
Of most interest was its inability to lift off in very low density atmospheres (0.57), approximating that of to 100% Methane. This needs to be considered in any future development as post explosive atmospheres are variable, generally with high methane levels (although extremely unlikely to be at 100%)

Communication node development was a major challenge in this development as traditional electromagnetic communications operating under harsh underground conditions encounter major performance issues:
- High levels of signal attenuation
- High path loss
- High bit error rates
- Multi path fading

Commercially available technology does not meets the unique requirements of size, weight, and performance in a cost effective form that provides a capable communications platform to operate a UAV underground.
Additionally no one up to this time has been able to effectively stream “real time” video of frame rates greater than 1 per second over a node mesh Wi-Fi system.
The project focused on the development of a wireless network as a proof-of-concept communications platform for operating a UAV in a coalmine environment with the following key features:
- Battery powered, light weight
- On-the-fly deployment and configuration (self-configuring)
- Highly resilient (self-healing)
- High bandwidth (video transmission capability)
- No interference with other equipment in mines
- Heterogeneous – Capable of interworking with existing underground communications systems

Three different types of systems were considered, developed and trialled, proving to be the most onerous, difficult and time consuming part of the project as each system was sequentially developed and tested in Canberra, then tested at Woonona and then tested for integration with a remote control system. The final working solution was only being made possible by latest release of the latest Wi-Fi technology found in the latest iPhone technology.

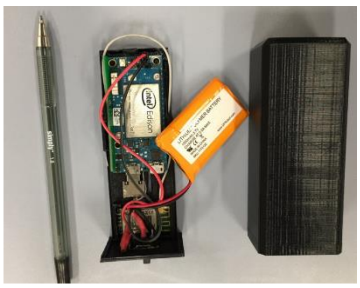
Staged development was as follows:
Stage 1: The Blade RF
This was the 1st system trialled and had the following properties:



- Software Defined Radio
- Heterogeneous – Wi-Fi, ZigBee, Bluetooth
- Prototype
- Large,
- Non IS
- Non meshing

This was found not to be suitable for the project and discounted in late 2015.

Stage 2: The Intel Edison
This was the 2nd system tested and had the following properties:



- Mesh routing
- Heterogeneous – Dual band Wi-Fi, Bluetooth
- Low data rates – sensor data, UAV control, VoIP
- No video

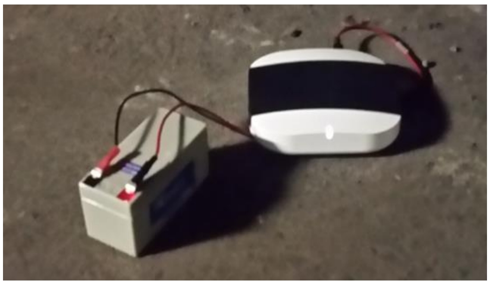
- 52 g (with battery)
- 48 hour battery life
- Non IS

Whilst this is an extremely good product for VOIP (Voice over Internet Protocol) and indeed offers tremendous possibilities for wireless Mines Rescue communications, it was found to be inadequate for video transmission.
It was discounted as an option in July 2016 following a trial at Southern Mines Rescue Station (SMRS) Woonona, in which whilst a network was established it was extremely poor at transmitting moving video once line of sight was lost resulting in experiencing extended lag.
In summary it was felt that a self-healing mesh system may not be suitable for video transmission due to system programming whereby it is always looking for a signal (this leads to a drop out of video signal). Most importantly the Intel Edison and associated software (BATMAND) platform is not capable of delivering a video stream with suitable quality to enable the remote flying of a UAV in a mine.

