NIC 2018 -RRES Project Progress Report 3
Element 1

2nd April 2019

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SGN©

Co-Authors:

ULC Robotics
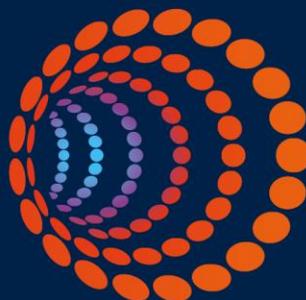
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Contents

Document Control

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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 26th December 2018. 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 RRES' sensing and excavation technology. Below is a list of the major achievements by the development team during this period of the project.

- Full assembly and testing of the CNC machine
- Design and assembly of the chainsaw for cutting the concrete
- Development of a new excavator head with flexible nozzles
- Building a test site for evaluation of the excavator head
- Design and build of the mock roadway for testing the sensors
- Development of stereo slam for 3D mapping of the excavation environment
- Design and assembly of a base platform for the robotic arm
- Installation of the robotic arm and development of control algorithms
- Chassis design and FEA analysis for the robotic platform
- Design of the electrical components and power management system for the robot

The content of this report and the identified 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.
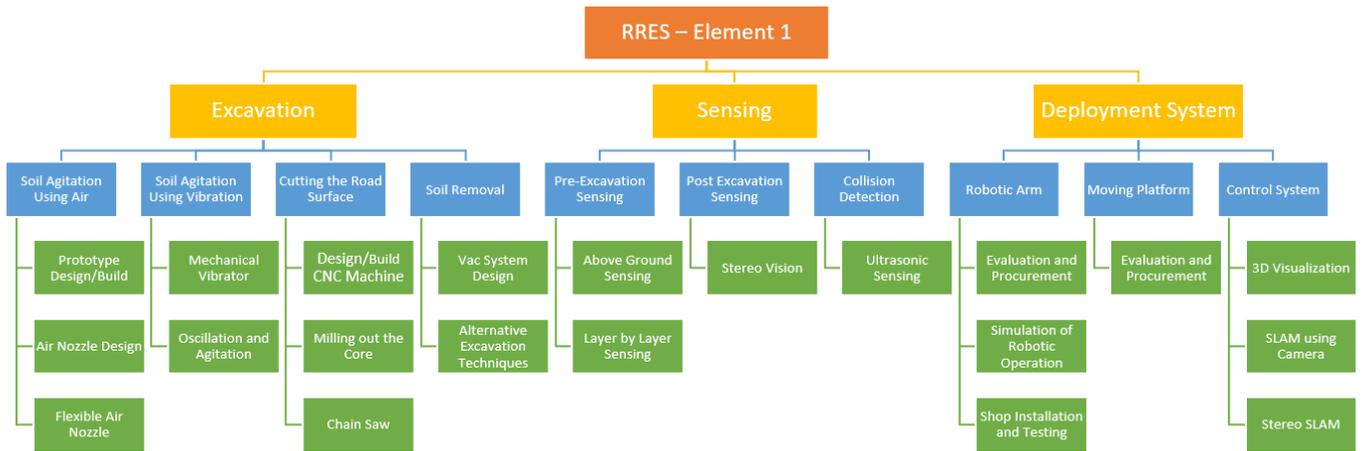
Figure 1 – Element 1 Overview

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.
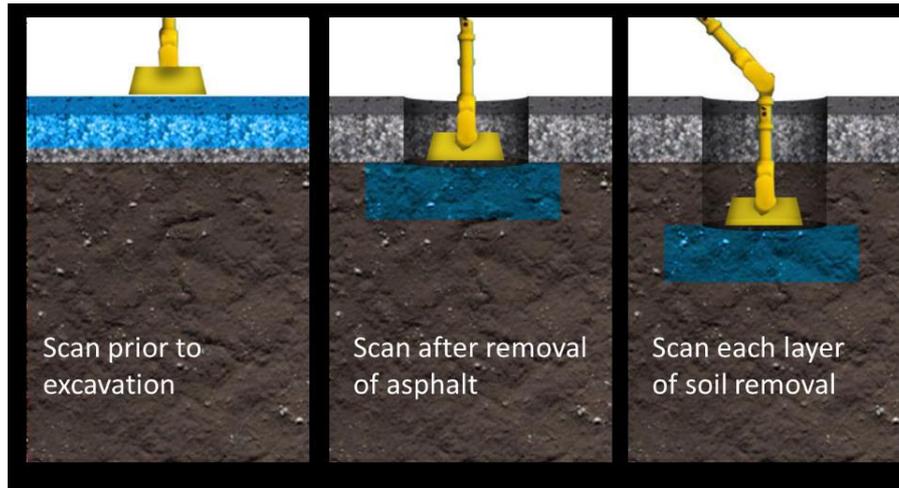
Figure 2 – Below Ground Sensing

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

The project has entered an exciting time where the theory and research conducted during the first stages of the project are being put through extensive testing. The results of these tests are being fed back into the ultimate design. There has been substantial development in the excavation and sensing subsystems.

3.1 Excavation

One of the main benefits of RRES is the ability to excavate the ground without causing any damage to the buried utilities. During this PPR period, we have made developments within the cutting of the road surface and the excavation head which will contain the air nozzles that will agitate the soil.

Cutting the Road Surface

The RRES operation is intended to cut the road surface with minimum assistance from the operator. Deployment of the cutting tool using a robotic arm provides a high level of accuracy and precision to the operation. Since the process of cutting the concrete using non-traditional equipment and tools such a robotic arm has not been commercialized, there are many unknowns involved with the design

of a proper tool for the application such as the amount of load and torque applied to the robotic arm's end effector throughout the process of cutting.

To properly evaluate and study these factors during the cutting process a 3 DOF CNC test platform was designed and build. ██ ██ The concrete CNC machine will be an intermediate step in the development of tools and end effectors for the robotic arm.

