NIC 2018 - RRES

Project Progress Report 4

6th August 2019

Oliver Machan – NIC RRES Project Manager

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Contents

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1 Executive Summary

The purpose of this document is to report on the progress the project has made since the last submission on the 4th April 2019. The report contains a summary of the progress made from SGN, with subsequent reports from ULC Robotics as the principle project partner. Also, the planned progress and the key milestones to be delivered over the next PPR period is included.

RRES is an innovative and advanced robotic system which will be designed to improve existing methods of excavation, repair and maintenance operations performed daily at SGN and the other GDN's. The objective is to reduce the excavation size, costs, labour and equipment while making the work safer.

Since the last PPR, we have progressed with the development of each of the excavation, sensing and deployment systems. Through fabrication and testing of the individual subsystems, valuable learning has been generated which is driving progressive iterative design changes. Furthermore, integration of the prototype has commenced with the fabrication of interfaces between subsystems.

Below is a list of the major achievements by the development team during this period of the project.

- Shop testing of the prototype excavator
- Integration of the excavator into the robotic arm operation
- Excavation test using the robotic arm
- Developing a migration algorithm for automatic processing of GPR data
- Creating a 3D model of the buried assets based on the GPR raw data
- Complete shop testing of sensors and vision systems
- Installation of the robotic arm onto the chassis
- Perform mobile platform design modifications and testing
- Engaged MTC in development of cutting bits for the chainsaw

The content of this report and the project progress aligns with the project plan conveyed in the submission.

2 Background

The goal of the project is to develop a prototype RRES system that can demonstrate automation of the excavation and reinstatement process and the installation of a Universal Access Fitting (UAF). Two field tests will be executed: one on dead pipe and the following one on a live gas main. Collectively, the two field tests will demonstrate the following:

a) Transport and setup of the RRES (including a vehicle and a mobile platform with a robotic arm and excavation sensors/tooling)
b) Removal and reinstatement of asphalt, concrete and soil

c) Soil vacuum excavation in urban and rural environments
d) Prevention of damage to buried assets throughout the excavation process
e) Detection and avoidance of other buried objects
f) Exposure of the target pipe for operations
g) Preparation of a low-pressure distribution pipe for UAF installation
h) Installation of the UAF on a low-pressure distribution pipe

Element 1 of the project focuses on the selection and development of the robotic arm, mobile platform, a below-ground sensing module, excavation tooling, and the computing platform needed to command and control the RRES.

The subsystems to be developed under Element 1 have been categorized into three main groups: Excavation, Sensing and Deployment System.

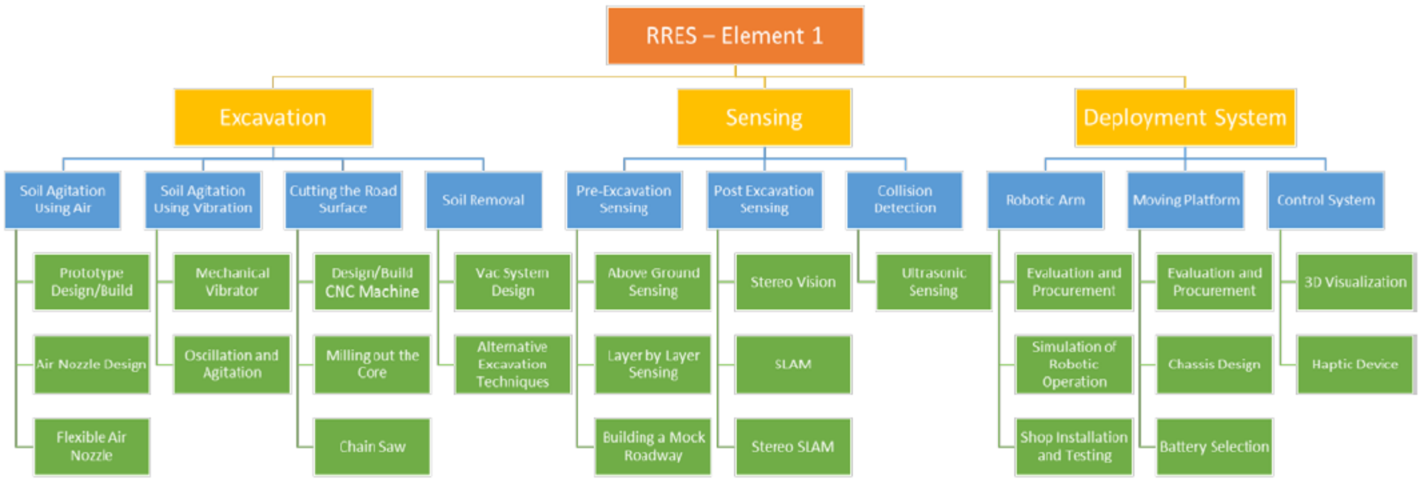


Figure 1 – Element 1 Overview

Excavation

Conventional excavation, when compared with the RRES, requires a much larger excavation to allow direct access for operatives to carry out repairs or install fittings. Due to the larger excavation footprint and the amount of gas and third-party plant exposed within them, the risk of damage is high. If there is too much third-party plant in the excavation, the process must be carried out manually by the operatives using hand tools. This process is time-consuming, physically taxing and carried out in hazardous environments. The RRES core removal technique, 'soft-touch' excavation capabilities and automated above ground tooling will significantly reduce the footprint of the excavation and the risk to third party damage.

Sensing

Prior to starting excavation, and during the excavation process, the robot operation will utilize sensors to scan in "layers" to identify buried assets in its excavation path.

To better focus research and development efforts, the sensing operation is broken down into two main categories of sensors. (1) Pre-Excavation Sensing and (2) Post Excavation Sensing

Pre-Excavation Sensors will be used to scan the roadway above the excavation zone prior to cutting the road surface to identify utility lines and other obstructions in the first layer of the work path. Although not a focus, ULC will also review sensors that may be used with the system increase the accuracy of robotic operations in target location.

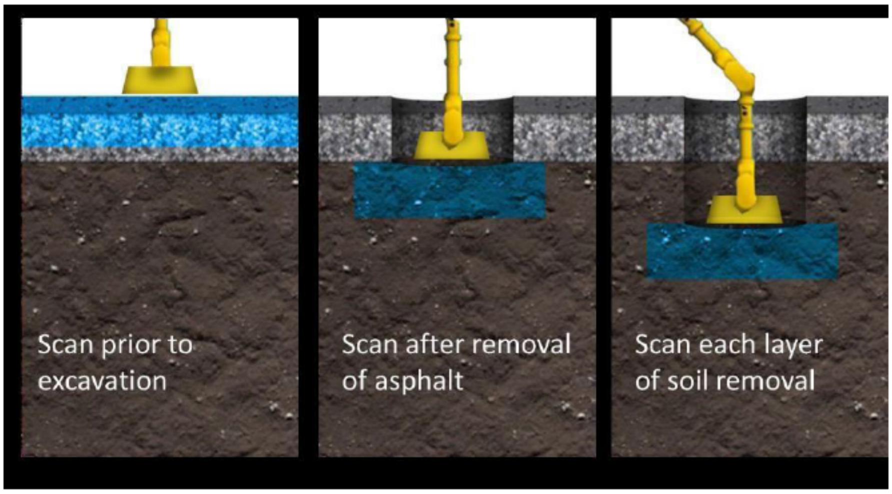


Figure 2 – Below Ground Sensing

Post-excavation sensing system can be used after every stage of excavation to create a point cloud and texture model of the bottom of the keyhole. A point cloud is a set of data points which represent points in 3D space and can be used for measurement, navigation and to generate accurate 3D models of environments. Point clouds are generally produced by 3D scanners, which measure many points on the external surfaces of objects around them.

Deployment System

The deployment system consists of the robotic arm, the mobile platform and the computing system that carries out all robotic operations. To properly identify, develop and specify different components for the system, and to design the most optimal deployment method, preliminary specifications and capabilities required to perform each of the operations have been defined. These specifications will be adjusted based on the new findings from site visits as well as the feedback from SGN.

3 Project Managers Summary

Since the last PPR, the project has progressed as planned in line with the project plan and budget. Further development has been made in each subsystem of element 1. Integration of the different subsystems has evolved and more realistic testing has been carried out.

3.1 Excavation

One of the main benefits of RRES is the ability to excavate the ground without causing any damage to buried utilities. During this PPR period, we have made developments within the cutting of the road surface and the excavation head by progressing with more realistic testing and feeding the results back into the excavation system's design.

Cutting the Road Surface

The RRES operation is intended to cut the road surface with minimum assistance from the operator. In the early stages of the project, we evaluated various standard and non-typical techniques for cutting the road surface. Through the process of design, fabrication, and testing, options were eliminated as being too disruptive, time-consuming or requiring too much supervision and attendance from an operator. Because chainsaws can be used to make deep cuts without the overcuts associated with a circular saw, it is especially useful in situations where precise cuts are necessary with no impact to the area surrounding the cut.