Stage 3: Next Generation Mesh
Development of this system commenced in August 2016, with the 1st test at SMRS conducted in October 2016 showing significant potential.
It has the following properties:

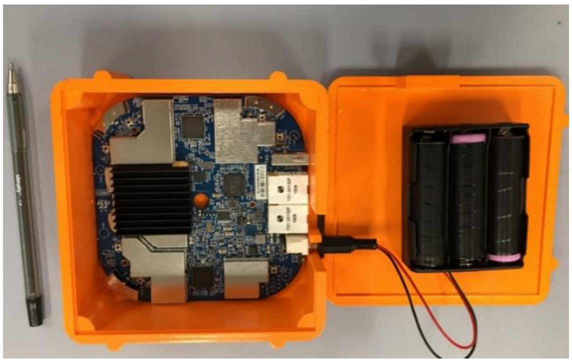
- True Mesh routing technology
- Seamless handoffs – based on Wi Fi network roaming with 802.11 k/v/r
- High data rates – Gigabytes per second range
- Real-time Video
- MIMO with Beam Forming
- Non IS

The photos below show the development of the concept



1st node design for test in October 2016

2nd node design as used at Russell Vale for final testing in March 2017 (note: positioned on top of a bucket, has independent large battery pack underneath node, and blue CSE pouch adjacent to node positioned to give perspective)



3rd node design – untested at this time, inbuilt battery, total weight of 240 grams

Testing and Integration

Whilst individual components were independently developed, effective combined trialling and testing was required to develop a successful final product. Successful communication node testing carried out at the University of Canberra in laboratories and hallways usually proved unsuccessful at the numerous tests carried out at Woonona in the Mine Simulator, which more closely replicated loss of signal strength in a mine.

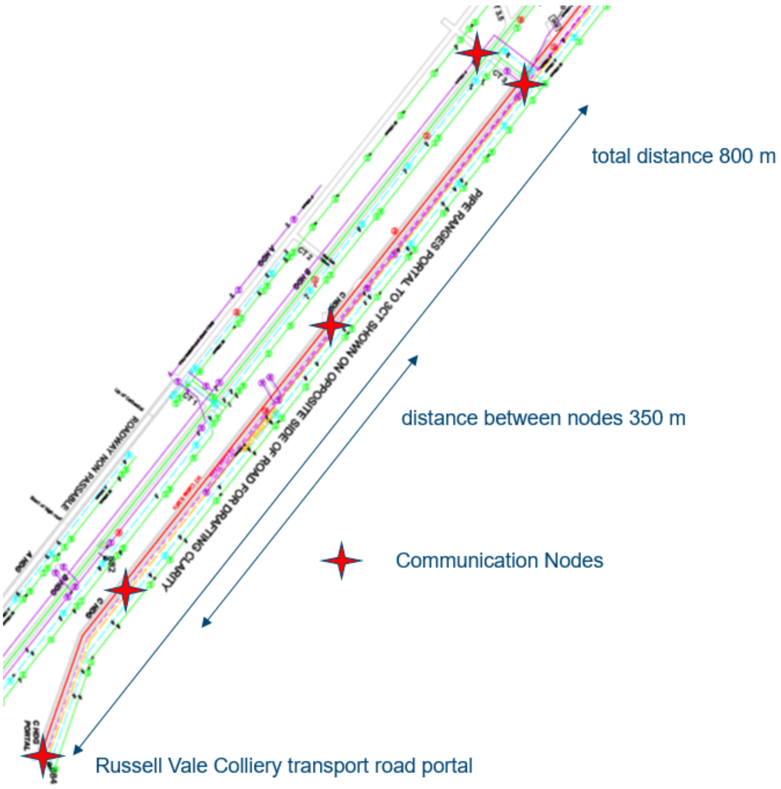
Integration and transmission of UAV control commands proved challenging with many options available and needing testing and verification. The development and integration of communication nodes was especially difficult with 3 iterations required prior to developing the current product.

The culmination of the UAV development is summarised by the testing summarised below:

1. Node design at Russell Vale on 13 March, 2017

The ability of the nodes to mesh, and transmit video and remote control (RC) control signals were successfully demonstrated on 13 March at Russell Vale mine.