Once the system was assembled and calibrated, testing of the tooling started. ████████████████ ██

Endmill Cutting

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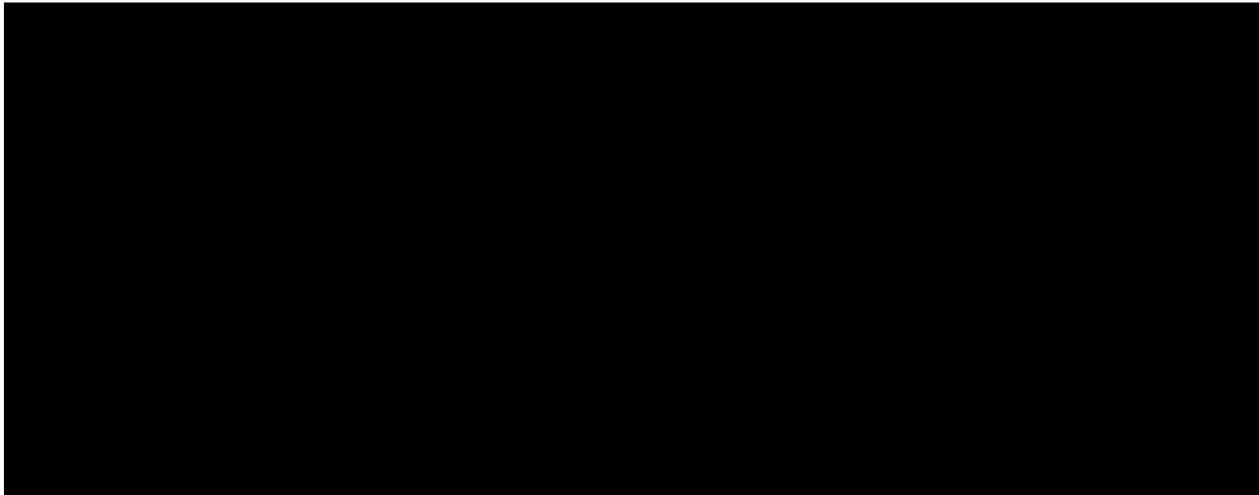
Cutting concrete with endmills were found to be successful and effective. Based on the test results the endmill is more than capable of cutting the concrete and aggregate.████████████████████████ ██ The project team are in the process of contacting endmill manufacturers to custom make more tools for deeper and thinner cuts.

Chainsaw Cutting

One of the various cutting methods explored in the initial phase of the project is the use of a concrete chainsaw for cutting. Handheld concrete chainsaws are utilized in the construction industry for many purposes, most of which include precision sawing. Some uses include cutting doorways in foundations, sump pits in flooring, and many other precision concrete cuts that require substantial depth. ██ ██ ████████

After the chainsaw was mounted to the CNC machine, testing of its performance was evaluated. The teeth of the chainsaw can be shown in figure 3.

Figure 3 - Chainsaw teeth showing diamond grit segment

Initial cuts with the chainsaw were successful, and the process was found to be more than capable of cutting concrete and aggregate at high speed. ██ ██

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Figure 4 Chainsaw cut - circle, triangle and straight lines for testing

Currently, chainsaw development and testing occupy most of the time on the system. ███████████ ██ ██ ██

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- Using pre-scan data to locate steel reinforcement and surgically snip it before high-speed cutting
- Alternate cutting tools for use exclusively on the steel reinforcement after exposing it
- More powerful chain drive motor – currently, on overload, the chain motor detects the condition and gracefully shuts down. While the motor used in the system is more powerful than the one normally used with these chains (7.5kW versus 5kW), it is conceivable that a more powerful motor would be able to safely get more performance out of the chain. Further research is necessary to determine how much more force can safely be put into the chain.

Soil Agitation

To agitate the soil, the excavation head will have integrated air nozzles that will control the characteristics of the air profile. As the air nozzle design will be critical in breaking up the different types of soil structures, research and testing is ongoing into determining the most optimum design. Simulations with different designs have been conducted to understand the most promising designs that will be added to the prototype for the excavation head.

After successful simulations, we designed 2 innovative nozzles and measured their performance against a commercially available nozzle. The selected nozzles are: (1) a commercially available straight nozzle, (2) ULC designed minimum length, and (3) ULC designed gradual expansion nozzle.

(a)   (b)
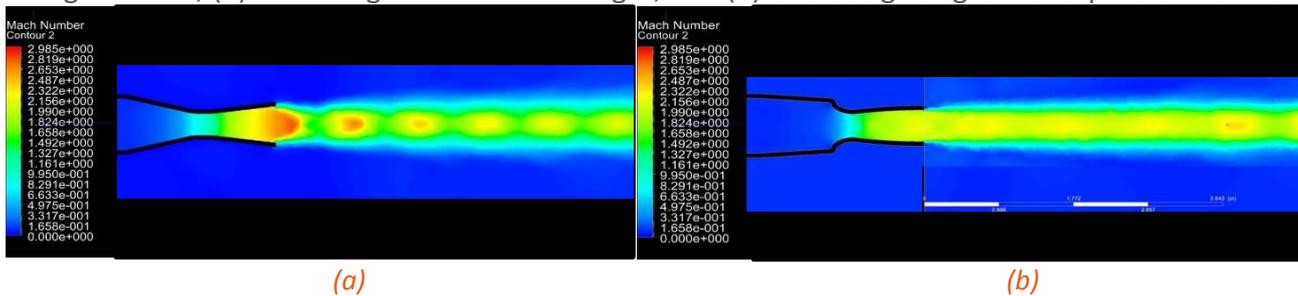
Figure 5 - Simulations of the 2 designed air nozzles: (a) Gradual Expansion and (b)Minimum Length

A minimum length nozzle is used when size and weight are critical, which is why they are used for rocket engines. These nozzles utilize complex curves and a sharp throat exit to help facilitate rapid expansion of the gases creating the supersonic flow. They are capable of producing supersonic air speed and large thrust in a more compact package. The calculations and manufacturing are more complicated and require higher precision.

