Review of Detection and Monitoring Systems for Buried High Pressure Pipelines

Final Report

Ministerie van Infrastructuur en Milieu

VELIN
VERENIGING VAN LEIDINGEIGENAREN IN NEDERLAND

VEILIGHEID voorop

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The people involved in this research are shown in the table below. The research group executed the study, the steering group had three meetings to support and direct this process. The advisory group is installed to reflect on the results of this study, and to consult the client while determining the activities that follow after it.

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List of definitions

Detection system	a technology that is capable of locating an underground pipeline without requiring a priori information (such as KLIC-maps)
Electromagnetic field	a physical field produced by electrically charged objects. It effects the behavior of charged objects in its vicinity
False negative	the result when a detector does not generate a positive signal while the object it searches for is actually within its detectable range
False positives	the result when a sensor gives a positive signal while the object it searches for is not in its proximity
Local pull detection system	a device on the surface emits signals to the subsurface and receives reflections to a pipeline
Local push detection system	a buried object system that transmits signals to make pipes detectable from the surface
Location-centered monitoring	monitoring based on the known locations of either an excavator or a buried object close to a pipe
Magnetic field	the magnetic effect of electric currents and magnetic materials
Mapping system	a technology that is used to comprehensively map the underground with the ultimate aim to create a utility plan
Maturity	an indication for development and applicability of a technology
Monitoring system	a technology that integrates known locations of a pipeline and tracked excavation positions to anticipate pipeline incidents
Multiple layered strike avoidance system	a system which can be the combination of detection, monitoring and warning systems to avoid damage to the pipelines during the excavation
Off-pipe	mounted above or near the pipe
On-pipe	mounted on the pipe
Pipe-centered monitoring	monitoring based on information of a pipeline location
Pipeline incident	damage to an underground pipeline, and its direct surrounding, caused by excavation work
Post-processing	the effort required to obtain clear information from the raw field data obtained during a scan
Real Time Locating System (RTLS)	using positioning system like GPS to track moving objects
Roadmap	a plan that outlines constraints and specific steps that altogether help achieving a target

Scanning pattern	the moving pattern required when using a detection device
Third party	a person or organization who is not directly hired by the pipeline owner to conduct excavation work
Transportation pipeline	high pressure steel pipelines that carry hazardous substances (e.g. oil and gas)
True positive	the result when a sensor correctly detects the object that searches for
Unknown pipeline	a pipeline of which its location is not known to the excavator operator
Warning system	the actual technology that processes detection/monitoring signals and triggers the alarm for excavator operators or pipeline owners

List of abbreviations:

APL	Acoustic Pipe Locator
EML	Electro-Magnetic Locator
EMI	Electro-Magnetic Induction
EMS	Electronic Marker System
FOS	Fiber Optic Sensor
GPR	Ground Penetrating Radar
GPS	Global Positioning System
I&M	Infrastructuur en Milieu (Ministry of Infrastructure and the Environment)
INSPIRE	INSPIRE (Infrastructure for Spatial Information in the European Community) is a directive about European spatial data infrastructures
KLIC	Kabel en Leidingen Informatiecentrum. The Dutch dial-before-you-dig center; One Call System
LDV	Laser Doppler Vibrometer
MFL	Multi Frequency Locator
MTU	Mapping The Underworld; the UK research programme about utility mapping
RFID	Radio Frequency Identification
RD	Radio Detection
RTLS	Real-Time Locating System
TRL	Technology Readiness Level
UAV	Unmanned Automated Vehicles
UXO	Unexploded Ordnance
UWB	Ultra-Wide Band
WION	Wet Informatie-uitwisseling Ondergrondse Netten (WION). The Dutch Act for Exchange of Underground Network Information)

Samenvatting

In Nederland ligt circa 22.000 kilometer aan transportleidingen die gevaarlijke inhoud (aardolie, chemicaliën, gas) onder hoge druk transporteren. Graafincidenten waarbij deze buisleidingen geraakt worden, komen zelden voor. Ongevallen in het buitenland (België 2004 en Duitsland 2014) hebben echter laten zien dat de consequenties van graafincidenten aan transportleidingen enorm kunnen zijn. Naast de fatale gevolgen voor de graafmachinist en andere direct betrokkenen, wordt schade aangericht aan de omgeving en het milieu. In Nederland hebben er tot op heden nog geen grote incidenten plaatsgevonden, maar doen zich jaarlijks wel een aantal schadegevallen voor. Werkzaamheden van derden (drainage, hei-werkzaamheden op festivalterrein) blijken een van de meest gemelde oorzaken van deze schades.

Hoewel de meeste gemelde schades relatief gezien nog goed aflopen, kan niet worden uitgesloten dat een schadegeval in de toekomst grotere consequenties heeft. Het ministerie van I&M, de Vereniging van Leidingeigenaren in Nederland en Veiligheid Voorop hebben daarom samen ten doel gesteld om het aantal graafschades aan transportleidingen tot nul terug te dringen. Daartoe zijn een viertal zogenaamde Safety Deals (onderzoek- en ontwikkelprojecten) opgesteld. Door middel van deze deals zou een overzicht gemaakt worden van de werkwijzen, methoden en technieken die gebruikt kunnen worden om de veiligheid tijdens grondroering nabij transportleidingen te vergroten.

Dit onderzoek brengt verslag uit van het vooronderzoek voor deze Safety Deals. Het onderzoek is getiteld: "Het inventariseren en ordenen van bestaande en innovatieve technologieën voor detectie en signalering van ondergrondse buisleidingen (in het bijzonder buisleidingen voor transport- & distributie van gevaarlijke stoffen)". De motivatie voor dit onderzoek is dat een actueel, volledig en systematisch overzicht van technologieën ter detectie van buisleidingen momenteel ontbreekt. Dit terwijl de ontwikkeling op gebied van detectie en monitoringtechnologieën niet heeft stilgestaan. Het maken van een eerste overzicht van technologie die in het veld (bijv. op de bouwplaats, het festivalterrein en landbouwgebied) door de grondroerder kan worden gebruikt, is daarom zinnig. Vanuit hier kan gekeken worden naar vervolgstappen voor implementatie, ontwikkeling en onderzoek op gebied van veilig grondroeren.