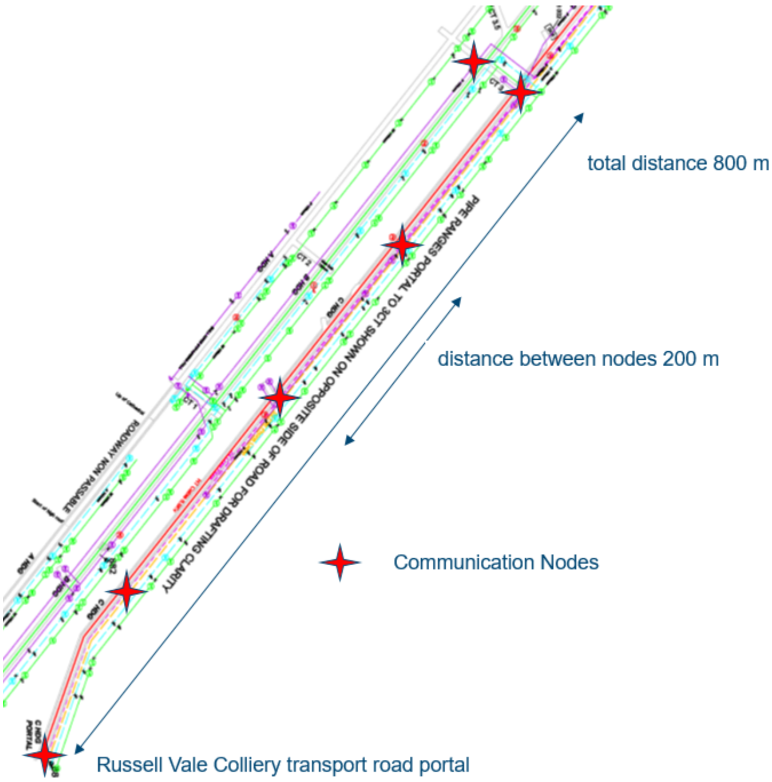
The communication nodes were laid out as per the attached diagram, after which a camera mounted on a remote controlled "vehicle" was "walked" in with the video recorded and the operator activating vehicle actions via a remote control system from the mines surface control room.



The diagram above shows node spacing and penetration into the mine.

Video streaming was overall very good with only a few momentary small breaks in constant streaming (some small pauses of normally only a few seconds but with several up to a maximum of 10 seconds when nearing maximum penetration) and the observed successful response of the "vehicle" to surface initiated controls.. Video streaming "breaks" were attributed to the distance between some of the nodes, up to 350 metres.
This test was successful in that video signals were relayed with minimal signal breakdown between the most in bye node and the laptop on the surface, and the successful transmission of RC control signals from the surface to the most in bye node.

2. <u>Node and UAV integration at Russell Vale on 30 March, 2017</u>
The nodes were laid out as per the previous testing on the 13th, but with the addition of an extra node in order to maintain a node distance of approx. 200 metres (recommended as optimum distance).
The "controlling" laptop was set up on the surface, in contact with the 1st node, positioned immediately outside the control room, then nodes were laid out sequentially in the mine (each additional node was positioned only after the previous node successfully meshed into the network).