To test this, the team has designed a custom concrete chainsaw for use as an end effector for the robotic arm. This new and unique tool will enable the RRES to make flexibly shaped and sized cuts in a wide array of road surface materials.

After the successful development of the chainsaw and its installation on our CNC machine, different chains, designed and manufactured by various vendors were tested. [redacted]

The primary measurement of cut efficiency is based on the volume of material removed per minute (MR/M). This measurement is a result of all of the variables involved in the system – cut depth, cut speed, chain speed, motor power, lubrication, etc. Since a hole has a defined volume to remove in order to cut (perimeter of the hole * cut kerf *cut depth), the MR/M will define the time which any given hole will take to cut. MR/M is measured in cubic centimetres (CC) per minute.

[redacted]

Wide Kerf Cutting Test

[redacted] The results can be seen in figure 3 and 4.

Figure 3 - Initial round cut performed slowly with a wide kerf chain

Figure 4 - 12" diameter plunge-only cut test

Standard Kerf Cut Test

The second chain that was tested [redacted] This chain is compatible with the existing drive mechanics, and with a simple swap of the chain, the machine was upgraded for a new round of tests. [redacted]

[redacted] This would equate to a 24" diameter hole 12" deep being cut in just over 10 minutes. [redacted]

[redacted]
While the wear that is being encountered is in line with the wear experienced in normal existing

nonmechanized field use of these saws, we are operating with a goal to improve wear characteristics of the system in order to lower operating costs and increase the time between servicing of the equipment. [redacted]

[redacted]

[redacted]

[redacted]

These tests were repeated with other commercially available chains [redacted]

- [redacted]
- [redacted]
- [redacted]
- [redacted]

[redacted]

Design Improvements

Following the rigorous tests conducted in the laboratory environment, the limitations of the designed prototype chainsaw were identified. To eliminate these limitations and improve the efficiency of the operation, we started the design and build of a new version of the chainsaw.

[redacted]

[redacted]

[redacted]

- [redacted]
- Tool mount modifications – Now that the design of the robotic arm is nearly complete, the second version of the saw can be designed to accommodate the use on the arm – including mounting brackets, and if necessary, a rapid tool changing mount.
- [redacted]
- Software development – In order to maximize the efficiency of cutting, several overall cut factors must be optimized. [redacted] The dynamic cutting software that is under development will be able to pre-plan the exact cuts to be made, and more importantly, adjust the plan according to what is encountered by the system during the cut.

While the new chainsaw is in the process of detailed design and manufacturing, more tests are being carried out on using the original prototype chainsaw. Based on the findings from testing the prototype chainsaw, we have derived a test plan for effective testing of the newly designed chainsaw which will involve asphalt cut testing and alternate diamond segment geometries.

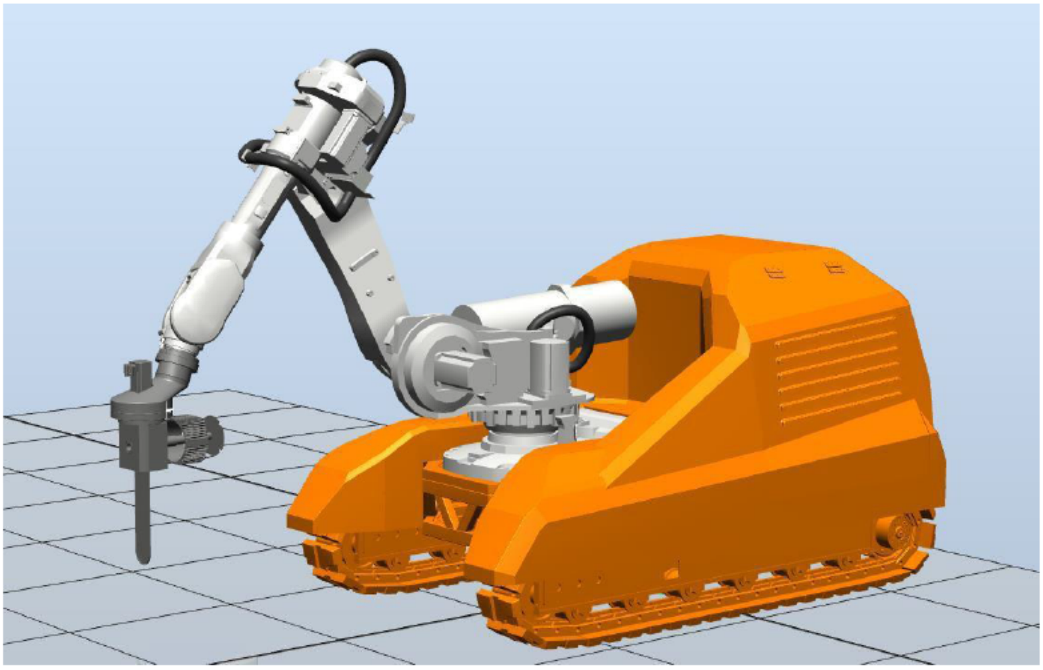


Figure 9 - Schematic model of the new chainsaw mounted on the robotic platform

Excavator Head Design

The RRES Excavator head serves to be the main tool to break up and remove the soil under the removed core and uncover the target pipe. Our goal is to create a compact robot arm mounted excavator head, with an integrated supersonic nozzle, and vacuum pipe that will replace a two-person operation. The robotic arm will be used to move the excavator's head and perform the operation.

The excavator head for the RRES has gone through numerous design iterations ranging from complex motion continuum robots to a simple vacuum pipe and hose combination. After fabrication of each prototype, thorough testing was done to evaluate the performance of each design. With each iteration, we were able to overcome obstacles, combine aspects of the designs that were promising, and settle on a solid path forward toward a design method that proved to be the most effective.

[redacted]

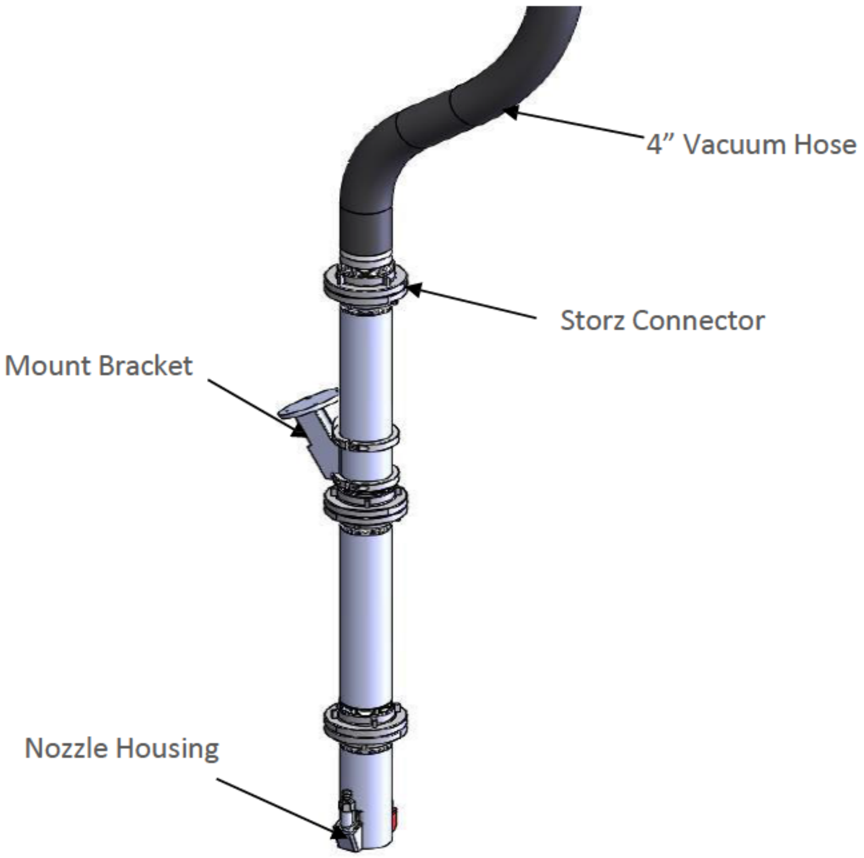


Figure 10 - Integrated Nozzle and Vacuum

This 4" ID excavator head was tested in a controlled environment where the soil type and its level of compactness were known. [redacted]

Figure 11 - Testing in Medium Density Clay

[redacted]

The integrated head was able to excavate very well at the beginning of the test. [redacted]

- [redacted]
- [redacted]
- [redacted]

Design Improvements

The next iteration sought to overcome some of the issues that were seen during the first round of testing. To prevent the soil from being projected from the excavation area, many changes were made to the excavator head.

[redacted]

3. A custom designed 3D printed cover to contain the agitated soil from spreading around. This cover, shown in Figure 23, is made of TPU, 3D printed on an SLS printer, has the profile of an accordion boot for flexibility, and custom fit for the excavation head. The design allows for the cover to compress down to 3/8", making the cover conformable to the excavation hole and control the distance of the nozzle to the ground. It also helps harness the projected soil from spreading around.
4. The vacuum hose was replaced with a more flexible and smoother inner wall hose.