Vanaf augustus 2016 tot en met januari 2017 hebben onderzoekers van de afdeling Bouw-Infra van Universiteit Twente daarom op basis van literatuurstudie en expertconsultatie een review uitgevoerd. Ze voerden een scan uit naar bestaande en ontwikkelende technologieën in, onder andere, de geofysische sector, graafsector en aardobservatie. Dit leverde 134 bronnen op die op basis van kernwoorden (o.a. toepasbaarheid bij graafwerk; nauwkeurigheid; diepte-bereik; kosten; sterktes en zwaktes) werden doorzocht op relevantie voor het onderzoek. Ook werden elf personen benaderd voor een interview. In sessies van zestig tot negentig minuten werd gesproken met ontwikkelaars, technologiegebruikers, netbeheerders en wetenschappers. Dit leidde tot een overzicht van technologieën die na een eerste categorisatie systematisch werden vergeleken.

In de resultaten worden op hoofdlijnen twee type systemen onderscheiden, te weten: (1) detectiesystemen en (2) monitoringsystemen. Het eerste type systeem detecteert leidingen zonder dat daarbij enige gegevens over de ondergrond bekend zijn. Het doel is hierbij het identificeren van een ondergrondse pijpleiding. Dit principe werkt door een signaal naar, of vanuit, de grond te sturen naar een detectie-apparaat. Het monitoringsysteem is niet gericht op het detecteren van buisleidingen, maar op verstoringen nabij deze leidingen. Dit principe werkt door op netwerkniveau sensoren te installeren, of door locatiebepaling en liggingsgegevens te overlappen. In het eerste geval wordt een sensor op, of nabij

buisleidingen geplaatst die verstoringen van graafmachines detecteert. Een andere manier van monitoring is om de real-time GPS-posities van graafmachines over kaartgegevens van buisleidingen heen gelegd om te monitoren of graafmaterieel in de buurt van gevaarlijke leidingen opereert.

Detectiesystemen zijn onder te verdelen in lokale pull systemen (zoals elektromagnetische radiodetectie, magnetische detectie, grondradar, akoestische detectie) en lokale push systemen (zoals RFID tags, glasvezelkabels, signalen van kathodische bescherming). De monitoringsystemen zijn onder te verdelen in respectievelijk buisleiding-gebaseerde systemen (die gebruik maken van akoestische sensoren en glasvezelsensoren) en locatie-gebaseerde systemen (die gebruik maken van zoals real-time plaatsbepaling en bestaande leidingkaartgegevens).

Een analyse van deze technologieën en methoden heeft tot de bevinding geleid dat géén van de bestaande systemen momenteel direct toepasbaar zijn om graafschade aan transportleidingen te voorkomen. Lokale pull systemen zoals GPR en akoestische detectie moeten bijvoorbeeld op technisch gebied nog flinke ontwikkelingen doormaken opdat zij kunnen functioneren op een bewegende graafmachine. Lokale push systemen zijn in staat om conflicten tussen graafmaterieel en buisleidingen te detecteren, maar leiden veelal tot foutief-positieve (‘false positive’) alarmering. Monitoringsystemen zijn verder afhankelijk van ontwikkelingen van nauwkeurige en betaalbare positiebepaling en accurate kaartgegevens. Voortgang op al deze vlakken is nodig technologieën in de praktijk te kunnen laten landen.

Op basis van de ondervonden technologische beperkingen zijn er een aantal aspecten die van belang zijn voor doorontwikkeling:

- Detectie-/monitoringtechniek moet rigide en stevig genoeg zijn om gebruikt te kunnen worden tijdens grondroerwerkzaamheden;
- Metingen die uitgevoerd worden door een detector dienen niet verstoord te worden door de metalen onderdelen van de graafmachine;
- Detectietechnieken dienen functioneel te zijn met de snelheid en het werkpatroon van de graafmachine;
- Detectie-/monitoringsignalen die omgezet worden in een alarm dienen zoveel als mogelijk ‘true positives’ te bevatten;
- Detectie-/monitoringsignalen die omgezet worden zouden zo min mogelijk foutieve (false negatives) alarmen moeten genereren;
- Detectie en monitoring dient – zonder post processing - plaats te vinden tijdens graafwerkzaamheden waarbij (real-time) post-processing niet nodig is;
- De output en het alarm dat wordt gegenereerd door een detectie of monitoringsysteem moet begrijpelijk zijn voor de graafmachinist (professioneel en niet-professioneel).

Op basis van deze punten is een technologie roadmap uitgestippeld waarin een aantal korte- en langetermijn stappen worden benoemd die naar eerste inzicht relevant lijken voor toekomstige ontwikkeling. Er wordt onderscheid gemaakt tussen de trajecten: lokale detectietechnologie, globale monitoringsystemen, waarschuwingssignalen en beschikbaarheid van data. Tot slot worden in het rapport drie werkpakketten aanbevolen: (1) doorontwikkelen van lokale pull detectiesystemen zoals GPR en radiodetectie; (2) doorontwikkelen van lokale push systemen door middel van glasvezelkabels en RFID; en het (3) doorontwikkelen van monitoringsystemen zoals glasvezelsensoren en geo-fencing. Deze pakketten bieden hopelijk de volgende stap naar een veiligere graaf- en buisleidingsector.

Lists of figures and tables

Voorwoord (Dutch Preface)

Wanneer buisleidingen met gevaarlijke inhoud beschadigd worden, is de impact vaak groot. Incidenten kunnen aanzienlijke gevolgen hebben voor direct betrokken personen en het milieu. Om incidenten te voorkomen, is in Nederland de Wet Informatie-uitwisseling Ondergrondse Netten (WION) van kracht. Het besluit en de regeling (respectievelijk BION en RION) die hierop aansluiten zijn momenteel in ontwikkeling. Daarnaast zijn er ook ontwikkelingen op technologisch gebied die graafveiligheid kunnen vergroten. Hoewel dit onderkend wordt door de sector, bestaat er op dit moment geen overzicht van bestaande technologieën en hun potentiele bijdrage aan de reductie van graafincidenten aan stalen buisleidingen.

