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# Prototyping during the requirements elicitation process in the development of an underground unmanned aerial system.

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*Abstract*— **Prototyping of subsystem and system components is most often thought of as a development task. This paper shows the usefulness of prototyping as an activity in the requirements elicitation process, prior to any developement activities. It is approached from the field of engineering and technology management. It uses the Requirements Engineering approach to identify tools and methods for the development of the requirements for an underground unmanned aerial system for use in South Africa's' gold mines to inspect box-holes and ore-passes. Box-holes and ore-passes are vertical tunnels through which the ore must pass in moving from the stope, where it is mined, to the shaft, where it is hauled to the surface for processing. The more familiar new product development framework is compared to the requirement engineering process. The prototypes of a number of subsystems are presented, namely, a quadrotor platform, a platform preservation sensor array, an optical flow sensor for position holding, a vision sensor for operator visualization, and an operator interface. The perceived significant technological challenges are discussed as motivation in the choice of these subsystem prototypes that will be used in the interviews that are to form the basis of the requirements elicitation activity.**

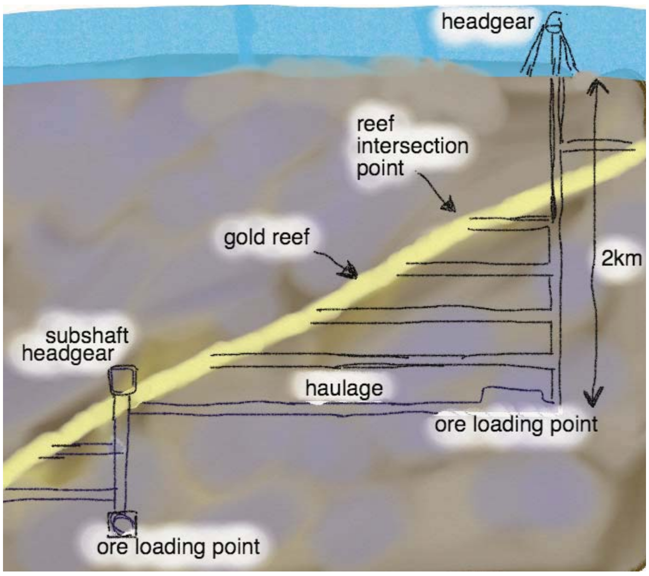

Fig. 1. Gold Mine Structure

## I. INTRODUCTION

In the research field of *engineering and technology management*, *prototyping* occurs at two phases. The more common use is as a technology demonstrator during the project development phase. Typically there will be many prototypes during this phase. However, this paper focusses on the other use of prototypes, that of during the *requirements elicitation* phase. At this stage there is no development team yet. The problem is still being understood and the requirements are being discovered. Thus enabling the formulation of the requirements specification that will be used to create and direct the development team [1]. The prototypes discussed in this paper are used not to demonstrate technologies (or solutions), but to encourage discussion about, and gain insight into, the problem, and improve the general understanding. Thus in this mining case study, there is no testing of the systems in a mine environment yet.

Section II discusses the background from three perspectives, mining, requirements elicitation, and requirement classification. Section III discusses the case study, specifically the requirements engineering tasks, technical challenges and the proposed subsystem prototypes to be used in the requirements elicitation process. Section IV then expands on each of the subsystem prototypes. Section V concludes the paper with conclusions and proposed future work.

## II. PROJECT BACKGROUND

### A. Mining

The project under discussion in this paper is of the development of an Unmanned Aerial/Aircraft System (UAS) (a quadrotor ) for use in the inspecting box-holes and ore-passes in underground gold mining in South Africa. The project developed from a mine rescue conference workshop session about how robots could assist in mine rescue situations [2]. Because the acquisition of emergency equipment is hard to justify financially, an application was found that would also have benefits in a routine production environment. The basic functional requirements were documented for a case where a machine can inspect the vertical voids during production, as well as when they become periodically blocked creating an the emergency situation [3]. Thus releasing people from such dangerous jobs that have in the past resulted in fatalities [4].