[redacted]

Figure 12 - Excavation Head Cover

The testing was performed under the same conditions and using the identical equipment as the previous tests. The changes to harness the soil worked very well. When the excavation head contacted the ground, the soil was not projected outwards, and the cover was able to conform to the uneven terrain. [redacted]

After a relatively successful round of tests, several other issues were observed:

- Lack of accuracy in articulating the end-effector. This will be greatly improved after replacing the backhoe with the robotic arm for excavation.
- [redacted]

- [redacted]

In order to improve the shortcomings of the previous tests, major modifications were made to the design of the excavator head. In the new design, the following considerations were taken into account:

- [redacted]
- [redacted]
- A more precise method of articulating the end effector was necessary
- The flexible cover did an acceptable job of containing the projected soil
- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

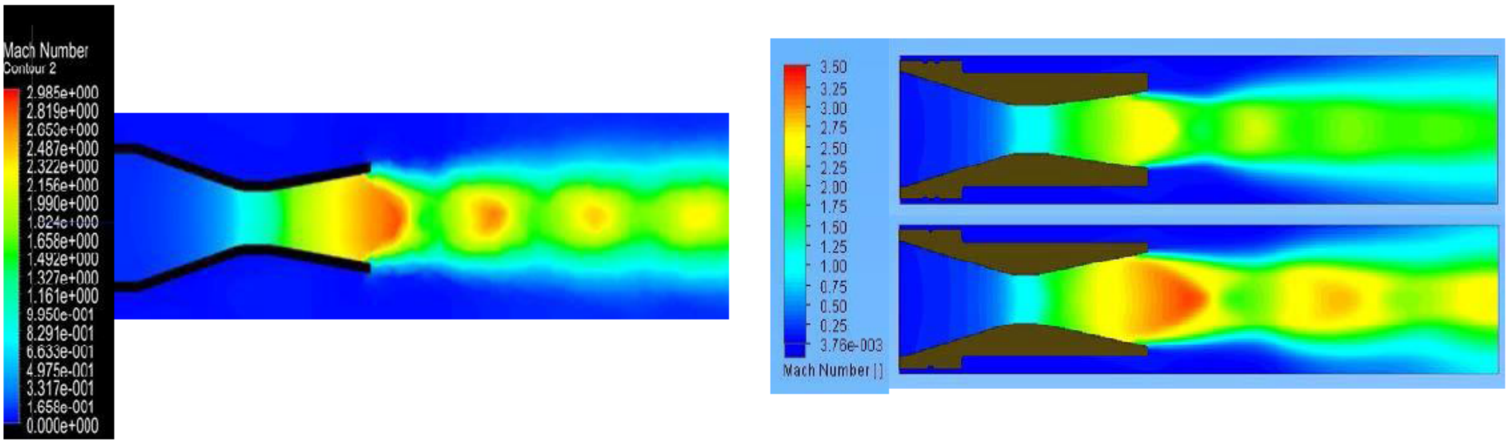


Figure 13 - New Nozzles designed to be used with the new equipment

Additionally, to accommodate the 6” vacuum system, new changes were made to the design of the excavator head:

[redacted]

- The system was designed to be tested (1) using a hydraulic backhoe, (2) as a manual excavator attached to the boom of the vac truck, or (3) mounted on the robotic arm.
- A new cover was designed based on the lessons learned from the previous tests

[redacted]

After multiple tests in different soil environments with various levels of compactness, [redacted] Many of the issues seen previously were minimized or eliminated after the upgrade.

- [redacted]
- The vacuum was powerful enough to remove the dense wet clay and harness the projected soil.
- The tests were done in a manual configuration to control accuracy, which helped better isolate the excavated sections.
- [redacted]
- Neither the pipe nor the hose got clogged throughout the operation.

There were however, a few issues with the new design that need to be mitigated before any further testing:

- [redacted]
- Lack of accuracy in articulating the excavator head was still causing difficulties in conducting the operation properly

In order to overcome the few shortcomings observed in the last set of tests, we made some minor modifications to the design of the excavator head. [redacted]

Manual Excavation in Virgin Soil Test

Up until this point, most of the testing has been done in a controlled test environment with known soil types and compactness level. To test the performance of the system in a different environment the excavation process was done in a hardly compacted and virgin soil in front of ULC headquarter.

[redacted]

- [redacted]

Figure 15 - Excavator head used during manual operation

The site chosen for this test contained the most compacted soil that RRES had ever excavated. [redacted] The rate of soil removal, however, was slower than the other tests due to the compactness of the soil.

During the excavation, the plunging operation was halted a couple of times with an assumption that the excavator head hit a rock or some hard obstruction. It turned out that what blocked the excavation was a water sprinkler line that the team didn't know about. Once the contact spot was inspected it was clear that the excavator was able to remove the soil surrounding the pipe and underneath the sprinkler line without causing any damage to it. This test was a coincidental and realistic test of the soft touch system and the proof that the air nozzles will not only avoid damaging the buried assets but also can effectively remove the soil from the surrounding area. Figure 17 shows the excavation hole that was created in this test. The exposed water line is visible.

Figure 16 - Excavation results in the hard-compacted soil and removal of the soil from the surrounding area

[redacted]

- [redacted]
- [redacted]

The limitations of the system found during this test was the lack of ability to accurately control the excavator. The excavator had the tendency to slip into the centre of the excavated keyhole since the only driver of the tool was the weight of the excavator head. This issue is not a major concern since this test was done fully manually and the robot will be able to carry the weight of the tool and not let it slip inside the excavated keyhole.

Robotic Excavation

Testing progressed with mounting the excavator head onto the robotic arm [redacted] This will greatly improve the accuracy of the operation and will allow an investigation into effective methods to articulate the excavator head inside the hole and effectively agitate and remove the soil. Figure 17 demonstrates the excavator head mounted at the end of the robotic arm.

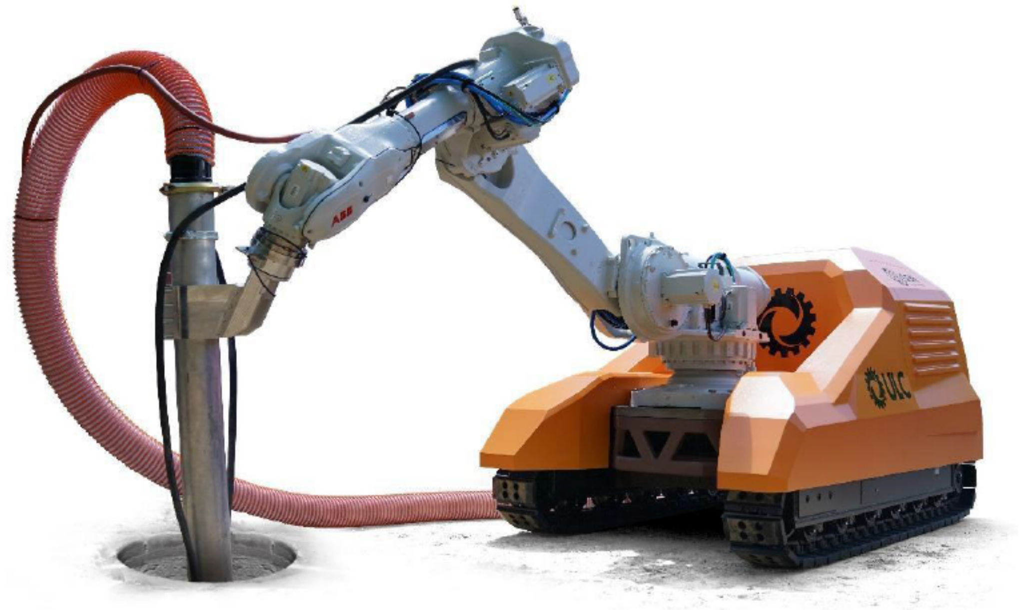


Figure 17 - Excavator head mounted at the end of the robotic arm

The semi-automatic operation mode was used during this operation. This means that the operator would manually position the robot using the control pendant and then run one of the four pre-programmed routines to conduct the excavation. The following pre-programmed routines were designed to be used in this operation:

- Plunge – Steady movement parallel to the excavator pipe.

- Twist – Plunging with a +/- 60° rotation of the excavator head.
- Small Circles – orbiting around starting point in a predefined diameter.
- Full circle – following the full circumference of the keyhole.

In each of these modes, the force-torque sensor mounted at the end of the robotic arm would prevent any damages to the arm or the excavation tool. Once the forces in any direction would exceed a predefined threshold, the robotic arm would stop the movements in that direction and halt the operation until the operator inspects and assesses the situation.

The testing was done in the controlled test bed that was created for excavation operations with known soil type and compactness.

Figure 19 - Excavation operation using the robotic arm

This was the first excavation operation that was performed with the robotic arm. One of the main achievements of this test was using the end to end operation using one control procedure with a single platform. This tests also helped the design team to identify the areas for further improvement of the tools as well as the control algorithms. [redacted]

- [redacted]
- [redacted]

- The vac truck faced some technical issues and could not maintain proper suction occasionally during the test which slowed down the operation substantially. [redacted]

Based on the test results and the findings, we have identified improvements to make to the excavator head and the procedure. The ability to utilize the robotic arm for excavation improves the precision in excavation operation. The current focus of the design team is to conduct more tests and improve on the system and the process to make the excavator more robust and effective.