In juni 2016 hebben de graafsector, vertegenwoordigd door VELIN en Veiligheid Voorop, daarom het initiatief genomen om tot een Safety Deal te komen met het ministerie van Infrastructuur en Milieu (I&M). I&M startte daartoe voor dit vooronderzoek naar preventie van graafschade aan hogedruk transportleidingen met gevaarlijke inhoud. Dit eindrapport is getiteld *"Review of Detection and Monitoring Systems for Buried High Pressure Pipelines"* (Engelse vertaling) en presenteert de uitkomsten van het onderzoek. Het onderzoek werd uitgevoerd door Universiteit Twente en maakt deel uit van het programma Zorgvuldige Aanleg en Reductie Graafschade (ZoARG). Dit lange-termijn programma koppelt onderwijs, onderzoek en ontwikkeling met overheid en bedrijfsleven om expertise op gebied van ondiep ondergronds bouwen te vergroten.

Het rapport dat voor u ligt heeft als doel om een systematisch overzicht te geven van experimentele en bestaande technologieën voor het opsporen van stalen buisleidingen en monitoren van grondroerbewegingen nabij deze leidingen. Naar inzicht van de onderzoekers was een dergelijk actueel en compleet overzicht tot voorkort niet beschikbaar. In een tijdsbestek van zes maanden hebben zij daarom literatuuronderzoek uitgevoerd en experts geraadpleegd. Dit leidde tot een overzicht van drie soorten technologieën, te weten: monitoringsystemen, lokale push detectie systemen en lokale pull detectiesystemen. In vervolgstappen gericht op adoptie en toepasbaarheid van deze systemen raden we aan om onderscheid te maken tussen soorten grondroering (op bouwplaats, festivalterrein en buitengebied) en professionaliteit van de grondroerder.

Dit gepresenteerde onderzoek is een aanzet in het kader van een mogelijke reeks Safety Deals. Deze richten zich op ontwikkeling van veilige graaftechnieken, ontwikkeling van apps ter ondersteuning van veilig graven en ontwikkeling van scholingspakketten voor machinisten, toezichthouders en leidingcoördinatoren.

De auteurs bedanken graag Frans Driessen (Vereniging van Leidingeigenaren in Nederland), Sebe Buitenkamp (afdelingshoofd) en Charles Tangerman (programmacoördinator Safety Deals) van het Ministerie van Infrastructuur en Milieu voor het initiëren van dit onderzoek. Dit onderzoek heeft het mogelijk gemaakt om een actueel overzicht te verkrijgen van de stand der techniek en geeft bovenal een gedegen fundament om nieuwe onderzoek- en ontwikkelingstrajecten op te starten. Tot slot danken de auteurs in het bijzonder de heren Kees Theune (I&M), Mark Engbersen (bestuurlid VELIN) en Herman van der Geest (voorzitter Vereniging van Nederlandse Drainagebedrijven) voor hun rol als stuurgroep lid.

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1 Introduction

The Netherlands has approximately two million kilometers of underground cables and pipelines. One specific type of buried infrastructure is the distribution network of hazardous material such as gas, oil, and chemicals ('transportleiding gevaarlijke stoffen'). This network comprises 22.000 kilometers of high-pressure transportation pipelines. Because they are located under the ground, these pipelines are subject to excavation damages. Incidents in them Belgian Gellingen (2004) and German Ludwigshafen (2014) show that consequences of pipeline damages are significant. They can cause fatalities to excavation workers and impact the environment too. In addition, only direct costs for recovery of damages are estimated by the pipeline owner association (VELIN) to range already from several hundreds of thousands to even a few millions of euros. This figure does not yet include the indirect costs. Serious incidents will eventually undermine the public's acceptance for hazardous pipelines, so it goes without saying that pipeline excavation incidents should, therefore, be avoided.

Nowadays, third parties seem to be causing most of the damage to underground pipelines (Capstick, 2007; CONCAWE, 2013; EGIG, 2015; J. M. Muggleton & Rustighi, 2013). Reasons for this, often mentioned by industry, are that utility location information (KLIC-melding) is not always available and, when available, it is not always accurate or too difficult to interpret by excavator operators. It is crucial to detect underground infrastructure in a timely fashion to avoid damages. For this purpose, initiatives are needed to help excavator operators to detect pipelines and monitor groundworks taking place close to pipelines. Such initiatives could focus on the identification and the development of technologies for pipeline strike avoidance. The first step in this direction was this study – which in turn is related to the Safety Deals that are prepared by the association of pipeline owners in the Netherlands (VELIN) and the Dutch Ministry of Infrastructure and the Environment. VELIN and I&M requested the University of Twente to systematically review existing technologies for excavation damage avoidance. Such an overview is not available to the Dutch industry to date. The project team therefore identified and described existing systems for global monitoring and detection of utilities. These systems eventually help detect clashes between excavator equipment and high-pressure transportation pipelines.

In about six months the project team conducted a literature review and expert consultation round. They identified a range of technologies that can be categorized into two types: global monitoring systems and detection systems, which in turn comprises local push detection systems and local pull detection systems. Monitoring systems essentially detect interference between pipelines and excavator equipment. This can be done by using location-centered systems that integrate utility location information and excavator's tracked position to warn against collisions (examples are real-time localization systems, geo-fencing, etc.). Alternatively, monitoring can happen by means of pipe-centered systems (such as fiber optic sensors and acoustics) that generate warning signals when external objects, such as excavators, disturb the soil close to pipelines. Local push and pull detection do not necessarily need utility maps. Instead, they scan the underground for signals indicating the presence of an object. Pull systems (such as the Ground Penetrating Radar (GPR) and electromagnetic localization) scan for pipes on a surface level, while push systems (such as fiber optic and RFID) use sensor based auxiliary devices s embedded on or near pipes to signal the presence of utilities.

We concluded that the use of only one of the existing technologies may not result in significant reduction in the number of damages. Also, there seems not yet a single best configuration of technologies that could be developed further. At an abstract level, however, we suggest further developing multi-layer safety solutions that at least include a global monitoring and a local push or local pull system. The research team explored the possibilities and technical limitations of all existing systems. The technology roadmap at the end of the report aims to help make informed decisions about which technologies should be further developed.

The remainder of this report is structured as follows: Chapter 2 explains in detail how the research team conducted the literature review and expert consultation. The results – i.e. a categorization and overview of monitoring and local detection systems - of the research are presented in Chapter 3. Next, chapter 4 draws conclusions. Chapter 5 discusses the research limitations, and finally chapter 6 provides recommendations and gives an outlook by presenting a technology roadmap. In a metaphorical sense, this map suggests various tracks that could be followed to improve the development and implementation of existing technologies.