A gradual expansion nozzle will produce a more stable and higher quality flow at the exit, is easier to design, and is easier to manufacture. This design is more typically suited for supersonic wind tunnels. The downside to these nozzles is that due to their more gradual formation of the sonic and supersonic flow, they are larger and heavier.

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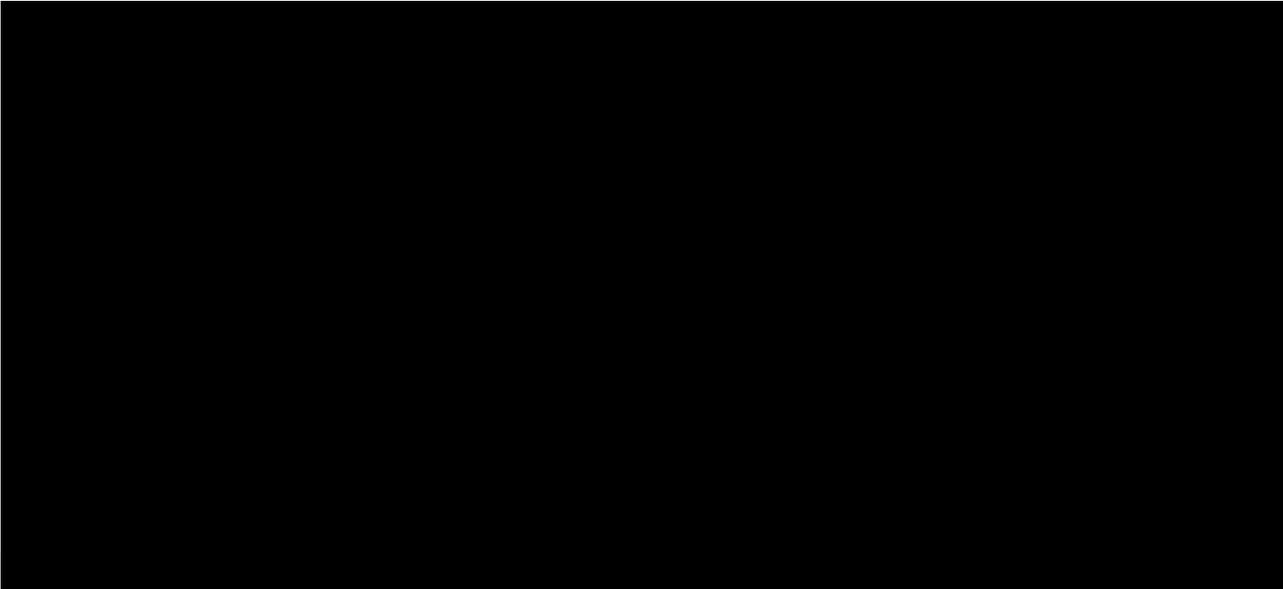
From the testing it was proved that we were able to design and produce supersonic air excavation nozzles in two different styles that, in many aspects, outperformed the commercial nozzle. With our knowledge, we can provide a more custom solution for our excavator and have a more specialized excavator tool. At the present time, we have adequate information through simulations and environmental testing to feel confident that we have a sound and effective design.

Excavator Head Design
The RRES Excavator head is an integral part of the RRES project. It 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. We are testing high promising designs and will finalise design once testing has been completed.

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Figure 7 - Excavator head mounted at the end of the robotic arm

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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. Although not in the scope of work, ULC is reviewing the sensors that may be used to increase the confidence in the selected location for excavation.

After evaluating all the findings from the previous phases of the project, a comprehensive study was conducted by ULC Robotics on possible sensor technologies that can be beneficial in pre-excavation sensing. Below is a list of high potential technologies that were selected for more in-depth research:

Tech	Pros	Cons	Target
GPR	████████████ █████ ████████████████ ███████████ ██████████ ██████████ ████████████	██████████████ ████████████ ████████████ █████████████████ ██████	Metal, Plastic, Concrete
Acoustic	█████████████████ ██████████████ ██████ ███████████ ███████████ ███████	████████████ ██████████████ ████████████ ██████ █████████████████ ██████████████ █████ ███████████████ ███████████████ ███	Metal, Plastic, Concrete
Magnetometer	███████████████ ████████████████ ██████ ██████████████ █████████████ ██████████ █████████████ ███████████ █████████	██████████████ ███████████████████ ███████████████ ██████████ █████████████████ ████████████ ███████████ ███████	Ferromagnetic and magnetic objects, Metal with current
EM	███████████████ ██████████████ ██████████████ ███████████	██████████████████ █████████████ █████████ ███████████	Mostly metal conductor

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Table 2 - Summary of sensor technologies

To understand the capability and limitation of each technique, controlled test environments were necessary to test each technique in detecting various types and sizes of buried material. To understand the capability and limitation of each technique, a controlled lab environment was necessary to test each technique in detecting various types and sizes of buried material.