3.2 Sensing

The RRES will employ a combination of sensors and other hardware to detect and avoid a wide range of buried assets and to identify the target asset. To find the most suitable sensors for the operation high potential sensor technologies were identified, and different products manufactured by different vendors were researched and evaluated.

Sensors will be used to scan the roadway above the excavation zone prior to cutting the road surface to identify utility lines and other obstructions in the first layer of the work path.

Pre-Excavation Sensing

After evaluation of all the high potential sensors, based on their capabilities in detecting different assets and the potential of integrating each sensor in the RRES project sensors were selected for procurement and the initial round of in-depth lab testing.

At the RRES mock roadway, the GPR cart has been used to scan and detect the underground utilities, The layout of different pipe and cables buried in the RRES mock roadway is shown in Figure 4. The buried utilities are divided into two group. The first group includes the 4”-to-2” steel, 3”-to-2” HDPE and three 45° angled pipes. They are buried at the depth of 2ft. The second group includes the rest of the pipes that are buried at the depth of 3ft.

[redacted]

[redacted] [redacted]

[redacted] [redacted]

[redacted]

[redacted] [redacted]

[redacted]

[redacted]

Figure 20 - Scanning the RRES mock roadway using the custom GPR system.

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]
- [redacted]

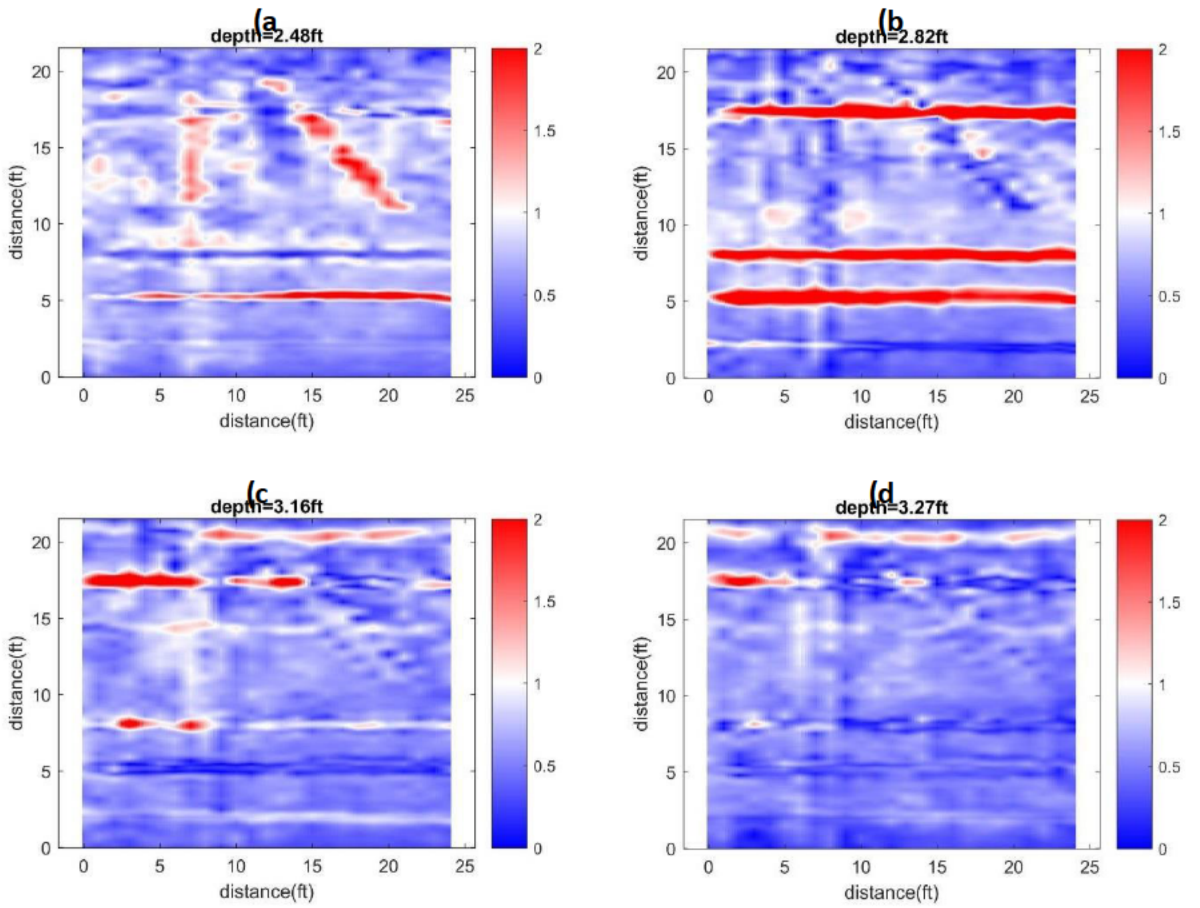


Figure 23 - The C-scan results at different depths [redacted]

[redacted]

[redacted]

[redacted]

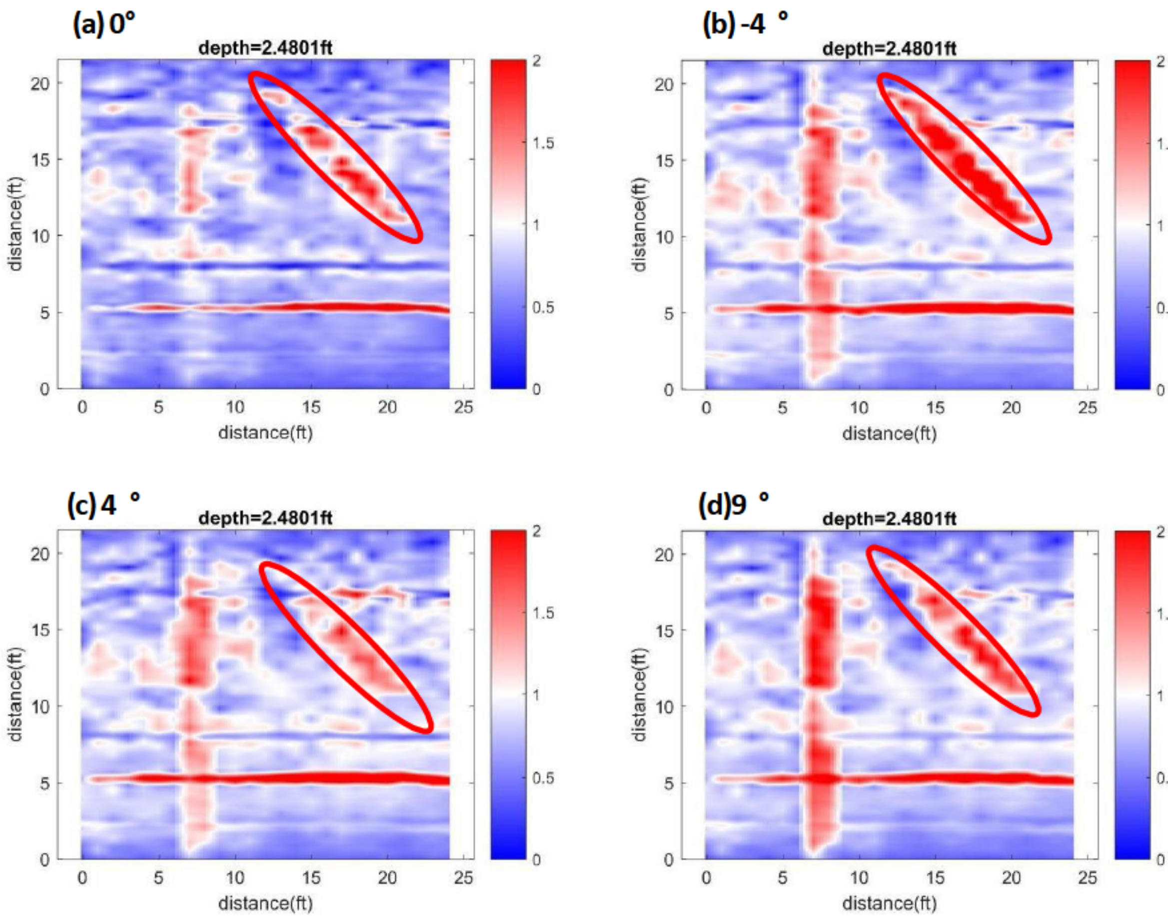


Figure 25 -. The C-scan results at a depth of 2.48ft with antennas placed at different orientations

These two examples demonstrate the importance to have the antenna's polarity aligned correctly with the utility lines to improve the sensitivity as well as increasing the level of confidence is correct detection.[redacted]

Post Excavation

At the current stage of the project, all the software development that was initially done to evaluate different techniques for creating a 3D point cloud of the environment, all the developed technology is being adapted into the operation of the robotic arm and their use cases for the robotic operation are being evaluated. Below is a summary of the work that has been done.