2 Research approach

This chapter discusses the scope of this study and discusses the research steps that were undertaken to achieve the objective.

The expected process of a strike avoidance technology is shown Figure 1. In this chain of critical events, first, a system needs to be found that is able to detect signals from pipelines. As a next step, the system evaluates the signal quality, and – if necessary – passes an alarm to the end user. The end user can either be the operator of excavation equipment, the utility network owner, or even an automated system in the excavator. In the last step, the end user takes action based on the signal received and stops excavation work.

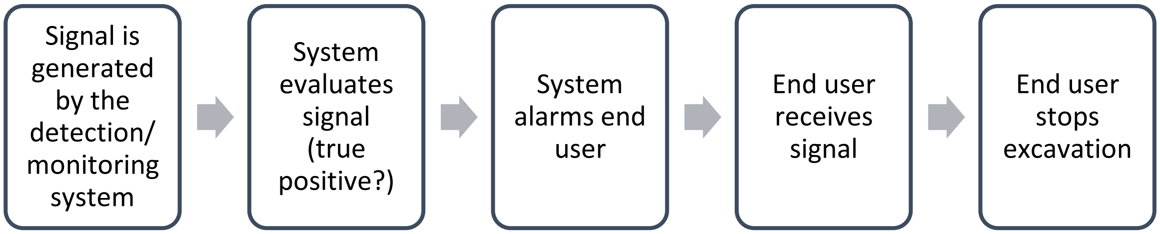


Figure 1 - critical event chain for pipeline strike avoidance

This research mostly focuses on the first step in the chain of critical events shown in Figure 1. This means that we investigated technologies that help detect unknown location pipelines and locate machineries operating close to pipelines with known locations. The next steps were explored briefly which means that the signal evaluation and the ways in which end users can be alarmed were also addressed.

This study was based on the desk research and expert interviews. We explain below how these activities took place. To create an overview of technologies that help detect excavation near transportation pipelines which carry hazardous materials, we consulted both literature and practice. First, we defined some preliminary keywords to search for sources such as scientific papers, conference papers, books or book chapters, presentations, thesis, website, etc. Based on preliminary keywords, some academic literatures were found. These academic literatures were reviewed to get an overview of the state-of-the-art in detection and monitoring technologies. While doing so, we also found experts and companies that were of interest for this study. We, therefore, interviewed developers and users of detection and monitoring systems. We collected data about utility detection and *monitoring* technologies and conducted a systematic analysis of the data. These steps are summarized in Figure 2.

The research was started by generating a series of relevant keywords that relate to underground utility detection technologies, pipeline monitoring technologies, warning technologies and pipeline safety. Such keywords are *underground utility detection, underground infrastructure, excavation damages to underground utilities, mapping the underworld, ground penetrating radar, pipe locator, radio detection, acoustic method, magnetic method, multi-sensor methods, warning systems, underground utility protection, pipeline monitoring systems, and utility safety.* As a next step, we developed search queries to search for information in scientific databases on the internet. A number of scientific journal papers, conference papers, book chapters, presentations, reports, thesis, and websites were found and reviewed either briefly or completely. The most relevant ones were selected to be reviewed accurately and based on citations of them, other sources were found.

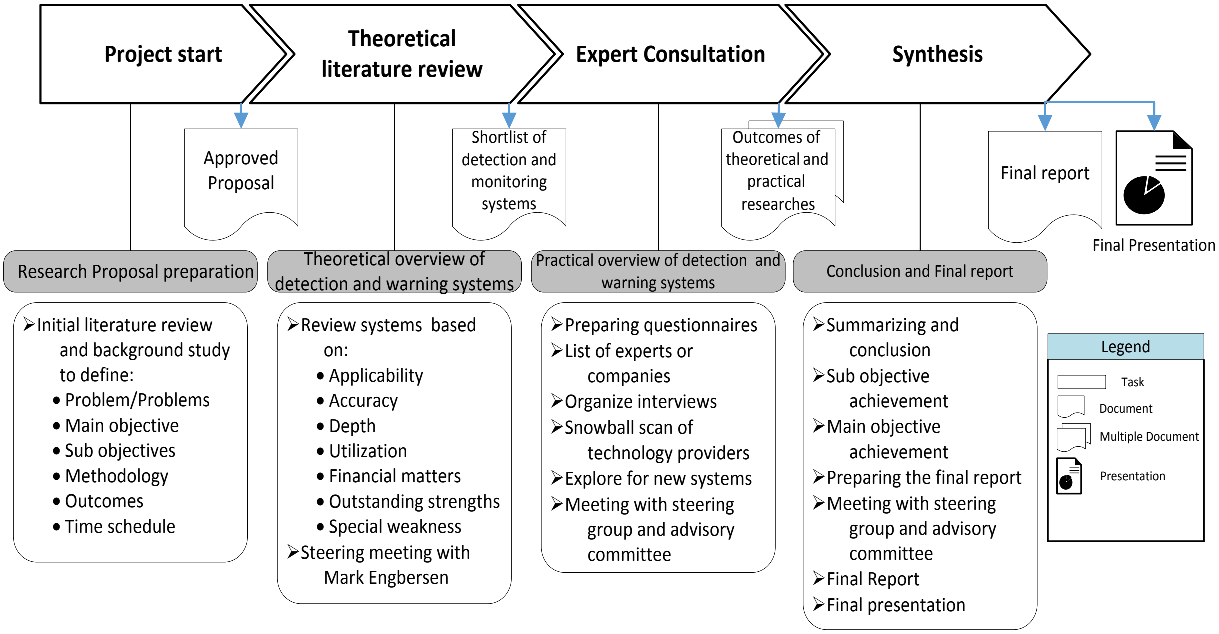


Figure 2 – visualization of the research process

Often, references and citations also led to new articles that were relevant in the context of this research. This strategy is often referred to as snowball sampling. In the literature review, first, all the available technologies for underground utility detection were identified. A preliminary review of all founded literature, provided some key factors to select the most relevant literature to review deeply and very accurately. Table 1 shows the outcomes of the search exercises for most of the keywords mentioned above.