Therefore, various test environments have been designed and built at ULC Robotics to test the sensor performance. The soil box and mock roadway are illustrated below:
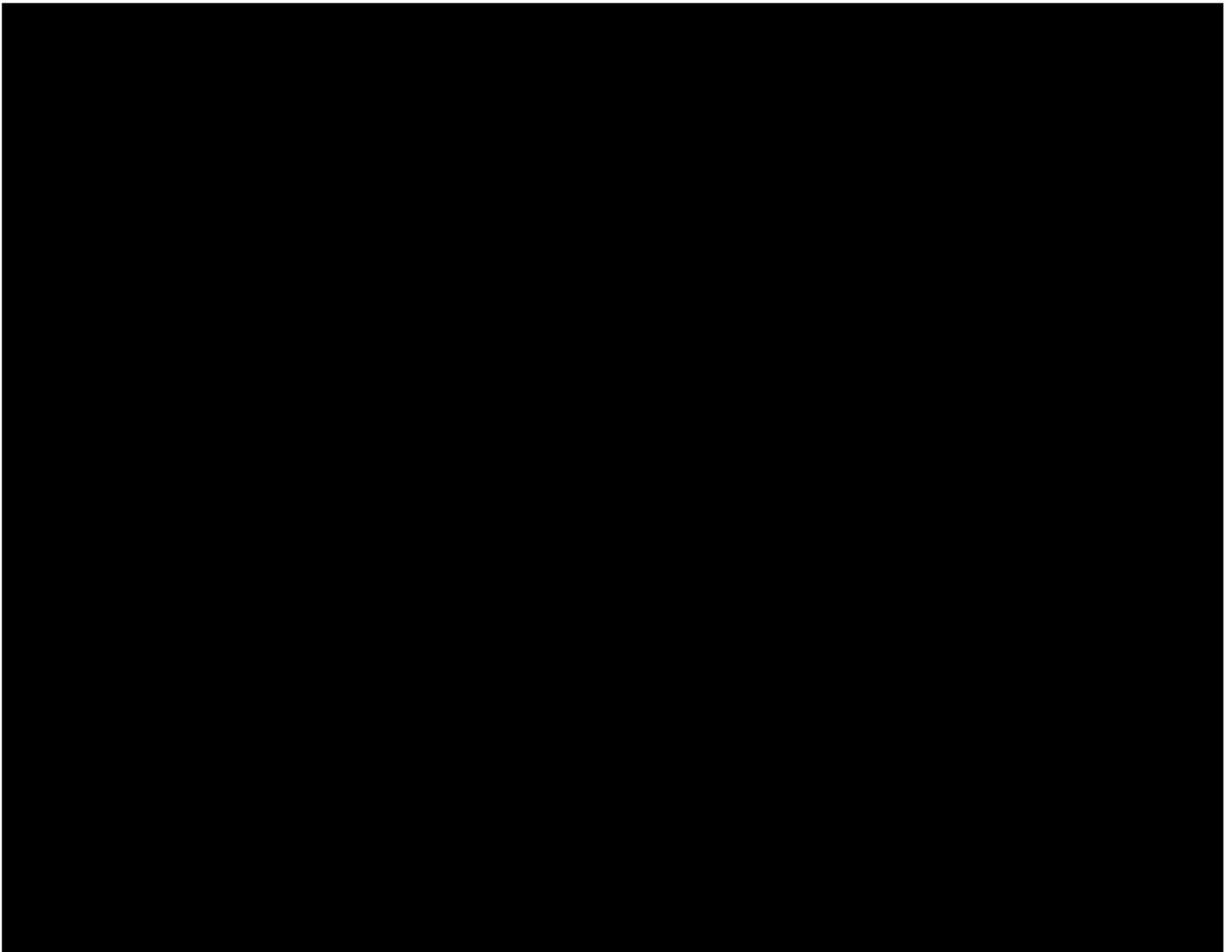
The sensing technology was used to detect the typical utility infrastructure within the test environments to measure their performance. The results for each technology have been sectioned below.

GPR

GSSI is one of the major GPR manufacturers and produces a variety of antennas with different centre frequencies for different depths of penetration. To test antenna frequency impact on the GPR signals, GSSI application specialist was invited to visit ULC to provide a demo of their products.

Five different frequency antennas were brought to ULC for testing on the internal built soil box. The antennas were connected to GSSI handheld SIR 4000 equipment for data collection. The scanning was driven by stepper motor linear motion control system that was built on top of the soil box. The speed and scan distance are controlled by PC software. The purpose of this test was to verify which frequency is the best to obtain strong and clean reflections from the buried objects in the soil box. GSSI also brought their underground survey GPR antenna installed on a mobile cart. Therefore, some experiments were conducted in the ULC front yard, to scan the buried utility lines, such as electrical and telecommunication cables.

All the antennas to be tested were installed on the motorized scanner system and were connected to SIR 4000 which is used as data acquisition system for antenna-reflected signals, also for control, signal processing, in- the-field display, and data export. After collecting data from every antenna, the test data was exported from SIR 4000 to a local computer for further processing. The following figures are the GPR B-scan raw data without any extra post-processing.
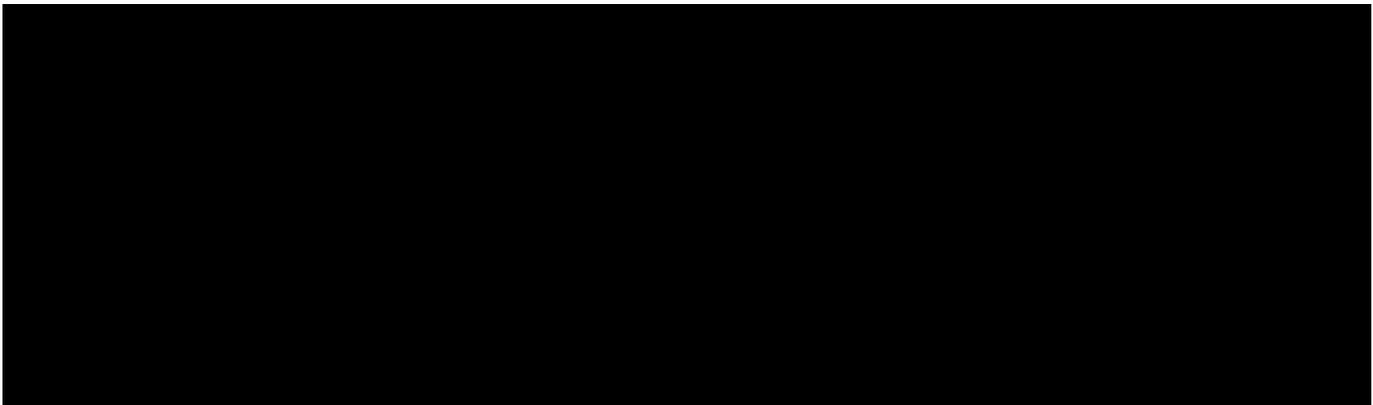
Since the dielectric constants of sand and clay are different, the attenuation of the signal from one antenna in the two environments is very different. With moisture level differences, the dielectric constants of both sand and clay vary drastically. For GPR signal, the conductivity means induction and absorption. Thus, attenuation on the signal strength is highly increased. Due to the clay inhomogeneous nature, the scattering of the signal is also increased compared with dry sand. By comparing the signals from clay and soil, the GPR signal in clay has more attenuation and scattering than in sand.