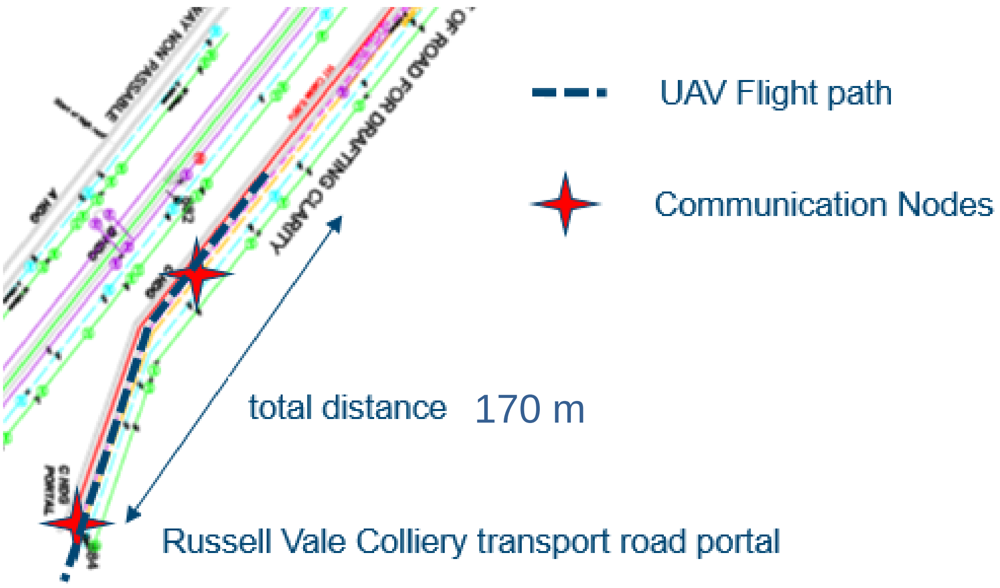


Unfortunately whilst the system to the 3rd node appeared very healthy it proved practically impossible to maintain a high quality consistent signal in bye of this point with a reason not evident, hence the UAV was not flown along this route. Subsequent investigations appear to show that the battery voltage in the 4th node were significantly lower than ideal thereby detrimentally affecting signal strength.
Ultimately a consistent network was formed though via 3 nodes: on the surface, inside the portal, and 130 meters in bye the portal and utilised to undertake a number of short flights.
An initial 50 metre flight took place from the portal in bye, where the effect of a 3 metres/second ventilation stream behind the UAV was found to detrimentally affect the ease with which the UAV could be controlled. Whilst previous testing found that the UAV's ability to "stir" up stone

dust was found to be negligible there were instances when the UAV stirred up some dust clouds affecting pilot vision. This could be a factor in post explosion environments.
A secondary test took place where the UAV was positioned 170 metres in the mine and was successfully flown out of the mine against the ventilation. The UAV proved easier to pilot and the mesh network was 100% reliable with no signal drop out during the flight.
This project demonstrated that a pilot cannot successfully fly a UAV remotely for any length of time utilising only video signals due to the time "lag" on signal (i.e. the length of time behind "real time" that the pilot is seeing the video footage transmitted by the UAV). As a result the pilot is reacting to changes in the environment that have occurred after he actually sees them, an analogy is driving a car remotely around a corner, where the pilot can see the corner and turns the car, but by the time he directs the car to turn the car has driven straight off the road. The delay achieved during this project of approximately 300 milliseconds with an additional 12 milliseconds for every additional engaged node whilst unprecedented and truly excellent makes it practically impossible for any pilot to successfully manage flying the UAV for any length of time in an underground environment.

Key learnings from this test included:

- Video streaming and UAV control commands are able to be successfully streamed over a wireless Wi-Fi mesh network
- An experienced UAV pilot can successfully remotely pilot a UAV in an underground coal mine
- Mine ventilation airflow does affect the flying characteristics of a UAV: flying inbye significantly increased the velocity of the UAV, hence increasing the response timing required of the pilot and thus the degree of difficulty, flying outbye proved easier as the "stance" of the UAV was less aggressive and thus more easily controlled.



3. <u>Node and UAV integration at Russell Vale on 31 March, 2017</u>

The final testing of the UAV was carried out on the 31st of March at Russell Vale mine.
The nodes were established early, and at what was believed to have been an appropriate spacing (approx. 200 metres) with good signal established in the 1st instance.
Unfortunately when the test was actually carried out, some 4 hours later a consistent signal could not be achieved.
The UAV was nonetheless physically carried to approx. 250 meters into the mine with the plan being for the pilot to remotely fly it out of the mine utilising the node network and live video streaming. The pilot remotely activated the UAV achieving lift off and stabilisation before the signal was lost and the UAV crashed.