This search exercise additionally helped generate a list of scholars, company representatives, and technology providers to add a practical point of view to the research. A list of experts for the interview was prepared. Due to the limited time available, there was no chance to interview them all. Therefore, we selected one representative per technology and contacted him for an interview. On average, each interview took about 60-90 minutes, but finding a suitable expert and organizing the interview procedure took much more time. Also, when an interview became definite, some preparation and post processing were required. We intended to let each interview take place at the office of the respondent. If it was not possible, we invited them to our office or arranged a skype meeting. A questionnaire was prepared for each interview based on the expert specialty. An example of questions in the questionnaire are: facts about the technology? How does the technology work? For which kind of material is the technology suited? What are the components? What is the depth range, accuracy, and maturity of the technology? How soil, weather and environmental conditions affect the technology? What are the constraints? What is the potential improvement? Is it possible to mount the technology on the excavator? A sample of interview questionnaire is shown in the Appendix.

Table 1 - quantitative information of reviewed documents

Technologies	Scientific paper	Conference paper	Book/ Book chapter	Report	Patent	Presentation	Other (thesis, guideline, …)	Total
Acoustic	12					1	3	16
Multiple technologies	4		1		3	4	3	15
GPR	5		1	1		2	5	14
Electromagnetic	3			1		1		5
Magnetic	1	1	1	1		2		6
MTU Multi Sensor	2					1	3	6
Fiber Optic	2	2						4
One call system	1	1						2
Pipeline	2			5				7
Pipeline and Urban				3				3
TRL	1		1				6	8
Ultra-Wide Band	4	2		1			1	8
Warning	7	3			11			21
Other technologies	2			3		14		19
								134

Finally, to make sure that each interview was interpreted correctly, we sent a transcript to the respondent for validation. Sometimes an expert suggested us to interview another expert too. This is referred to as snowball sampling. Table 2 provides an overview of all people that were interviewed for this study (this is a short list of the people who we originally selected for an interview).

The literature review and interviews created a set of data that we used for further analysis. During the analysis we focused on: Type of the materials that the technology can best detect, the accuracy of the technology, the depth range within which the technology works effectively, the duration of the detection procedure, the effectiveness of technology in different soil conditions, the effect of weather condition on the technology's effectiveness, frequency range of the technology, the effect of surface terrain condition on technology effectiveness, the scanning pattern, the data processing, complexity of the output of the detection, other the strengths and weaknesses of the technology, the applicability of the technology for the pipeline detection, and the maturity level of technology.

Apart from detection technologies, monitoring technologies were also reviewed and promising ones for pipeline safety were identified. This systematic literature review led us to find the most suitable technologies in terms of pipeline detection and pipeline monitoring. Also, focusing on the application of various technologies for improved safety of excavation work, we identified each technology's strengths, weaknesses, and the possibility/trajectory for further improvements and developments. It was founded that some extra activities in terms of regulation, education, training, data management, and infrastructure management can help to reduce the number of pipeline incidents. These trajectories are explained in the roadmap in detail.

Table 2 - details about respondents

Name	Expertise	Company	Position	Country	Interview Location
Dick Van der Roest	GPR developer	GT Frontline	Director	NL	UTwente Enschede
Karel Meinen	Utility surveyor	Terra carta	Director	NL	TerraCarta Hoogeveen
Roland Bakker	Utility network owner	Enexis	User	NL	Enexis Zwolle
Jim Anspach	Subsurface utility surveying expert	Cardno	Director of Utility Market	US	Skype
Jim Bach	Subsurface utility surveying expert	Schonstedt	Director of Sales and Marketing	US	Skype
Nicole Metje	Utility mapping researcher	University of Birmingham	Researcher	UK	Skype
Aryan Hojjati	Utility project researcher	University of Birmingham	Researcher	UK	UTwente Enschede
Jen Muggleton	Acoustic mapping researcher	University of Southampton	Researcher	UK	Skype
Kovalenko Vsevolod	Senior geologist	Fugro	Technical advisor	NL	Skype
Peter Boermans	Safety systems	Sick	Consultant	NL	Sick Bilthoven
Michael Montgomery	Fiber optic warning systems	Senstar	Applications Engineering	US	Skype

During the study, a steering group was created to provide feedback to the research team. The steering group participated in a formal kickoff, mid-term meeting, and final meeting. They provided feedback to the researchers, asked for clarifications, suggested focus, and helped us distinguish between required and optional research activities. An advisory group was invited to discuss the outcomes of this project, and to evaluate which of these outcomes should be addressed at an industry level.

3 Results

This chapter discusses the outcomes of the analysis of both the desk research (i.e., literature and web study) and expert interviews. Our review shows that there are many different technologies that can be used for pipeline strike avoidance. In this chapter, we group these technologies based on their core functional behavior. Below, we explain this categorization, and then elaborate the studied technologies.

Figure 3 shows that the excavation damage prevention technologies are categorized into two main classes, namely *detection* systems and *monitoring* systems. At its core, a detection system identifies the location of an underground pipeline by transmitting signals into, and receiving them from, the ground. These systems are applied locally and at a certain moment to detect pipeline sections. Alternatively, a monitoring system uses known pipeline location data, and combines this with 'measured' equipment locations to anticipate conflicts. Compared to detection systems, monitoring systems are more global and permanent solutions.

In turn, detection systems are further categorized into two groups. The first, *pull detection*, uses a device on the surface that emits signals to detect pipes. The second, *push detection,* uses buried transmitters that emit signals to make pipes detectable from the surface. Within the monitoring systems category, we further distinguish between two groups. One is the *pipeline-centered* system that uses buried detection sensors (e.g. acoustic emission sensors) to identify soil disturbances caused by excavators. The second is the *location-centered* system that uses pipeline maps, and overlay these with location information from real-time localization systems (RTLS) to identify potential clashes.