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Based on these test results, ULC Robotics has a better understanding of the impact of soil conditions, object size and material properties, antenna frequencies, etc. on GPR B-scan signals.

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In summary, the GSSI antenna tests on the soil box provide much insight about different frequency antennas interaction with objects buried in sand and clay. Based on these test results, ULC Robotics has a better understanding of the impact of soil conditions, object size and material properties, antenna frequencies, etc. on GPR B-scan signals.

Acoustic
The acoustic method for underground utility detection is an echolocation method which employs acoustic/seismic wave to detect the underground utility as well as measure its depth. The transmitter and receiver for the acoustic waves are usually separated by a distance Both transmitter and receiver are coupled to the ground through dry-coupling by pressing the transducer against the ground surface. The incident wave (red arrow) propagates to the obstacle which can be a pipe and get reflected by the pipe due to the difference in acoustic impedance between the pipe and the soil. The

Two tests had been conducted by ULC to test the performance of the APL. The first test was conducted at the mock roadway which has a hard surface of 8" un-reinforced concrete and 4" asphalt top. The second test was conducted at a site with compacted soil and no hard surfaces.

Figure 11 – Test results of APL

By testing the APL (acoustic pipe locator) at two sites with different ground conditions, we were able to determine that:

Magnetometer

The magnetometer measures the magnetic field difference of two separated receiving coils in the body of the meter. To properly evaluate this technology, we rented Schonstedt GA-92XTd magnetic locator to find the ferrous targets underground for pre-excavation sensing validation.

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Figure 12 – Magnetonmeter Soil Box Test

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EM Sensors

After research and review of many EM locators in the market, ULC selected three leading vendors and their flagship products for investigation and comparison. The followings are the EM locators selected for this evaluation:

- Radio detection RD8100
- Radio detection CAT4
- Vivax vLoc3-Pro
- Ridgid SeekTech SR-60

From this list, CAT4 and SR-60 do not support local or remote data storage and export which makes it impossible to integrate them into the robotic system. Therefore, only the RD8100 and vLoc3-Pro were selected for further investigation. These two locators are equipped with an interface for data export and a remote trigger to collect measurement data, which are the core functions for the RRES project.

Therefore, the most promising RD8100 and the Vivax vLoc3-Pro progressed to testing. Both antennas were used in peak/null mode and 60 Hz frequency. The gain setting is very critical in the measurement and comparison of the data collected by each antenna and is adjusted to maximize the collected signal without any saturation.

After going through all the sensor evaluation described in the previous section, based on the capabilities of each sensor in detecting different assets and the potential of integrating each sensor in