Hardware Selection

ULC Robotics is using two industrial level [redacted] cameras [redacted] to capture high-resolution and small-distortion image. The capture speed of 238fps guarantees the stereo cameras can acquire minimum-blur image even when the robot is moving. Global shutter on the camera can be triggered by external signals to synchronize the image capture and ensure the 3D reconstruction accuracy.

Camera Calibration

A high-accuracy calibration board [redacted] was acquired to calibrate the camera. To further remove negative effects of the external light to the calibration, transmission-based calibration method using backlight source was implemented. Image rectification algorithm was implemented and embedded to the camera calibration to remove the image distortion brought by in-parallel camera installation. This allows tolerance of the mechanical installation of the camera without reducing the 3D map accuracy.

Stereo Vision Algorithm

[redacted]

[redacted]

[redacted]

[redacted]

The goal of this project is to increase the autonomy of the operation as the system is developed and tested. Therefore, any autonomous operation can be developed based on this visualized 3D map. Figure 26 shows the results of visualization of the 3D point cloud around the robotic arm. In the bottom left of this figure the two images captured by the stereo vision cameras are displayed. The gray-scale 3D point cloud generated using the stereo vision algorithm, derived from the two captured images, is displayed in the top left image. In the right image in this figure the depth information about the 3D point cloud is shown in a 3D point cloud environment around the robotic arm. The point cloud in the right image is color coded to create a sense of depth and the distance of each point to the end of the robotic arm.

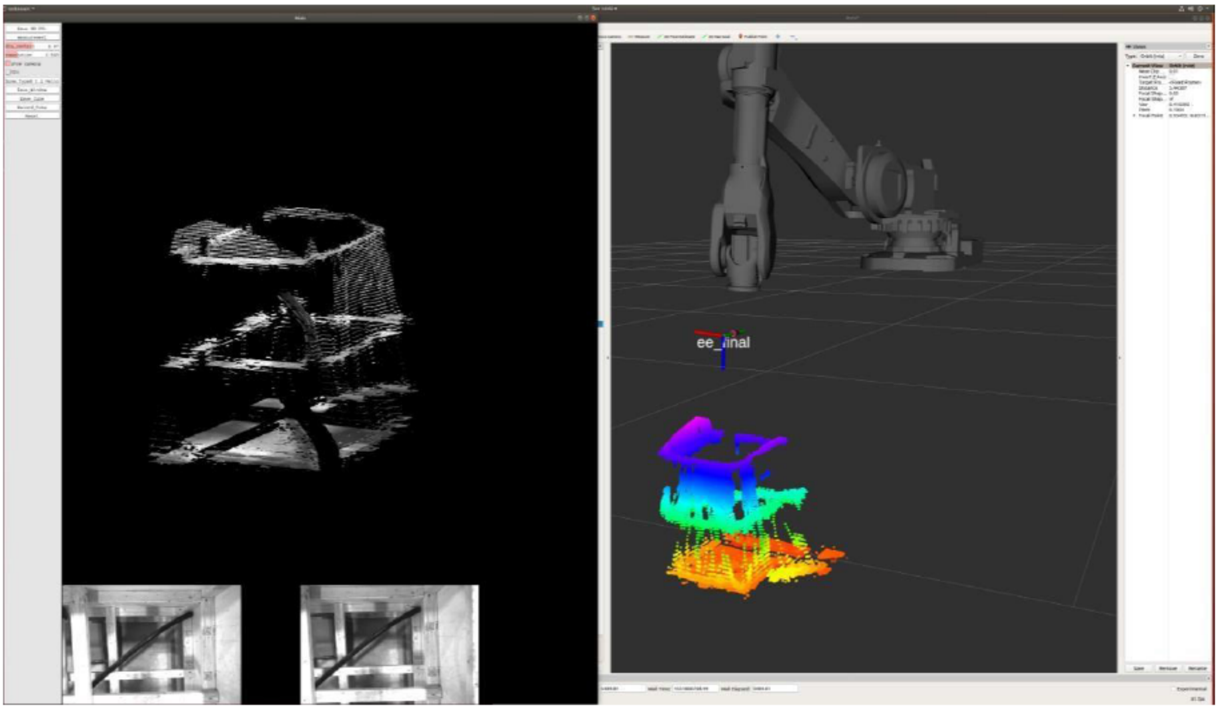


Figure 26 – Visualization of 3D point cloud generated by stereo vision

3.3 Deployment System

In designing the overall system, it was necessary to consider that it was desirable to use a single power source, a battery pack, to power everything in the system. This would allow RRES to be deployed remotely and move freely around site.

The battery pack had to be capable of meeting the power requirements for the entire system. Also, under consideration was the desire to design using commercially available components when possible therefore it was necessary to select combinations of components that would best coexist together using the same power source.

Batteries

In selecting batteries for powering the system, it was necessary to choose batteries that would have adequate capacity to power the system for an entire work day. The batteries must be safe, reliable, robust, and charge quickly. [redacted] The required battery capacity was determined with the assumption that the system will be performing four complete operations per day.

Each operation will consist of the following:

- Movement of the system to and from its trailer to the worksite for a duration of approximately 10 minutes [redacted]
- Operation of the chain saw [redacted]
- Operation of the robot arm [redacted]

Total energy usage per operation was calculated [redacted]

During the battery selection process, several different battery chemistries were examined. After investigating the various chemistries and the commercial offerings of suitable batteries for the application, [redacted]

[redacted]

[redacted]

It was determined that a suitable battery pack would have a nominal voltage of 48V DC, [redacted] have a high level of safety, a high discharge rate, and can be charged quickly.

[redacted].

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

4 Future Progress

The table below lists the key milestones that are planned to be delivered over the next progress period:

Milestone	Description	Due Date
Test plan/report for individual sensor/camera technologies	Complete shop testing of sensors and vision systems (PD6)	06/08/2019
Documentation of assembly progress	Assemble prototype RRES system	15/10/2019
Mobile operations specification document	Develop specifications for mobile platform motion planning and control	12/11/2019
Automated tool changing specification document	Develop specifications for tool changing method and system	26/11/2019

Table 4 –Planned Milestones over next PPR period

5 Business Case Update

No modifications have been required to the business case which remains valid in its current form.

6 Progress against Plan

The project has progressed as planned. The Gantt chart shown in figure 30 shows the project plan for Element 1 and 2.

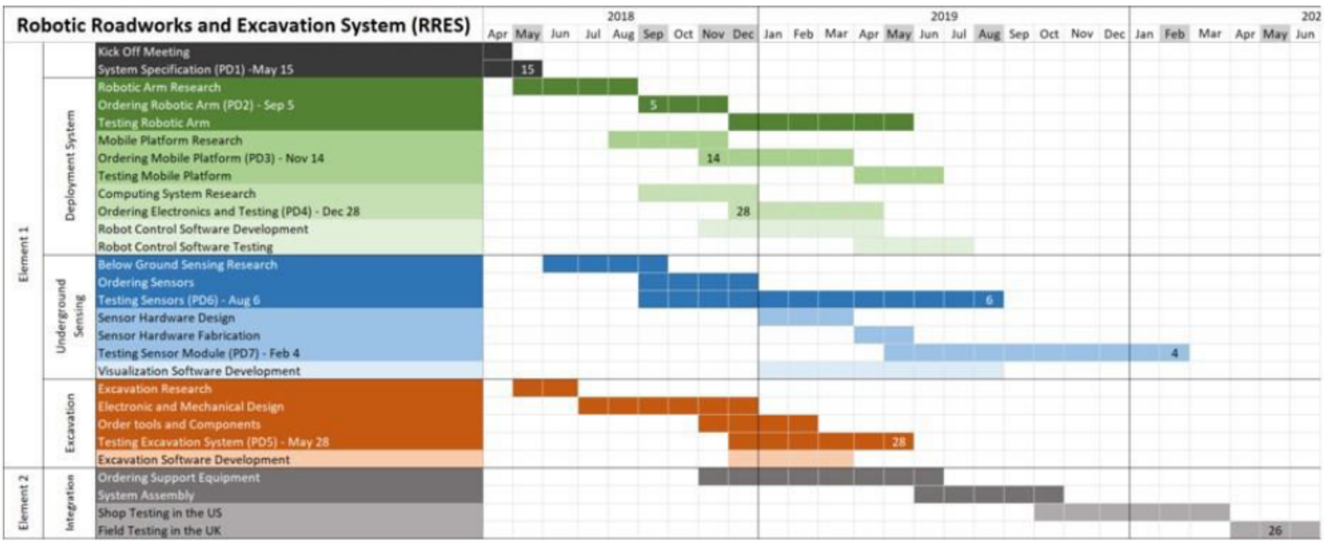


Figure 30 – Project Plan

Below are the milestones that were delivered on time as per this PPR period. Also, the planned millstones over the next progress period have been included:

Milestone	Title	Description	Planned Date	Delivered Date
12	Progress Report 3 Sensor module design documentation	Complete mechanical and electrical design of sensor module	02/04/2019	Approved
13	Test plan/report on prototype excavation tooling	Complete shop testing of prototype excavation tooling	28/05/2019	Approved
14	Test plan/report on mobile platform	Perform mobile platform design modifications and testing	25/06/2019	Approved
15	Documentation of design and build progress	Documentation of design and build progress	09/07/2019	Approved
16	Progress Report 4 Test plan/report for individual sensor/camera technologies	Complete shop testing of sensors and vision systems	06/08/2019	Awaiting Approval
17	Documentation of assembly progress	Complete shop testing of prototype excavation tooling	28/05/2019	On Target
18	Mobile operations specification document	Perform mobile platform design modifications and testing	25/06/2019	On Target
19	Progress Report 5 Automated tool changing specification document	Documentation of design and build progress	09/07/2019	On Target

Table 5 –Delivered Key Milestones

7 Progress against Budget

As the project has progressed as planned, the total expenditure to date is £ 3,320,873. A further £120,785 is set to be released on the 07/08 for the successful delivery of milestone 15.