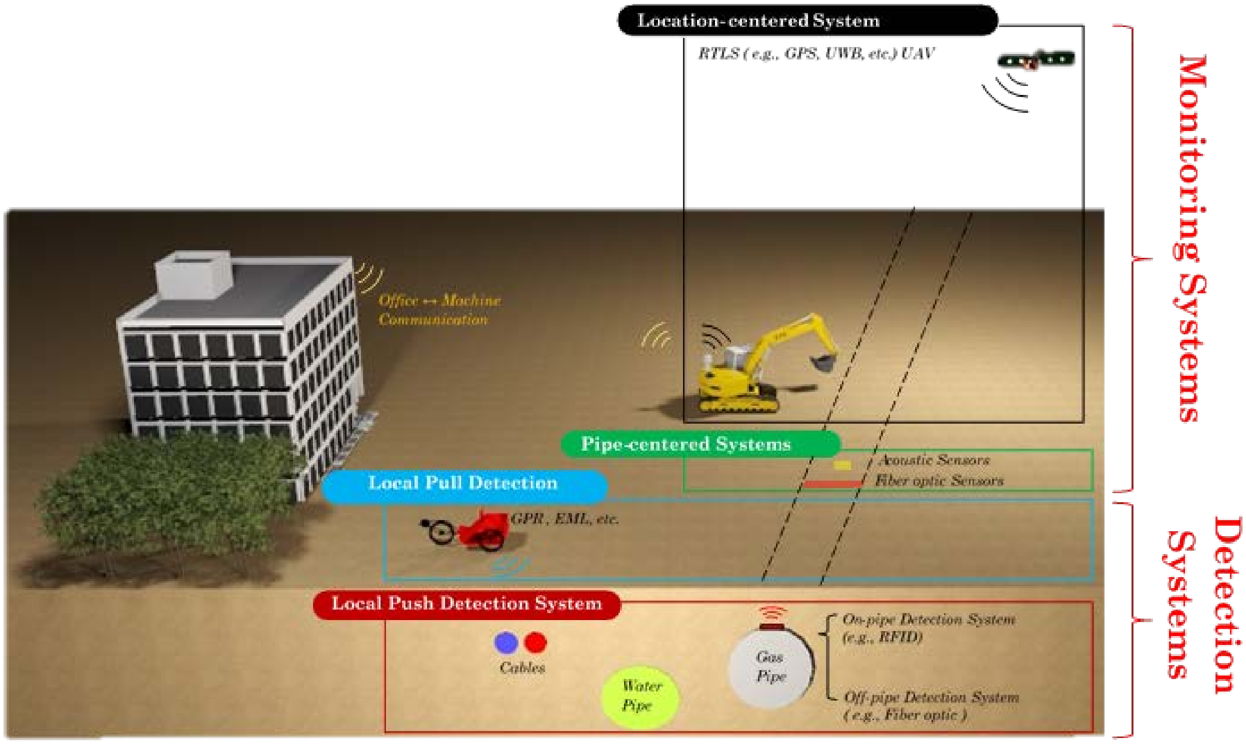


Figure 3 - schematic representation of the technology categorization

Figure 4 shows how we categorized the investigated systems in this study. The classes on the two highest levels represent the categorization that we explained above. The lower-levels contain instances of the technologies that belong to each of these classes. Figure 4 essentially is a categorized long list of all technologies we studied. Each of these will be explained below.

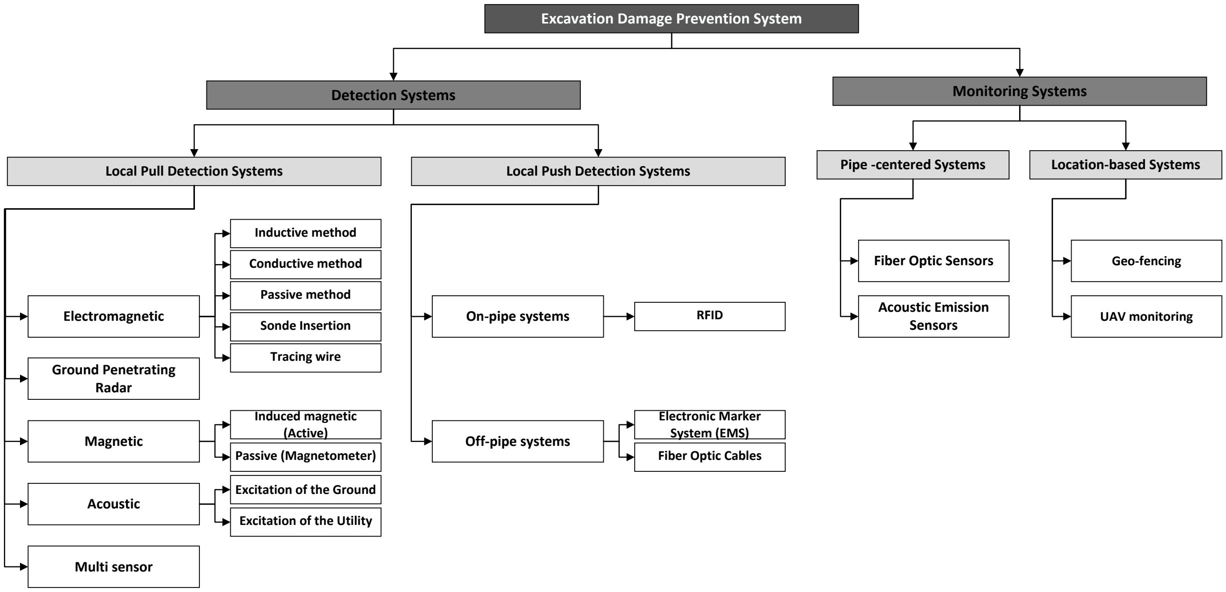


Figure 4 - categorization of the reviewed technology

3.1 Local detection systems

Figure 4 shows that there are various technologies for the application of underground utilities detection. These systems are categorized as pull detection systems and push detection systems. Examples of push detection system elements are RFID tags, fiber optic cables and electronic markers. RFID tags can store information about a pipeline, and can be placed on a pipe during its construction. This application is already common to some pipeline networks that are placed at surface level. The system may also be applicable to the subsurface domain. Another push system comprises fiber optic cables that are buried in parallel and close to the pipeline. Fiber optic cables can create a magnetic field near the pipeline. This eases the detection of pipes (Jeong, Arboleda, Abraham, Halpin, & Bernold, 2003). The disadvantage is that push detection systems need to be added to existing pipelines. This requires a significant amount of work that cannot be completed on the short term. In addition, only a full coverage and operation of this system can help making detection more reliable. This does not take away though that the systems suited alternatives for future. Due to time constraints, however, this study elaborated mostly on the pull detection systems that seem more applicable to the scope of this study. The remainder of this section addresses these systems in greater detail.