Once again the pilot was able to successfully pilot the UAV remotely, with video and UAV commands over a mesh network, but was unable to fly the UAV out of the mine due to a failure in the mesh network.
Key thoughts from this experiment is how to "proof" the UAV against signal loss. This is practically impossible in a UAV that only responds to remote commands in an underground environment (with ventilation flow and surrounded by hazards) as the command to simply "hover" entails maintaining a certain amount of rpms the pre-set level of which cannot be known for a ventilation flow that is variable. The alternative being to maintain its previous command, which is fraught with risk as that command was issued based on a real time lag of at least 300 milliseconds, and flying a UAV entails a continuous stream of commands.

4. <u>Node signal quality at Russell Vale on 21 April, 2017</u>
The purpose of this testing was to prove that a strong and consistent video signal over the node network could be established and maintained.
All node battery packs were fully charged prior to deployment with an initial strong signal established upon underground deployment at an approximate spacing of 200 metres.
Unfortunately a strong signal could not be maintained with fluctuating signal strength observed on all nodes except the node immediately at the mine portal.
This eliminated deteriorating battery voltage which was thought to bethe cause of signal failure at the final demonstration on the 31st of March.
The fact that signal inconsistency occurs over the node network is unquestionable with this noticed on three separate occasions.
The cause of this inconsistency is unknown but could be attributable to a number of factors including the heterogeneous nature of the network (rather than sequential node programming), or the nature of the equipment used (as equipment is rather quickly superseded the equipment we used was not the more optimal currently available models).
Whilst further testing of the system, components, and effects of an underground environment on signal propagation are warranted it is felt that future natural improvements in both equipment and capacity of the specific Wi-Fi protocols used in this system will naturally improve the ability of the system to deliver a product suitable for UAV deployment.

Achievements
The table below reports achievements against project targets (2014):

Target	Achieved status	Comments
1 Km Range	At the underground test conducted 30 March 2017 an observed average velocity of approx. 2.5 metres/sec heading out bye (against ventilation and over a 150 metre distance) was observed. This equates to an average velocity of 9 Km/h	Based on tested battery duration of 120 minutes, a range of at least 10 km appears easily achievable
Bump proof	The UAV was fitted with rudimentary bump protection which proved to be effective at testing performed on 30th of March when it struck the mine roof as well as the floor and adjacent roadway material	Significant improvements in design are possible as demonstrated in a UAV specifically designed and used for applications in tight environments with protruding hazards

Communications – deploy own Wi-Fi network	Mesh nodes in current format could not be deployed by the UAV	UOC believes they have designed small IS nodes that are UAV deployable. Considering that in post explosion environments the vast majority of roadway travel will be in non-affected roadways it may be possible to utilise pre-established nodes, thus requiring the UAV to drop a only small number of nodes for the final stage of entry into explosion affected area
Remote control video streaming	Communication network proved to be able to transmit video and control systems.	Mesh nodes/power supply/design require more work to prove consistency of signal.
Gas monitoring, and thermal imaging	Demonstrated ability to relay digital signals from UAV	
Payload flexibility (2kg max)	A full payload test was completed in 2016 and the drone easily lifted 2 kg.	For the next version of the UAV a full duration test flight is recommended to verify the effect of this on battery life
Anti-static materials used	Anti-static materials not used	Future development will allow full frame to be printed utilising a 3D printer and anti-static materials

Further research and development

Overview

Development to date is seen as Stage 1 of a 3 Stage process proving the capability of a UAV being flown underground by a remotely located pilot (external to the mine) utilizing live stream video transmitted over a specially designed Wi-Fi mesh node system, whilst simultaneously transmitting visual and thermal images, alongside data such as atmospheric gas levels.

Two important barriers were identified that need to be overcome to enable this concept to be a standalone system:

1. The time lag of video transmission, and
2. The ability of the UAV to be "self-sustaining" if the control signal is lost.

This is essential as relying on manual control for long term navigation is not practical as:

1. The pilot is dependent on a constant communication link at all times which is not guaranteed over long distances in a mesh environment.
2. The video feed and manual control "lag" or delay times make manual input control very difficult even for an expert operator
3. Unanticipated variable atmospheres (i.e. density changes) may be encountered
4. Unanticipated ventilation currents (i.e. wind speed velocities) may be encountered

To enable effective navigation the drone requires the ability to know where it is in relation to the mine roadway and associated obstacles and structures so it can then navigate accordingly.