*1) Structure of a Gold Mine:* The structure of a gold deposit and mine is shown in Figure 1. The gold ore deposit is called a reef. It is a narrow vein of ore ranging from several centimeters to a couple of meters thick. The reef dips from surface at between 18° and 25°, and plunges to unknown depths into the earth, while being 100's of kilometers in breadth. Current gold mines are considered

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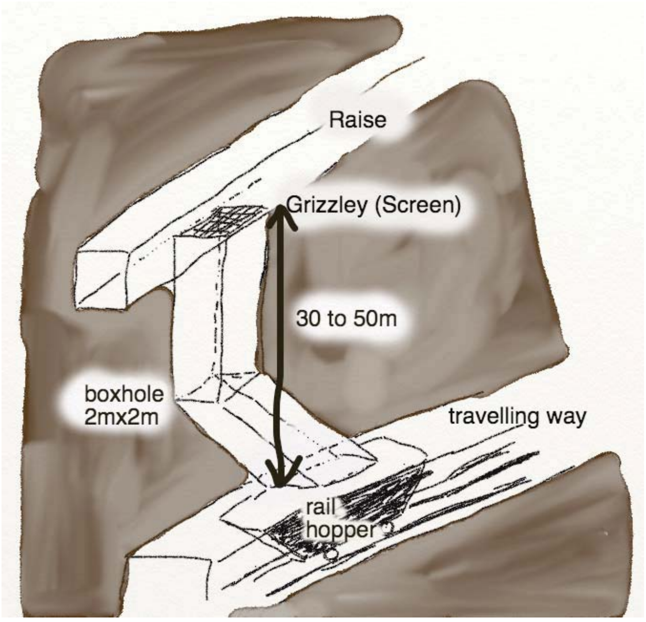

Fig. 2. Diagram of a box-hole structure and dimensions.

very deep, ranging from 1.5 km to 4 km underground. They are getting more dangerous to work, as well as more difficult to work, with the increased temperatures and rock stresses that accompany such deep workings, as well as additional costs of hauling the low yield ore further to the surface for processing.

A vertical shaft, or elevator, is used to access the mining depth with access levels approximately 200 m apart. Horizontal traveling ways (also called haulages or access tunnels) are used to access the deposit from the shaft, and can be tens of kilometers long, accessed by means of a railway system. An ore-pass (not shown in the Figure) runs parallel to the shaft. Ore from each level is deposited into the ore-pass, where it falls down to the lowest level of the mine for loading into the cage and transported to surface for processing.

At the reef intersection, the mine structure changes to match the dip of the reef. *Raise* tunnels are developed along the reef plane, and horizontal tunnels called gullies (not shown) enable access to the stope where mining occurs. Ore is scraped by hydraulic scrapers down the stope, along the gullies and then down the raise to the level intersection, where a box-hole is used to load the rail car.

Figure 2 shows the typical configuration of a box-hole. The box-hole links the raise and the haulage tunnel, and enables ore to be loaded into the rail cars (hopper) for transport from the reef to the shaft, where it is dumped into the ore-pass. A typical box-hole is approximately 35 m long and 2 x 2 m square in section. An upper vertical section is capped with a screen (grizzley) with a 30 cm x 30 cm aperture, to prevent large rocks from entering and blocking the chute. The lower section is at 50° to reduce the kinetic energy of the falling ore, and is capped by a 'box-end' which controls the flow of ore for the loading of the hopper.