Pull detection systems detect the underground pipeline by transmitting signals into, and receiving them from the ground. The reviewed technologies were systematically scrutinized in terms of several key features. These include: (1) *material type:* types of materials that can be detected using the technology; (2) *movement speed:* the ability of the technology to function at the same speed as an excavation – which is required when developing this technology further for use in a real-time excavator-based detection system; (3) *accuracy:* an indication of the average error in detection results, (4) *depth:* the maximum depth range at which the technology maintains its acceptable functionality, (5) *soil type:* the types of soil for which the technology is applicable, (6) *surface terrain:* the types of surfaces (e.g., rough or smooth) on which the technology functions, (7) *scanning pattern:* the requirements to scan the field using in a certain fashion to provide coverage and accuracy, (8) *data processing:* the ability to generate real-time results - as opposed to technologies that require post-processing, (9) *strengths:* any particular features that make the technology suitable for application under certain conditions, (10) *weaknesses:* any particular features that limit the applicability of the technology under certain conditions, and (11) *applicability:* the conditions under which the technology functions the best.

Not all technologies are at the same level of maturity, availability and relevance to the scope of this research. Therefore only the most promising - electromagnetic locators (radio detection), acoustic locators, Ground Penetrating Radar (GPR), and magnetic locators – were selected for further discussion in this report.

Since multiple of these technologies can be used for local push and local pull, they are discussed below at once. It is worth noting, however, that push technologies require access to pipelines, whereas not all pull technologies need to.

3.1.1 Electromagnetic pipe locators (radio detection)

Electromagnetic localization works by using a transmitter that emits a wave and a receiver that is tuned to detect any changes in the wave (Jeong et al., 2003). Electromagnetic sensors can detect cables and metallic objects that are buried at shallow depth. They also can provide a limited amount of information on the nature of utilities (such as, for example, depth, shape, size, material)" (Bruschini, 2000).

Figure 5 shows the types of electromagnetic detection technologies, and Figure 6 provides a schematic representation of an electromagnetic detection system.

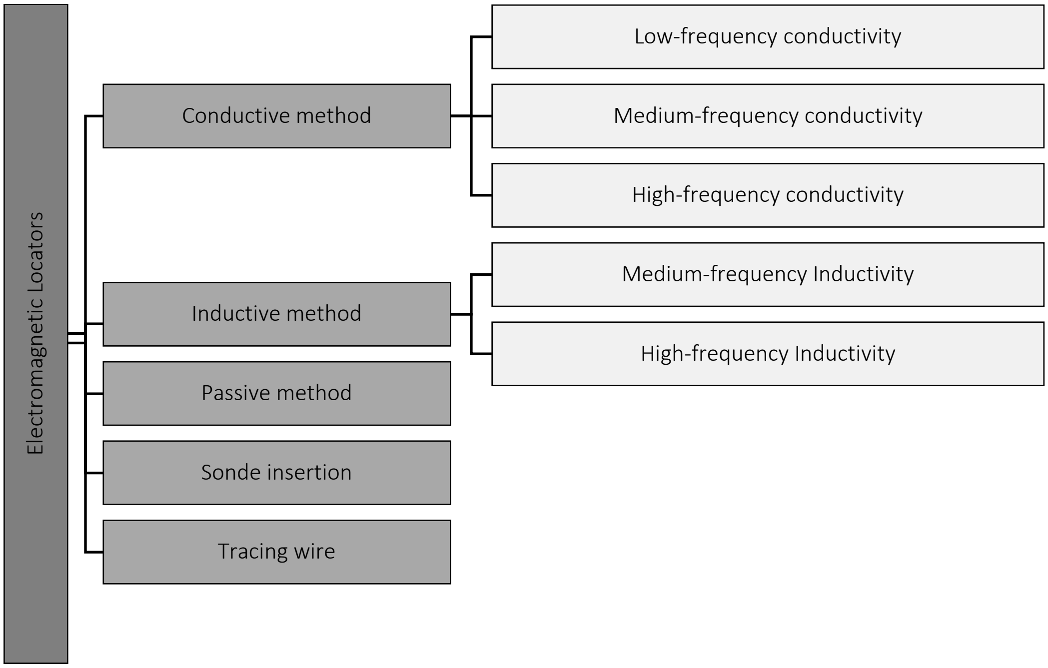


Figure 5 - categorization of electromagnetic detection techniques

Conductive and sonde insertion methods require access to the pipeline, while the inductive radio detection methods do not. Both the conductive method and sonde insertion are efficient systems in terms of pipe locating. For third parties and none professional excavator operators, the methods seem less suited since access points to the pipelines are needed to produce a magnetic field. Third parties and non-professional diggers do not have this access. This problem could be solved if pipeline owners transmit a signal through the pipe continuously.

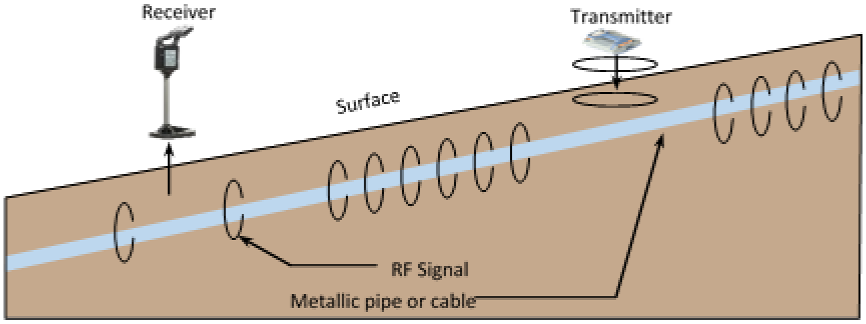


Figure 6 - system representation of the utility locator (adapted from Geo-Graf 2016)

The main advantage of radio detection is that a direct contact with the surface is not necessarily required. According to the Australian Standard AS5488 (Underground Service Locating Perth, 2013) electromagnetic locators are the most reliable technology for the accurate detection of metallic pipes and cables. Figure 6 shows the types of electromagnetic detection technologies.

One aspect about EML worth mentioning here is that the frequency range produced by electromagnetic methods is important for the detection and identification of utilities. Most metallic objects produce different responses to the electromagnetic waves that they receive. Electromagnetic Induction (EMI) sensors is a promising tool for the detection of buried objects (Royal et al., 2011). In addition, Ultra-Wide Band electromagnetic waves can improve the effectiveness of electromagnetic induction tools since they have a broader frequency range which can be specified to detect different types of utilities. (Zou, 2012).