The next stage (Stage 2) is targeted to develop a “self-conscious” UAV with the following technology as a minimum:

- Light Distancing and ranging scanner (LIDAR) based terrain scanning so the UAV is aware of current location relative to surrounding walls):
    - ✓ A LIDAR scanning system is a three-dimensional imaging system with a rotating multifaceted polygon mirror for transmitting modulated light from one of its facets to a surface. Solid state LIDAR is a fantastic way to allow a drone to accurately measure its distance from solid objects down to cm’s in accuracy. This LIDAR information allows the drone to calculate and then understand its position in relation to other objects (surrounding walls for example). This means it no longer requires constant input from the pilot for positioning and can self-manage its own spatial separation when this information is used in conjunction with the flight controller.
    - ✓ Small light weight solid state LIDAR systems now exist for the purpose of machine control. This advancement in technology is extremely significant for UAV utilization as it is now light enough to now be considered for our unique application whereas in the past LIDAR systems were prohibitive in size and power consumption.
    - ✓
- Ultrasound collision avoidance sensors that enable the UAV to position itself in centre of available space:
    - ✓ The UAV must be able to manage the need to constantly change height above ground as it traverses up and down and along the mine roadways.
    - ✓ Using ultrasonic sensors the UAV can accurately monitor and control its own height above ground. This is done in the same way a bat navigates its way in the dark in nature. These sound waves refract off the ground and give the drone an acoustic measurement of height above ground. A laser range finder, which is a basic, lighter weight LIDAR unit would also be added to help with precise z axis (height) control.
- Fail safe programming to maintain position if signal is lost
    - ✓ UAV remains in a safe location and status
- Full surround bump/intrusion protection
    - ✓ UAV maintains structural integrity in case of any collisions/impacts
- Onboard control system whereby a remote pilot directs UAV flight utilizing a very simple interface, i.e. up/down, forward/back, left/right, thereby enabling flight by a non-specialist pilot
    - ✓ UAV is easily able to be flown by a person familiar with the UAV but not an expert pilot

These technological advancements need to be of a size and weight that allow their integration into a specially designed UAV platform with the ability for extended underground flight. Additional to these it would be ideal if the UAV also incorporated a capability to have a pre-programmed flight path.

A future stage (Stage 3) would combine the developed UAV with updated and refined Wi-Fi nodes (from 1st Stage) into an intrinsically safe package that will deliver a complete deep mine penetration capable UAV based exploration system.

Whilst further testing of the node communication system, components, and effects of an underground environment on signal propagation are warranted it is felt that inherent future technological improvements in both equipment and capacity of the Wi-Fi protocols used in this system will greatly enhance the ability of the system to deliver a product suitable for remotely piloted UAV deployment.

Whilst full intrinsic safety is seen as ensuring the deployability of the UAV in all atmospheres it is would not be the intent of this stage of the project to deliver an intrinsically safe capability. The philosophy being that it is essential to prove an operating system, after which it can be intrinsically engineered.

The premise of this development is that providing the UAV meets the objectives it will enable remote deployment underground. The extent of the deployment will depend on the circumstances of the incident, anticipated underground environment and level of risk acceptability inherent in the deployment of a non-intrinsically safe UAV, measured against the risk of not sending it.

It is acknowledged that whilst the future ability to deploy a “self-awareness” is essential, the exact nature of that deployment is unclear. Will this be as a standalone UAV via remote control by a pilot on the surface utilizing video enabled Wi-Fi nodes, or will it be via a multitude of small UAV’s equipped to become Wi-Fi nodes, or will it be using a programmed drone to fly along a pre-programmed path, or will it be a UAV flying along a pre-existing WiFi network, or will it be a combination of a ground craft carrying a multitude of UAV’s?

Whatever system is utilized, it relies on having a “self-aware” UAV as its core component.