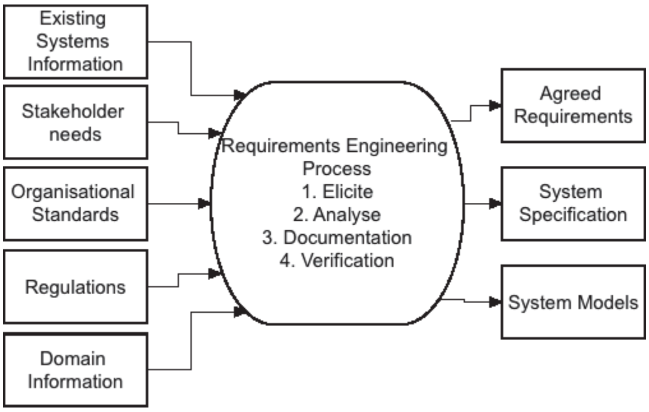

Fig. 3. Requirements process [9].

### B. Requirements Elicitation

Getting the requirements right is a fundamental step in ensuring a successful research project execution. Multiple input sources are interrogated to understand the need, which is then analyzed, documented and verified with the stakeholders to create an agreed set of deliverables, the System Requirements Specification (SyRS), [5] [6]. In New Product Development (NPD) and system development, the Requirements Engineering (RE) process is the same as it is for software engineering and business analysis, as in Figure 3.

The four steps of:

1) elicitation
2) analysis
3) documentation
4) verification

are common across disciplines, however, the techniques employed vary amongst the project types. There are many books written about the subject [7]. In [8] the NPD process is described as in Figure 4. The requirements engineering process maps to the concept development phase, combining the steps of 'identify customer needs' through to 'set final specifications'.

Requirements elicitation is the process of gaining an understanding of the customers and users needs for the planned system and their expectations of it [10]. [10] goes on to define prototyping as a quick and rough (i.e. incomplete, untested and potentially flawed) version of a subsystem. Its purpose is to provide a physical artifact, around which discussions can occur that lead to a better understanding of the subsystem, and its required capability, by all stakeholders, both customers and future developers. [11] motivates for using rapid prototyping during the elicitation stage as an effective tool for acquiring information and knowledge about a new system or product (as opposed to analyzing and understanding an existing system or problem).

### C. Minimum Viable Technology vs. Commercially Viable System

In the discussion during the requirements elicitation process, it is typically the final system that is discussed and