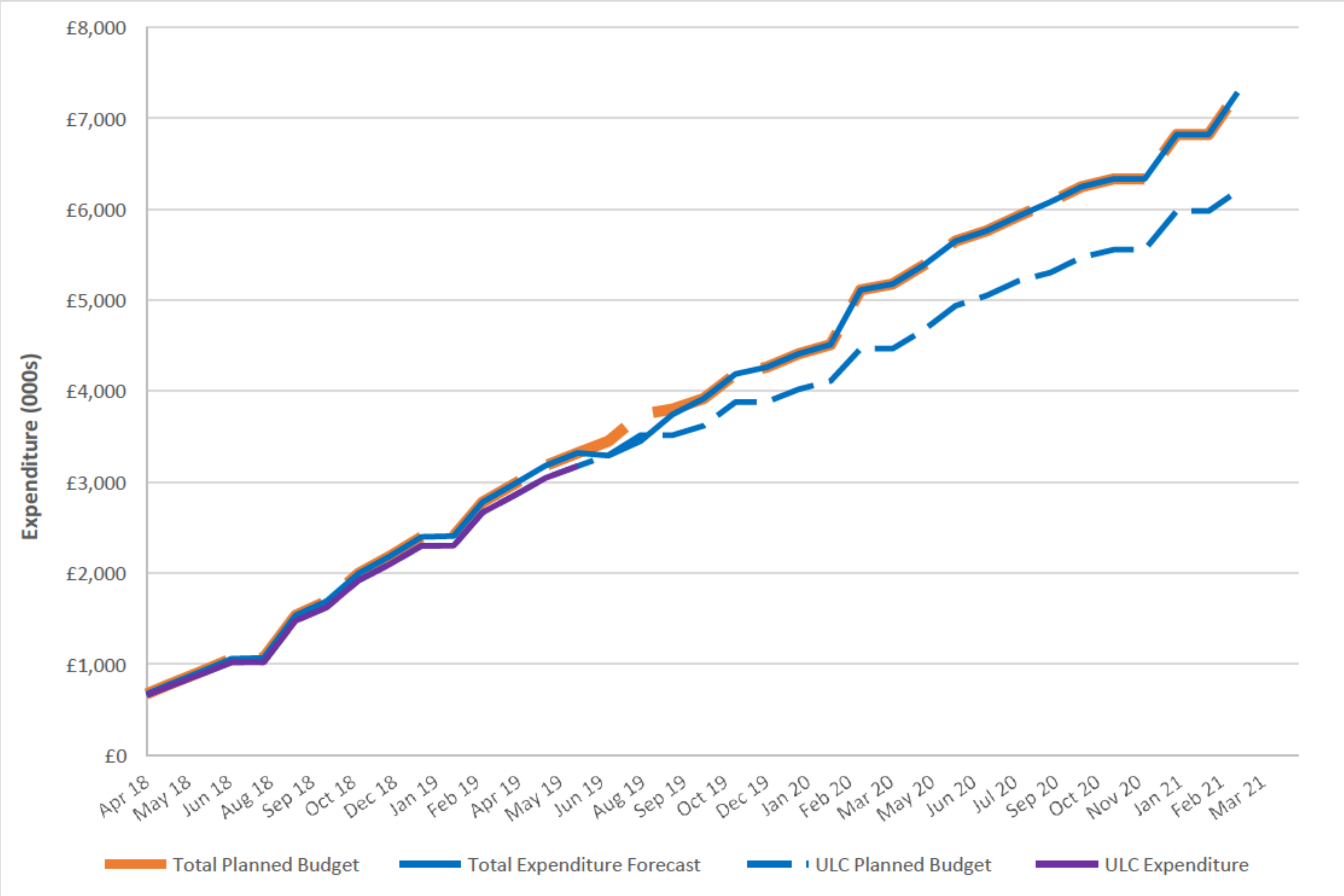


Figure 31 –Financial Overview

Milestone	Title	Main Project Achievements	Amount	Project Total	Status
12	*Progress Report 3* Sensor module design documentation	Design and fabrication of electronics to drive the mobile platform Design of a fiberglass cover for the robotic arm Fabrication of the parts for chassis Developing a migration algorithm for automatic processing of GPR data Testing the chainsaw operation using different chains Integration of the haptic device control into the robotic arm operation Creating a 3D model of the buried assets based on the GPR raw data Patent application on GPR data collection and processing technique	£190,398	£2,855,962	Paid
13	Test plan/report on prototype excavation tooling	Shop testing of the prototype excavator Chassis assembly and installation of the robotic arm onto the chassis	£190,932	£3,046,894	Paid

		Assembly of electronics and power system Testing the untethered driving system using the batteries Excavation tests using the 6" excavator hose and angled nozzles Study of Vac trucks and requirements of the support vehicle			
14	Test plan/report on mobile platform	Perform mobile platform design modifications and testing Design of the new chainsaw for cutting the road Integration of the excavator into the robotic arm operation Fabrication of boards and wiring the batteries and electrical components mounted on the chassis Static and Dynamic FEA of the chassis in different scenarios Program development for force feedback operation of the robotic arm	£129,566	£3,176,460	Paid
15	Documentation of design and build progress	Documentation of design and build progress Finalization of the design of the battery compartment Testing the 3 phase invertor setup for fully untethered operation Ordering and fabrication of parts for the new chainsaw Design of the power system for operation of the new chainsaw Modifications to the excavator head with different arrangement of the nozzles Finalization of the design of the new mock roadway Excavation test using the robotic arm	£120,785	£3,297,245	Approved
16	*Progress Report 4* Test plan/report for individual sensor/camera technologies	Complete shop testing of sensors and vision systems Installation of the chainsaw on the robotic arm Building the new mock roadway Testing the GPR antennas in the Clay environment Modifications to the excavation operation using the robotic arm Development of noise filtration techniques to eliminate 3D point cloud noise Engaging MTC in development of cutting bits for the chainsaw	£218,793	£3,516,038	Awaiting approval
17	Documentation of assembly progress	Assemble prototype RRES system	£103,827	£3,619,863	On Target
18	Mobile operations specification document	Develop specifications for mobile platform motion planning and control	£111,120	£3,730,983	On Target
19	Progress Report 5 Automated tool changing specification document	Develop specifications for tool changing method and system	£151,110	£3,882,093	On Target

Table 6 – Planned Key Project Deliverables

8 Project Bank Account

The statements for the transactions of the bank accounts for the NIC funds over this reporting period are available in appendix B.

9 Project Deliverables

In addition to the milestones completed as per the previous project progress reports, there have been a further 4 milestones delivered. The subsequent reports have been submitted to SGN and are available on request.

Sensor Module Design Document

The purpose of this report is to demonstrate the development efforts that has been carried out in the selection and evaluation of the sensors for the RRES system leading to the procurement of sensors and hardware for shop testing.

Test Plan/Report on Prototype Excavation Tool

The process of excavation is composed of two main tasks to be carried out by a robotic arm (1) cutting and removing the road surface (2) “soft-touch” excavation to agitate and remove the soil. The purpose of this report is to demonstrate the progress that was made by ULC Robotics in each of these areas and the plans for further development of these operations.

Test Plan/Report on Mobile Platform

The purpose of this report is to demonstrate the development efforts that have been carried out by to ensure proper selection of the mobile platform, design, and build of the chassis and integration efforts that make the system mobile.

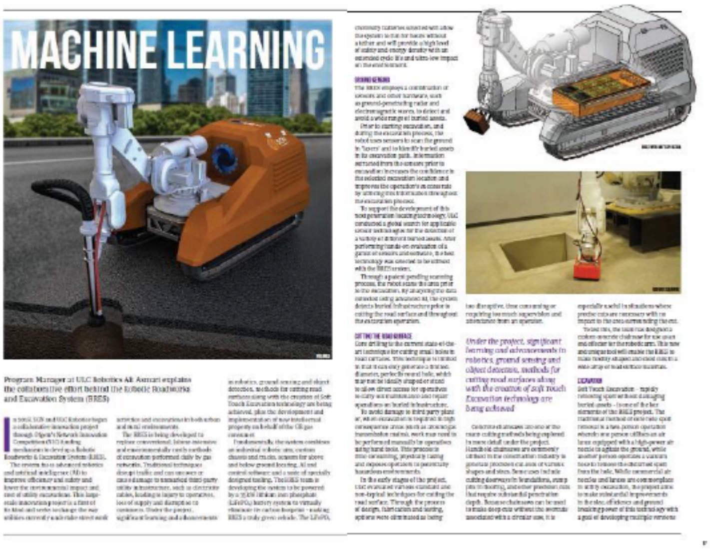
Documentation of Design and Build Progress

The purpose of this report is to demonstrate the development of control algorithms for control of the robotic arm during the excavation operation.