the RRES project the sensors, presented in Table 3 were selected for procurement and the initial round of in-depth lab testing.
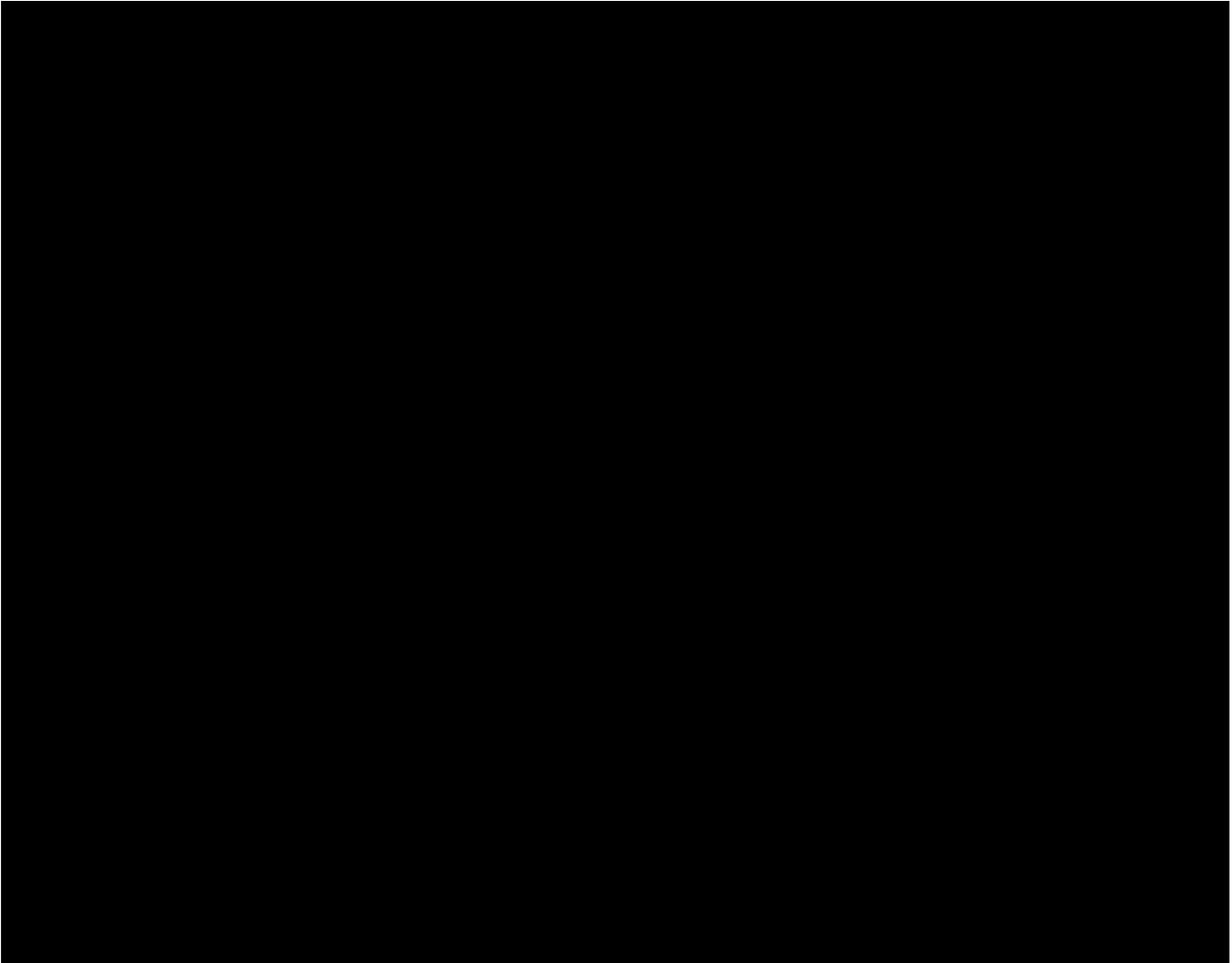
To increase the accuracy of the collected from the utilities under the ground using the GPR antennas, ULC robotics is developing a data processing technique for migrating the detected hyperbolas in the GPR b-scans. The two images shown in figure 15 demonstrates the raw b-scan data collected from GPR antennas before and after migration process. In the left figure, all the utilities under the ground show up in the form of a hyperbola without any concentration in the actual location of the utility but as show in the right figure, post migration, the reflected signal is concentrated in the centre of the pipe buried under the ground.
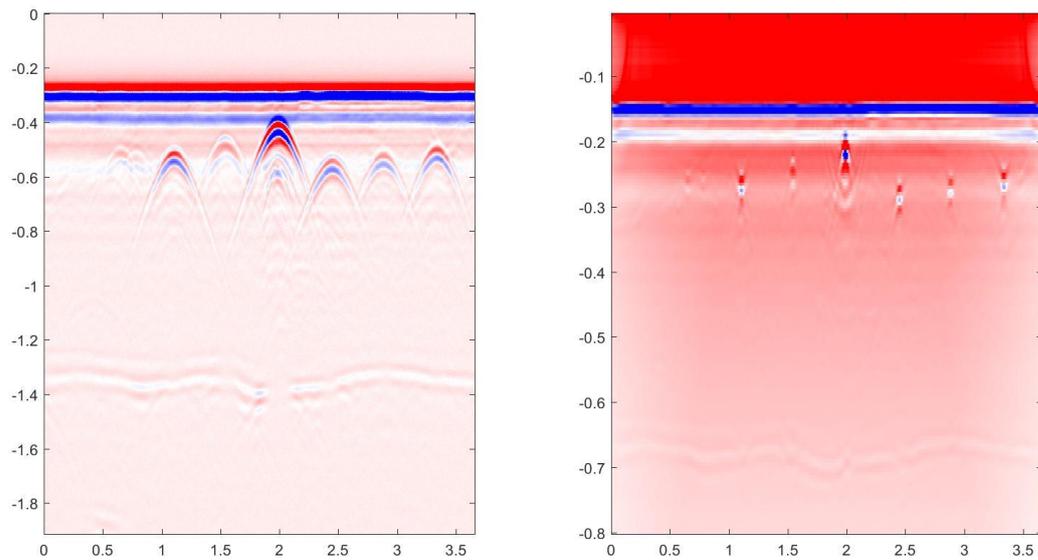
Figure 15 – Results from processing sensor data

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
Complete mechanical and electrical design of sensor module	Sensor Module Design Documentation	02/04/2019
Complete shop testing of prototype excavation tooling	Test plan/report on prototype exaction tooling	28/05/2019
Perform mobile platform design modification and testing	Test plan/report on mobile platform	25/06/2019
Design and fabricate interfacing hardware and electronics for prototype RRES	Documentation of design and build progress	09/07/2019