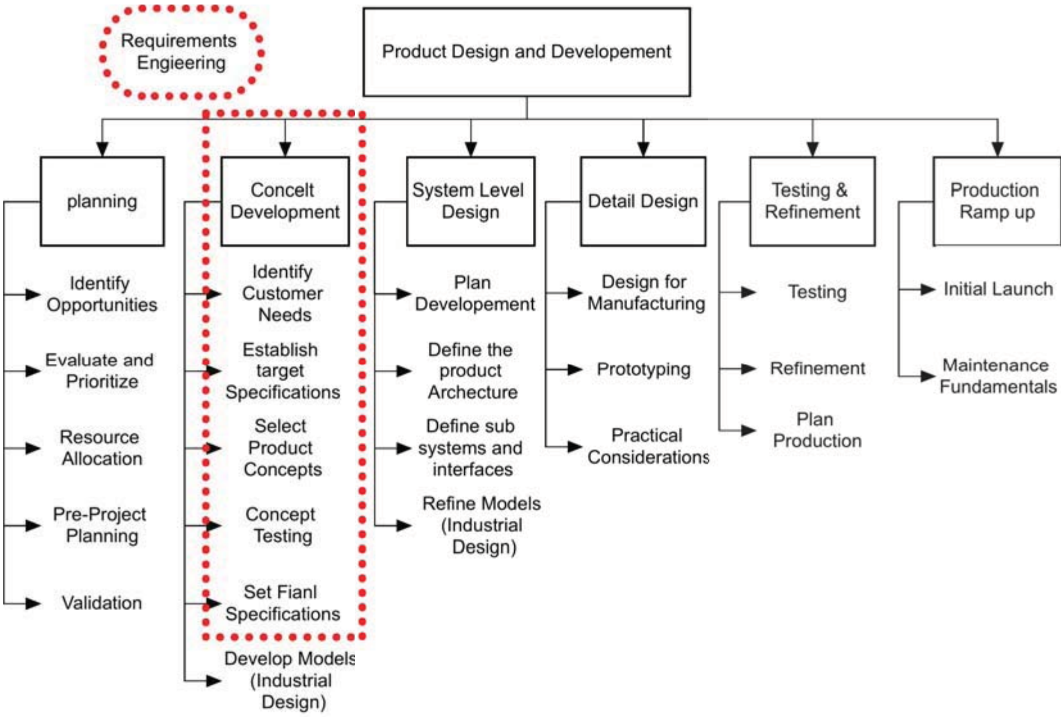

Fig. 4. New Product Development and Requirements Engineering combined

envisaged. In this text it is referred to as the Commercially Viable System (CVS). However, in a technology development project, there are interim development steps that are executed during the project. These project phases, or stages, will generate different prototypes. It is important to note that this is different to the prototypes discussed in relation to the requirements elicitation phase in this paper. One way of grading these prototypes is a Technology Readiness Level (TRL) progression. Initially developed by NASA for the development of complex systems like spacecraft [12], [13] defines TRL as follows: "*it is a discipline-independent, programmatic figure of merit (FOM) to allow more effective assessment of, and communication regarding the maturity of new technologies*". TRL's have gained much support and have been adopted by the United States Department of Defense [14], and other large research organizations [15]. The CVS may map to a TRL 8 or 9.

In this text we refer to the first system that is to be developed as the Minimum Viable Technology (MVT). These terms are discussed further in [16], but broadly speaking, the MVT represents a degraded subset of requirements from the CVS system. The MVT demonstrates a capability, reduces or mitigates some technical risk, clarifies the problem and solution by presenting a possible system, thereby enabling a better understanding of the CVS requirements. The MVT may map to a TRL 4, 5 or 6.

## III. REQUIREMENTS ELICITATION FOR THIS CASE STUDY

The requirements elicitation methods chosen for this project, as well as the justification for their choice are discussed in [16]. Interviews are the primary method, with the use of a questionnaire, brain storming, scenarios, use cases, and prototypes to prompt discussion to discover the requirements for both CVS and MVT. A domain specialist is used to create a baseline set of initial requirements. These initial requirements will be presented in the context of user scenarios for discussion during the interviews.

### A. *Technological Challenges*

There are a number of significant technological challenges that were identified in the background discussed in section II. Briefly, they are:

- **Platform preservation system:** To stop the aerial platform from flying into a wall, floor or ceiling, even if the operator inadvertently tries to fly it in that direction.
- **User interface:** Identifying the actual end user is to be a significant outcome of the elicitation process. It could be an unskilled mining operator, or it could be a specialized pilot, depending on the deployment model chosen. If the mine were to be the owner and operator of the hardware, it will be a task delegated downwards, potentially to an unskilled miner. If however, the system was deployed as a service by a specialised company, the mine would pay for the data resulting from the 'flight', and it will likely be a skilled operator. These two scenarios could well result in different requirements for the graphical user interface (GUI). In either case however, it is important to determine what information the operator needs/wants, and how the operator would like to transfer instructions to the aerial platform, i.e. control the Unmanned Aircraft (UA).

Fig. 5. Small, simple cheap quadrotor demonstration platform

- **Determining safe flight zone:** The operator will not always have visual line-of-sight (VLOS) to the platform, and will need to teleoperate the vehicle using only the GUI. There will therefore need to be some data processing to assist the operator to determine where a safe zone for flight is.
- **Drift due to ventilation air flow:** The aerial platform could drift down the passage due to the ventilation air without significant change in the sensor data or in the GUI. Unplanned movement is undesirable, as the platform should only move based upon an operator instruction.

Based upon these identified challenges, prototypes have been developed/proposed for use in the elicitation process.