10 Learning Outcomes

The main outputs of this project are the technical and engineering knowledge gained whilst researching new methods to assess and remediate the existing gas distribution network. Therefore, it is essential that learning opportunities generated by this project are successfully disseminated for GB GDN’s, the wider gas community, national and international standard bodies, academia, local authorities and other key stakeholders. Learning will be disseminated so that the technology can be incorporated by all GB GDNs upon successful completion of the project.

Over the duration of this PPR, it was an eventful dissemination period with RRES receiving a lot of publicity across different sectors. Presentations at utility week live conference, along with an article in the Gas International publication has helped dissemination across the utility industry.


MACHINE LEARNING

Program Manager at ULC Robotics Ali Asmari explains the collaborative effort behind the Robotic Roadworks and Excavation System (RRES)

Figure 32 - RRES Article in Gas International Magazine

Figure 33 - RRES presentation at Utility Week Live

Furthermore, at Utility Week Live, the machine learning and artificial intelligence that is being produced through RRES was presented as part of the Technology and Transition Keynote session. The session examined the potential of machine learning and AI, as well as assessing the impact they have already made on the utilities.

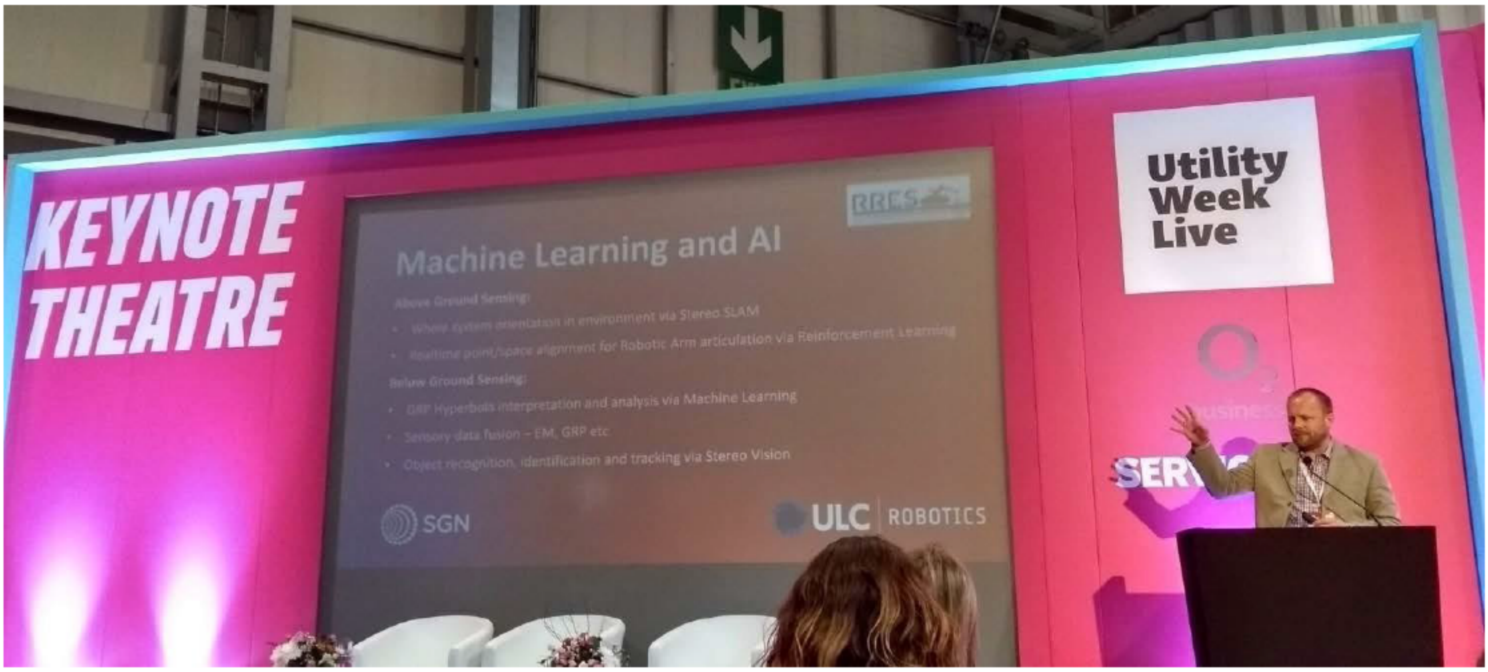


Figure 34 RRES presentation at Utility Week

A summary of the key learning outcomes and dissemination is shown in table 7.

Key Learning Outcomes

Cutting the road surface -Our testing has creating substantial learning in determining the performance criteria that impacts cement road surfaces.
Excavator Head - The most effective approach to agitate and excavate the soil was determined.
Pre-Excavation Sensing - Proper rotation of the GPR antenna can improve the detectability of the buried utilities.
Internal Dissemination
RRES update as part of innovation update within our executive monthly report
Steering Group Meeting was held in June with representatives from across the business including; legal, operations, Safety and Policy.
External Dissemination
At Utility Week Live, SGN and ULC had stands where RRES project information was disseminated to the utility industry. Also, RRES was presented as part of the keynote and innovation session.
An update of the progress made by the RRES team was presented at the IGEM AGM for the London Section.
Article in May's Gas International magazine which articulated the collaborative effort behind RRES.
RRES promotional video created by ULC and shared on Youtube

Table 7 – Summarry of learnining outcomes

11 IPR

In accordance with the Gas network Innovation Competition Governance Document, ULC Robotics will report on intellectual property rights (IPR) being pursued on the project. There is one application outstanding, however as the project progresses, additional filings will be pursued as several key parts of the system are finalised.

Application Type	Description	Application No.	Receipt Date.
US Provisional Patent	GROUND PENETRATING RADAR SYSTEM AND METHOD	62821107	20/03/19

Table 8 –Summary of patents

12 Risk Management

The live risk register that identifies risks and scores them appropriately is attached in appendix C. Notable updates to risk register are shown below:

Challenges with cutting the road surface

There is a risk that the designed chainsaw tool for cutting the road surface cannot cut the core in a timely manner. However, rigorous testing has commenced to understand the criteria that affects the cutting performance. This learning has been integral in the design iterations that have shown vast improvements when we come to retesting. Our plan is to further develop the subsystem with the aid of MTC, and carry out further testing in different environments, before we can retire this risk.

Limited Below Ground Detection Capability

There is a risk that the sensor suite is unable to detect all buried objects. [redacted] By using a robotic arm, scans with different angles can be conducted very accurately and fast. The probability to miss utility lines is minimized. [redacted]. More realistic testing is planned to ensure this risk is mitigated.

13 Accuracy Assurance Statement

The commercial and technical deliverables associated with this project are progressing on time and within budget. We confirm that we are following relevant SGN process and procedures in order to ensure that the information provided within this report are accurate and complete at the time of writing.

14 Material Change Information

No material change has occurred.

Appendix A - Additional Reports

Below are the milestone reports that are available on request:

Report
Sensor module design documentation
Test plan/report on prototype excavation tooling
Test plan/report on mobile platform
Documentation of design and build progress

Table 9 –Milestone Reports across PPR4

Appendix B - Bank Statements

[redacted]

May Statement

[redacted]

[redacted] **Statement**

[redacted]

July Statement

[redacted]

August Statement

[redacted]