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 16 shows the project plan for Element 1.
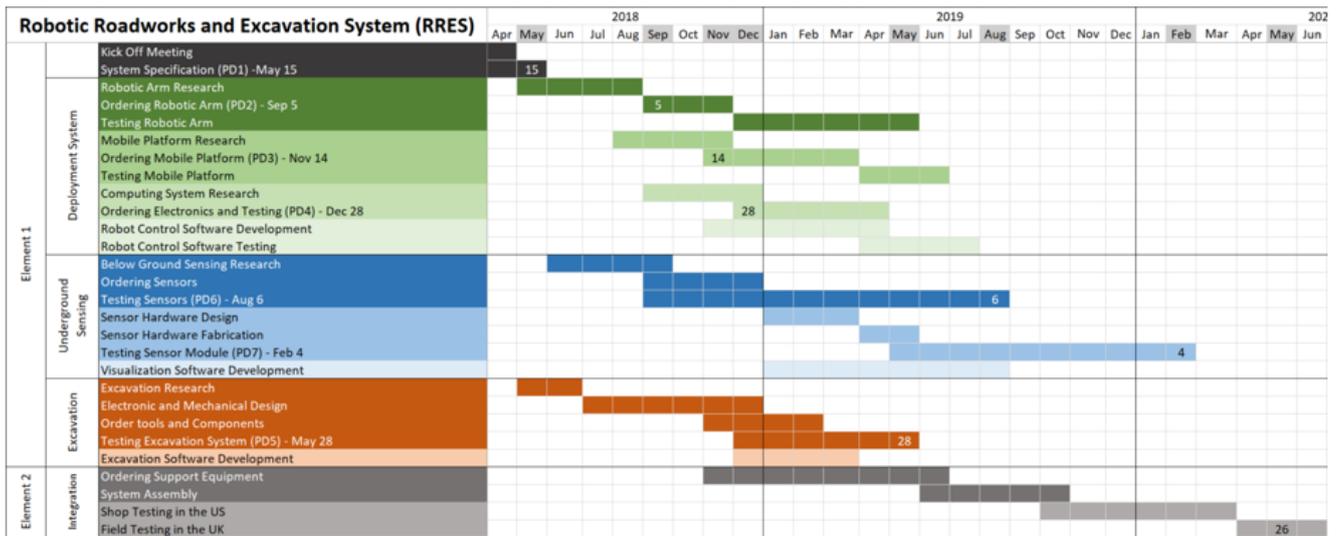
Figure 16 – Project Plan

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

Milestone	Title	Description	Planned Date	Delivered Date
8	*Progress Report 2* Computing system specification document and documentation of system design.	Order commercially available and custom electronic components for RRES onboard computing and communication	26/12/2018	26/12/2018
9	Documentation of sensor/camera research	Documentation of sensor/camera research	08/01/2019	08/01/2019
10	Documentation of excavation tooling mechanical and electrical design	Source and fabricate excavation tooling components	05/03/2019	05/03/2019
11	Documentation of software development for excavation tooling	Develop software for excavation tooling	25/03/2019	25/03/2019
12	*Progress Report 3* Sensor module design documentation	Complete mechanical and electrical design of sensor module	02/04/2019	Awaiting Approval
13	Test plan/report on prototype excavation tooling	Complete shop testing of prototype excavation tooling	28/05/2019	On Target
14	Test plan/report on mobile platform	Perform mobile platform design modifications and testing	25/06/2019	On Target
15	Documentation of design and build progress	Documentation of design and build progress	09/07/2019	On Target
16	*Progress Report 4* Test plan/report for individual sensor/camera technologies	Complete shop testing of sensors and vision systems	06/08/2019	On Target

Table 5 –Delivered Key Milestones

7 Progress against Budget

As the project has progressed as planned, the total expenditure to date is £2,301,663 with a further £177,280 set to be released by the 02/05. The deliverables for the 11th and 12th milestone will be reviewed, and payment will be processed once approved.
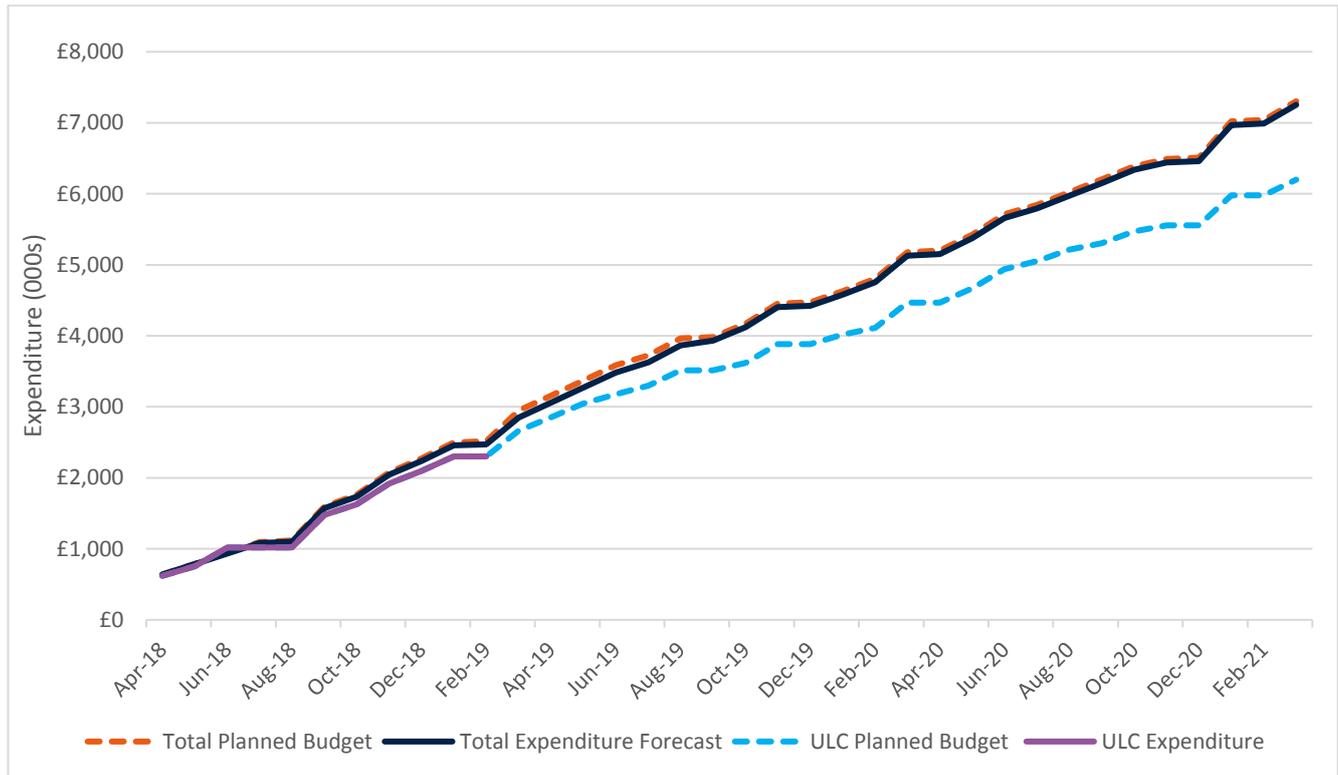
Figure 17 —Finacial Overview