### *B. Subsystem Prototypes*

Subsystem prototypes are to be used to generate discussion about technical issues and possibilities for addressing the challenges. The prototypes do not represent the actual solutions, but rather are used to indicate some technology capability as well as to generate discussion about the required CVS capabilities. The subsystem prototypes are:

- A basic quadrotor platform.
- An ultrasonic array as a platform preservation system.
- An optical flow sensor as a possible way to overcome drift.
- An ASUS Xtion Pro live for visualization and depth analysis to determine the access potential for the platform. i.e. will it fit?
- GUI, an illustration of how the operator could interact with and control the platform.

The prototypes are discussed further in the following section.

## IV. PROTOTYPES

The five subsystem prototypes are now discussed in more detail .

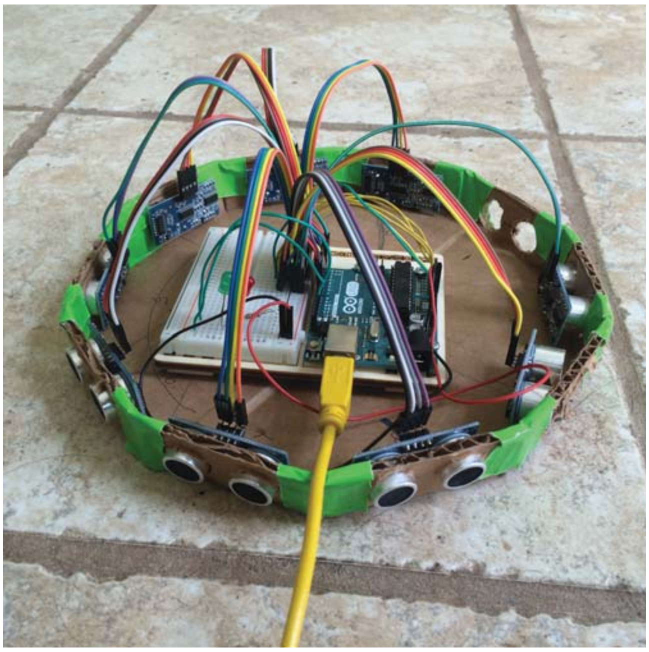

Fig. 6. Ultrasonic obstacle detection array

### *A. Platform*

The use of a quadrotor platform appears obvious in this instance, but some discussion is perhaps warranted. The possible platforms are ground, suspended and aerial [17]. As the intended application is in a near vertical environment, or in a cluttered floor environment, the use of a ground vehicle is unsuitable. The use of a suspended platform is feasible for top entry to the ore-pass and box-hole. However, in the case of a blocked chute, it is necessary to gain access from below to determine the position of the blockage. Access from below can only be achieved with the use of an aerial vehicle with hovering and vertical take off an landing (VTOL) capabilities. Thus a small, simple and cheap quadrotor has been chosen as a discussion piece for the interviews, shown in Figure 5.

### *B. Platform Preservation System*

The platform preservation system for obstacle detection/avoidance sub-system prototype that has been built (See Figure 6) is based upon an Arduino Uno and the HC-SR04 ultrasonic sensor [18]. An array of 10 sensors was initially intended, however, limitations in the arduino I/O has resulted in the initial prototype having six sensors that are sequentially polled with a 50 $\mu$s timeout to avoid crosstalk. The ultrasonic sensor sends out a 40 MHz 'ping' and measures the time taken for the sound to return as a reflection off an object. It has a 15° field of view. The cycle time for polling the sensors is dependent upon the response time of each sensor, which is dependent on the distance measured which is dependent of the environment around the sensor system. The cycle time for polling the 6 sensors in a 4 m x 4 m room varied between 70 $\mu$s and 90 $\mu$s, implying a ten sensor system would be 116 $\mu$s to 150 $\mu$s.