Appendix C - Risk Register

Ref	Risk	Business Risk	Inherent Risk			Controls & Mitigation	Owner	Anticipated Date for Retiring Risk (DD/MM/YYYY)	Residual Risk		
			Likelihood	Impact	Score				Likelihood	Impact	Score
1	**Project Team Resource Requirements** There is a risk that ULC Robotics and SGN will not be able to hire personnel in time for the project start date. *SGN have decreased the risk of resources by hiring a designated officer to the project. MTC resource has been aquired for the cutting the core package.*	Time / Financial	1	3	3	A - Generate requisitions and start hiring as soon as bid is approved. B - A 6-month lag between project award announcement and project start date to allow time for the required resource to be found and appointed before the project starts. C - ULC has a the option of moving resource from other projects or utilise additional resource available at the MTC.	ULC, SGN	01/04/2018	1	3	3
2	**Challenges with Single Arm-to-Toolhead Interface** IF a single robot arm-to-toolhead interface design cannot accommodate all end effectors due to variations in toolhead size, weight, power, and technical complexity, it may result in increased operational complexity.	Time / Financial / Technical	3	3	9	A - Development of the preliminary arm-to-toolhead interface specification has been scheduled to accommodate estimated toolhead specifications. B - Design, development, and testing of tools to be reviewed by robotic arm expert for feedback and modification of the design.	ULC, TSP	28/05/2019	1	3	3
3	**Limited Below Ground Detection Capability** The sensor suite is unable to detect all buried objects due to varying object types and sizes, sensor capabilities, and depth of excavation additional process may need to be added to the operation of the RRES which could increase the time and cost of the operation.	Technical	2	5	10	A - Soft touch excavation tooling will provide additional safety redundancy to support risk mitigation. B -Initial research has been carried out in early concept phases of the project to identify the sensor types available which meet the current requirements. C - Build a test environment that simulates the variations in the relevant ground conditions and buried infrastructure. D - Consult with sensor vendor and develop additional sensor data processing techniques to improve buried object visualization. E - Use a combination of different sensors to increase the level of confidence in accurately detecting the targets	ULC, SGN, TSP	02/02/2021	1	3	3
4	**Truck Size Exceeds Maximum Size Limit** All of the necessary tools, sensors, mobile drive platform with arm, operator control station, support equipment and other accessories need to be transported to site in a vehicle which maintains a minimal site footprint and comply with UK highway vehicle regulations.	Time / Financial / Technical	2	5	10	A - Create 3D model of truck with sensors, tools and mobile platform. Develop layout and operator control workstation volume mark out. Determine estimate of size requirements. B - Design modifications to truck to increase storage volume and develop alternate mounting concepts. C - Evaluate low utilization tools, sensors and support equipment and consider transporting them to site only on-demand. D - Review vehicle specification requirements for the target areas of operation and the potential to separate out support equipment into multiple small vehicles instead of one larger one. E - Decrease the overall weight of the system through design and build optimizations	ULC, SGN, TSP	16/03/2021	1	4	4
5	**Field Trial Location Challenges** Suitable field trial locations for initial controlled testing, urban and rural sites cannot be found.	Time	2	2	4	A - SGN to carry out a review of criteria and identify multiple site locations which could be used for the trial. C - SGN and ULC to survey potential sites to determine suitability well in advance of the trials B - Engagement sessions with local authorities will be carried out in advance of the trial to ensure relevant stakeholders are supportive of the project and trial requirements.	ULC, SGN,	02/08/2021	1	2	2
6	**A Commercially available Robotic Arm Cannot Meet project Specification** ULC will identify and purchase an commercially available robotic arm to perform the excavation, pipe preparation, and installation of the UAF. If there isn't an arm that can complete all operations for the budgeted value there is a risk to the project budget and scope.	Time / Financial	3	4	12	A - Develop the operational strategy, tool specifications and end effector specification early when developing robot arm requirements. B - Consider options for increasing the capabilities by using other strategies such as multiple arms, end-effectors with increased degrees-of-freedom, robot arm support mechanisms to withstand larger loads etc.	ULC	12/05/2020	2	4	8
7	**Suitability of UAF for live gas installation** If the UAF design and installation procedure doesn't meet the required industry standards or performance criteria there is a risk it's use on live gas infrastructure will not be approved.	Technical	3	4	12	A - The relevant design and performance specification and designs will be identified and influence the UAF design. B - A test criteria will be agreed and extensive shop testing will be performed using field pipe of various conditions. C - An independent review of the fitting will be carried out and the process for the application of relevant industry approvals will have begun.	ULC, SGN, TSP	27/10/2020	2	3	6
8	**Use of the RRES does not meet SGN's Safety Management Framework Requirements (SMF)** If SGN does not provide approval for the RRES to operate in a field test due to inability to meet SMF requirements, the RRES design or operation may have to be modified, resulting in increased cost and time.	Financial/ Technical	3	3	9	A - The SGN Project Steering Group will contain leads from the Engineering Policy, Safety Health & Environment and operations to influence the development process and ensure the design meets all safety requirements. B - Engage with SGN Policy and Safety leads and consult with industry bodies including Ofgem and HSE to ensure all requirements are met. C - SGN will appoint an independent Technical Service Provider with a detailed understanding of industry requirements to review the development process.	ULC, SGN, TSP	27/04/2021	1	3	3
9	**RRES Usage is Limited Due to Component Compatibility with Hazard Area Requirements** Once the system has been conceptually designed a review will be carried out to assess its suitability for key components use in all of the target environments. If the specification does not meet the requirements of the review or control measures are required it could cause a delay to the project and additional cost.	Financial/ Technical	3	5	15	A - Incorporate a safety review process into the design of each component. Develop a checklist for collaborative design reviews with the project team. B - Incorporate a safety risk management program that identifies, assesses and mitigates safety risks. C - An independent review will be carried out by the technical Service Provider at key stages of the project to identify risk as they become apparent.	ULC, SGN, TSP	11/05/2021	1	5	5
10	**Scope Creep** If agreed system requirements or the agreed project scope changes late in the project the cost and time needed to complete the project could increase.	Financial/ Technical	2	3	6	A - ULC and SGN collaborate and finalise the specifications. B - SGN will create a Project Steering Group with leads from key areas of the business. The key component specification will be agreed with all members before being finalised to ensure all requirements have been met to mitigate the risk of any changes to the specification being requested later in the development process.	ULC, SGN, TSP	30/10/2018	1	3	3

11	**Communication between Project Team** Communication channels between the project team who are spread across the UK and USA at different time zones cannot be maintained.	Time / Financial	2	4	8	A - Face-to-face meetings for key stage gate deliverables B - Use of virtual meeting center and secure file share C - Regular interface meetings with the project team	ULC, SGN, TSP	27/10/2020	1	4	4
12	**Vendor Supply** Sub-contractor manufacturers and supplier delays could affect the overall schedule.	Time / Financial	3	4	12	A - Review project plan if required for sourcing sub-contracted vendors B - Engage a number of different suppliers to ensure continuity of supply where possible.	ULC	15/04/2021	2	4	8
13	**Stakeholder Opposition** A negative customer and wider industries perception of the project could cause issues with obtaining the necessary approvals for access to trial sites and impact wider industry acceptance of the technique.	Reputation	1	4	4	A - Implement and maintain a stakeholder management plan. B - Input from the SGN Regulation and Corporate Communications Officer to ensure high level of engagement with customers as early as possible. C - Presentations at industry events	SGN, ULC	02/03/2021	1	4	4
14	**Logistical Challenges** There is a risk that customs and shipping difficulties could delay deployment of the system to the UK from the US.	Time / Financial	2	3	6	A - Additional shipping time has been including in the project schedule for shipping and customs. B - Controlled testing facilitates will be identified to allow final preperations works to take place in the geographical area of SGN's network, allowing the system to be shipped ahead of the live field trial with limited impact on the test schedule.	ULC	15/04/2021	1	3	3
15	**Poor RRES Market Uptake** If the RRES market uptake is poor, the full value of the RRES as described in the cost-benefit analysis may not be realised.	Financial	1	4	4	A – Distribute customer and stakeholder questionnaires to ensure that customer needs are being addressed B – Design of soft-touch excavation tooling and below ground sensing systems will be evaluated for use without the use of robotics so as to enable operation and commercialisation without the use of a robotic arm C – Disseminate Interface Control Drawing (ICD) for open-source tooling to enable maximum market size potential through alternative application development D – Continue to seek out project partners in the utilities and industrial sectors	SGN, ULC	TBD	1	3	3
16	**Low RRES Utilisation** If the RRES utilisation is low, the cost per excavation will continue to increase and the full value of the RRES outlined in the cost-benefit analysis may not be realised.	Financial	2	4	8	A – Design control algorithms for mobile platform and toolpath generation such that the size and shape of excavations that can be performed is maximised B – Disseminate Interface Control Drawing (ICD) for open-source tooling so as to maximise the number repair and inspection operations which can be performed on excavated infrastructure	SGN, ULC	TBD	1	3	3
17	**Project Delivery** There is a risk that the project scope cannot be delivered within the allocated budget and schedule.	Time / Financial	2	3	6	A – Use a phased approach to project planning with go/no-go milestones such that the project can be reevaluated upon completion of key milestones and terminated if needed B – Maintain a prioritised list of potential scope reductions that can be exercised if needed (e.g. elimination of automated tool changing, UAF installation tooling, etc.); C - Pursue funding from alternative sources such as customers in industrial markets or venture capital firms	SGN, ULC	TBD	1	3	3
18	**Challenges with cutting the road surface** There is a risk that the designed chainsaw tool for cutting the road surface cannot cut the core in a timely manner. *Rigorous testing has commenced to understand the criteria that affects the cutting performance.*	Time / Financial	2	3	6	A – Design alternative solutions for setting the core such as endmill or a traditional core drill B - Conduct tests in different surface environments with a variety of depths of cut C - Development of different chains and cutting teeth for the chainsaw for operation in different environments D - Engage with tool manufacturers to develop custom made tools for the designed chainsaw	ULC	28/05/2019	1	3	3

Table 10 – Risk Register