The key project deliverables are attributed below:

Milestone	Title	Main Project Achievements	Amount	Project Total	Status
8	Progress Report 2 Computing system specification document and documentation of system design	Order commercially available and custom electronic components for RRES onboard computing and communication	177,280	2,097,314	Paid
9	Procure below-ground sensors and cameras for shop testing	Documentation of sensor/camera research	£204,349	£2,301,665	Paid
10	Source and fabricate excavation tooling components	✓ Data collection and processing from the Mock Roadway ✓ Build and test of the chainsaw on the CNC machine ✓ Design of the chassis for the tracked system ✓ Investigation into battery options for powering the system ✓ Development of a visualization system for presentation of point cloud and robot arm operation ✓ Development of Stereo SLAM ✓ Design of a new excavation head	£181,289	£2,482,953	Paid
11	Develop software for excavation tooling	✓ Visualization of the robot arm and point cloud in Realtime ✓ Detailed design of the robot chassis ✓ Engagement with battery manufacturers ✓ Detailed design of the electronics and power system ✓ Build and testing the newly designed excavator head ✓ Design and build of a test site for evaluation of the excavator head ✓ Simulation of excavation scenarios using the robotic arm ✓ Development of a haptic device for manual control of the robot arm	£182,610	£2,665,563	Awaiting Approval

12	**Progress Report 3** Sensor module design documentation	Complete mechanical and electrical design of sensor module	£190,398	£2,855,962	Awaiting Approval
13	Test plan/report on prototype excavation tooling	Complete shop testing of prototype excavation tooling	£190,932	£3,046,894	On Target
14	Test plan/report on mobile platform	Perform mobile platform design modifications and testing	£129,566	£3,176,460	On Target
15	Documentation of design and build progress	Documentation of design and build progress	£120,785	£3,297,245	On Target
16	**Progress Report 4** Test plan/report for individual sensor/camera technologies	Complete shop testing of sensors and vision systems	£218,793	£3,516,038	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 PPR 2, there has been a further 4 milestones delivered. The subsequent reports have been submitted to SGN and are available on request.

Computer system specification a document and documentation of system design

The purpose of this report is to demonstrate the development efforts that have been carried out by ULC Robotics in building different modules of the computing system for the control and operation of the RRES system.

Documentation of sensor and camera research

The purpose of this report is to demonstrate the development efforts that have been carried out at ULC robotics to procure appropriate sensing technologies that RRES will be able to combine to detect and avoid a wide range of buried assets and to identify the target asset.

Documentation of excavation tooling mechanical and electrical design

In this report, we demonstrate is to demonstrate the development efforts that have been carried out at ULC robotics since the beginning of the project to design and build a safe and effective excavation system for the robotic roadworks system.

Documentation of software development for excavation tooling

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.

At present a large proportion of the design work and specification can't be shared with external parties due to the IPR conditions concerning the design. Dissemination of this information prior to patent approval could jeopardise the commercial aspects of the system, and impact on the financial return to the GB gas consumer and SGN. This has been factored in to the Stakeholder engagement plan, with most key events planned after the expected approval date of the patents. An update on the IPR conditions of the project can be found in section 12 of this report.

We look to engage with external stakeholders and have organised a keynote speaker slot in the upcoming Utility Week Live event that will be held in May. Here Oliver Machan, will present the progress of RRES and as SGN will have a stand there, we will be able to disseminate the learning the project has produced.

Key Learning Outcomes
Excavation cutting technology advancement
Importance of soil nozzle design when agitating soil
Data processing capabilities in assisting in sensing readings
Internal Dissemination
Presentation of project progress to senior managers within SGN
Innovation piece in company team brief to inform the wider business
External Dissemination
ULC Post on IGEM magazine GI illustrates RRES
Creation of project webpage on ULC's website

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   –Summarry 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, with the custom-built CNC machine which offers a detailed test environment for the cutting tool, we can test the performance extensively to ensure RRES can cut the road surface effectively.

Limited Below Ground Detection Capability

There is a risk that the sensor suite is unable to detect all buried objects. However, with the completion of the mock roadway, the sensing technology and data processing system will be able to be extensively tested and improved to ensure RRES is able to detect buried infrastructure.

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
Computer system specification document and documentation of system design
Documentation of sensor can camera research
Documentation of excavation tooling mechanical and electrical design
Documentation of software development for excavation tooling

Table 9 –Milestone Reports across PPR3

Appendix B - Bank Statements

Appendix C - Risk Register

Risk Owner	Reference
SGN	SGN
ULC Robotics	ULC
SGN appointed technical Service Provider	TSP

Definition		Explanation	Probability	Score
Almost certain		event is expected to occur in most circumstances	>90%	5
Likely		event will probably occur in most circumstances	50-90%	4
Possible		event should occur at some time	30-50%	3
Unlikely		event could occur at some time	10-30%	2
Rare		event may occur only in exceptional circumstances	<10%	1

Scoring Key

16-25	10-15	1-9

Ref No	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.*	Time / Financial	2	3	6	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	3	5	15	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 - Implement 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

#	Risk	Category	P	I	Score	Mitigation	Owner	Date	P	I	Score
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 preparations 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	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