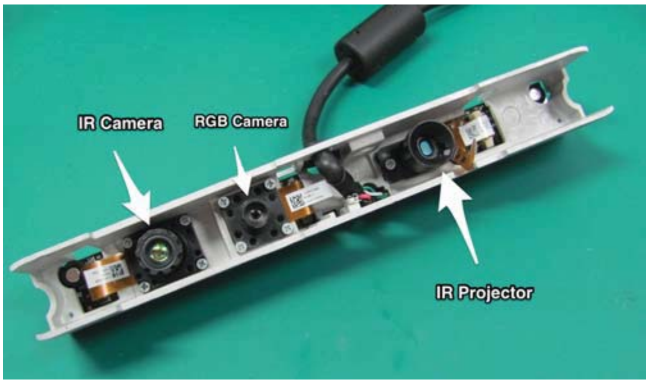

Fig. 7. Asus Xtion Live sensor

It must be noted that the intended platform preservation system will be a three-dimensional system. Upward and downward facing sensors will prevent collision with the ceiling (hanging wall) and floor (foot-wall), and/or maintain a constant position between the hanging and foot walls. While this prototype is a coplanar system designed to preserve the platform from collisions when moving left, right, forward and backwards.

### C. Operator Visualisation Sensor

For the operator to 'see' where the platform might move to, a Red, Green, Blue, Depth (rgbd) sensor has been chosen for the prototype. The Asus Xtion Pro Live [19] is an open source sensor that has been used in the past for similar visualisation activities in underground gold mines [20]. Figure 7 shows a disassembled Asus Xtion Pro Live, a 480x360 resolution rgbd sensor. The prototype uses Open NI and has a 0.8 m to 3.5 m range at 30 frames per second (fps), sufficient for the mine tunnel environment.

Figure 8 shows a depth map that can be used to determine where the platform can safely fly in a tunnel environment. The intention is to limit the operator instructions to those areas/directions that are safe. With a forward facing sensor, the platform will only be able to progress in the direction that the sensor is facing. 'Forward' will be different for different deployment scenarios. For example, in a tunnel, the sensor will point horizontal; in an ore-pass, the sensor will point vertically up or down; in an intermediate slope (raise or stope), the sensor tilts to match the proposed direction of travel for the platform, either upslope or down slope. There is no "backwards". The platform must rotate, tilt the sensor, determine if it will fit (through image analysis), then fly 'forward' in the direction that the sensor is pointing.

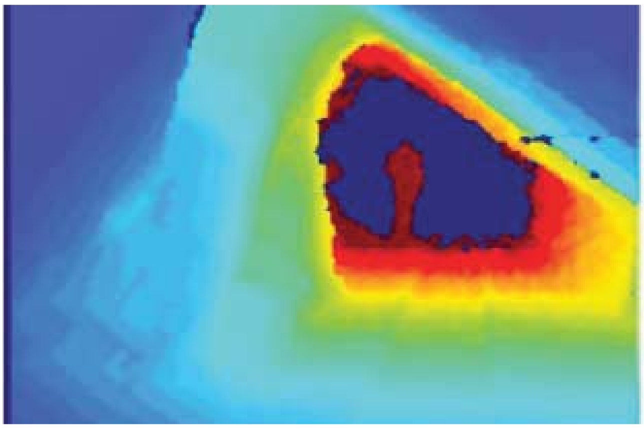

Fig. 8. Tunnel depth map from Xtion sensor from [21]

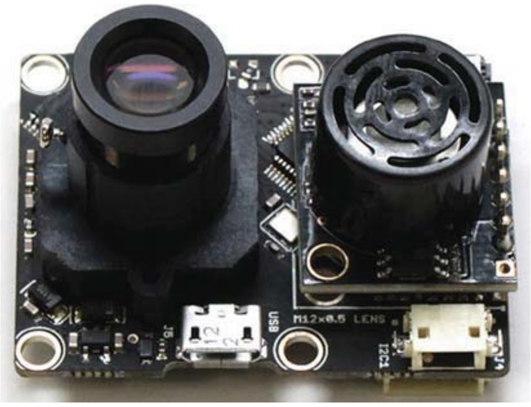

Fig. 9. optical flow sensor from 3D Robotics for $150

### D. Drift Sensor

Figure 9 shows an optical flow sensor from 3D Robotics [22]. The PX4FLOW (Optical Flow) Sensor is a specialized high resolution downward pointing camera module that uses the ground texture and visible features and a rangefinder to determine aircraft ground velocity. [23] has shown the potential for combatting drift with such a sensor. [24] provides a survey of techniques and hardware that can be employed. It indicates that while none have used it specifically for position hold implementations, it has been effective on VTOL platforms for obstacle avoidance, terrain following, vertical landing, velocity estimation, and visual odometry. Some additional work would be needed to develop a prototype specifically for this application, to combat drift due to crosswinds from the ventilation air flowing down the tunnels. No system is proposed for this prototype, just a discussion about the sensor capabilities and the problem requirements. This discussion will enable the discovery of the system requirements for the CVS and MVT.

### E. Operator Interface

The operator interface GUI will be on a portable computer. At lease some of the flight will be executed without VLOS of the aerial platform. Therefore, there needs to be sufficient information on the GUI for the operator to be able to make decisions about what to do. Figure 10 is a sketch of one such possibility. Using sketches is a simplistic first step in engaging potentially non-computer literate stakeholders, like miners, without intimidating them. Thus enabling them to easily add their thoughts, and enabling the capture of their inputs into what is, and is not, needed in the GUI. Proposing a GUI prototype will prompt discussion about

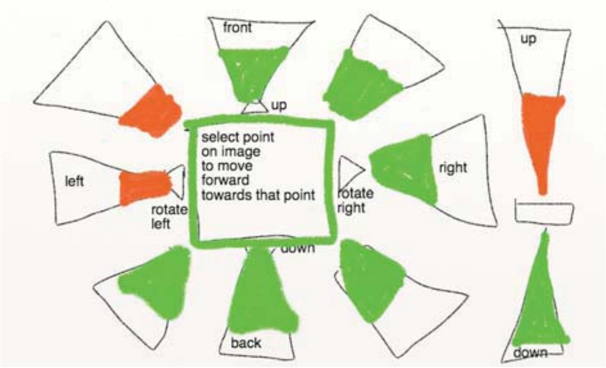

Fig. 10. Simple illustration of possible operator interface

a number of items: who the operator will be; what the operator environment will be like; how the operator will make decisions; what data/information they would need to make those decisions; how that information is to be displayed or conveyed to the operator such that it is unambiguous and useful. The logical next step is to develop the prototype on a computer system for the stake holders to interact with, and provide feedback on.

Typical GUI would include the readings from the ultra sonic sensor array displayed as a modified bar chart. Also, the sensor depth data can be analyzed to determine if the platform is dangerously close to an obstacle or wall. The display then colored to indicate the obstacle proximity (see Figure 10). Another example is that the rgbd sensor data are analyzed to indicate the possible trajectories that the platform can take. A green frame around the image indicates a feasible forward trajectory, a red frame indicates a blocked forward path, and the necessity to change the platform orientation and/or position, by either a left/right rotation or up/down movement, to find a clear forward path.

## V. CONCLUSIONS

In this paper we have discussed the requirements elicitation prototypes to be used in the development of an UAS for use in South Africa's underground gold mines for inspecting ore-passes and box-holes. A summary of gold mining is given, explaining the challenges, and a background to the project is presented, outlining how this application was chosen for investigation. A discussion on requirements engineering and new product development processes precedes motivation for how prototyping can be a valuable tool in the elicitation process. The significant technical challenges for a UAS in an underground mining environment were outlined. Five subsystem prototypes were described that would be used in the requirements elicitation process for the underground UAS for box-hole and ore-pass inspection. The prototypes will be used in the interview discussions to assist in determining what exactly a solution system needs to achieve, as well as to more fully understand the deployment environment, and how that environment will effect the solution.

Follow up work includes the completion of an accompanying questionnaire to lead the interviews, and enable comparison results from a variety of stakeholder interviews. The stakeholder network will classify the requirements into MVT and CVS requirements, and this classification is to be mapped onto the TRL framework.

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