Another radio detection tool is the Multiple Frequency Locator (MFL). It emits up to ten different frequencies simultaneously (330 Hz to 100KHz), and seems like the most promising technology that is readily available on the market (El-qady, 2014). The top-of-the-line MFL-models offer three active frequencies (512 Hz, 33 kHz, 82 kHz), and a choice of one passive frequency (50 Hz or 60 Hz). This combination enables the detection of any 512 Hz sonde or transmitter device. Unlike single frequency locators, MFL techniques allow operators to measure at multiple depths. Tests on sites with different environmental conditions indicate that the multi-frequency data is far superior in characterizing buried, metallic and non-metallic targets to data from conventional single-frequency sensors(El-qady, 2014).

Although data from most radio detection systems can be downloaded and stored in files that can also be read by commercial PC software, the systems can also be used at real-time. Finally, the literature review indicated that electromagnetic methods have the potential to complement GPR systems by locating utilities that GPR would have difficulty detecting (e.g. plastic pipes) (Rana, 2011). A more descriptive summary of our findings about electromagnetic locators which do not need to have an access point to pipelines are given in Table 3.

Table 3 - qualitative review of electromagnetic detection techniques

Method / **Features**	**Inductive electromagnetic detection**	**Passive electromagnetic detection**
Material type	Cable and metal	Cable and metal
Movement speed	No problem with the excavation speed, but preferably not more than 0.5 m/s	No problem with the excavation speed
Accuracy	Time domain is less accurate but the Frequency domain is accurate	
Depth	Up to 2 meters- in general less than 15 feet	
Frequency	• In general, frequencies from 50 Hz to 480 kHz • For deep steel pipelines: > 8 kHz • 82 kHz to trace gas and water line • 33 kHz to trace tracing electrical lines	50 or 60 Hz
Soil type	• Less effective in wet soil. • Less effective in clay dominated soil • Salty soil is a big problem	• Less effective in wet soil. • Less effective in clay dominated soil • Salty soil is a big problem
Surface terrain shape	No impact	No impact
Scanning pattern	Adaptable to excavation pattern	Adaptable
Data processing	Real-time.	Real-time
Strength	• No need to have an access to the pipeline • The most reliable technology for detecting metallic pipes • Work well for metal object	Non-intrusive method
Limitation	• Coupling to the adjacent utilities. • Should not be used where the cable is below a metal cover or reinforced concrete pavement	Not applicable in absence of magnetic field around the object.
Applicability	Considered applicable for steel pipeline detection by excavators	Only applicable when there is a current

3.1.2 Magnetic locator

Magnetic surveying is based on the anomalies in the earth's magnetic field resulting from the magnetic properties (Hrvoic, 2011). In principle, buried ferrous metal objects distort the earth's magnetic field in their vicinity. Accordingly, any anomalies in the earth's magnetic field can be potentially associated with the secondary magnetic fields produced by ferromagnetic materials (Mariita, 2007) . As shown in Figure 7, magnetic locators use this phenomenon to locate buried metal objects. Two approaches are used to locate metal objects with magnetic locators, namely the passive and active. In the passive approach, the natural magnetization induced by the earth's magnetic field is used to detect ferrous materials. Passive systems do not radiate any energy, and typically measure tiny disturbances of the earth's natural magnetic field (Mariita, 2007). Using two sensors spaced about 50 cm apart, a magnetometer measures both the orientation and strength of two magnetic fields to identify the differences. When the magnetic field is stronger in one sensor, this higher frequency will signal (by sound or visual) the operator. A magnetometer is a highly accurate instrument. These very sensitive devices are usually employed to detect large ferromagnetic objects (such as UXO) can be effective to depths of several meters but do not react to non-ferromagnetic targets (Bruschini, 2000).

In the active approach, on the other hand, permanent magnetization is artificially introduced to ferrous objects to produce a strong, long lasting field. Magnetic fields can, for example, be introduced in cables close to pipelines. In both approaches, magnetic locators detect the magnetic field of ferrous objects (Hrvoic, 2011; Schonstedt, 2003).

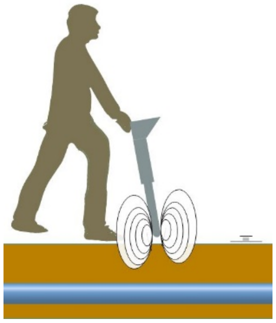


Figure 7 - system representation of the magnetic detection method

Most magnetometers are designed to operate in 60-Hz and radio frequency fields. To obtain the maximum area coverage, a locator should be swept from side to side. In long ferrous metal, such as a pipe, the magnetic field extends from the beginning to the end of an object. A pipeline has a maximum magnetic signal at the joints; where they are welded together. Total field measurements are useful for a utility search over large distances where no sources of interference (e.g., power lines, railroads and vehicles) exist.

The application of magnetic methods in airborne surveys (aeromagnetic surveys) suggest that the magnetic method is suitable for integration also with excavators (Brauer, 2000). It is important to highlight, though, that as long as integrative detection systems (i.e., two or more methods are combined) are concerned, there is a potential conflict between electromagnetic and magnetic sensing technologies. These issues are listed briefly below (Jeong et al., 2003):

- Current injected by electromagnetic methods can distort signals that the magnetic device receives;
- The electromagnetic plates could distort the magnetic field associated with the buried cables;
- Power frequency eddy currents in the electromagnetic sensors distort magnetic fields (simple modelling suggests that if the magnetic coils are maintained at least 640mm away from the electromagnetic plates, the distortion will be limited to about 1%)

Finally, the descriptive summary of the magnetic location method is given in Table 4.

Table 4 - qualitative review of magnetic detection techniques

Features	**Findings**
Material type	Metal (Low conductive metal is difficult to find)
Movement speed	No problem with the excavation speed
Accuracy	~10% depth
Depth	3 to 6 m (Bilal, Chen, Dou, & Dutta, 2012). Exploration depth is limited to approximately 15 feet below ground surface
Frequency	Up to 50-60 Hz
Soil type	Less effective in wet soil.
Surface terrain	No impact
Scanning pattern	Adaptable to excavation pattern
Data processing	Real-time
Strength	• Can be used in passive way • High electrical conductive material and saline ground water do not impeded penetration of magnetic surveys (Mariita, 2007)
Weakness	• Steel and other ferrous metals (e.g. power cables) in the vicinity of a magnetometer can distort the data • Extremely low frequency fields caused by adjacent material or equipment can be a problem • In congested, urban areas parked cars, buildings, fences and utilities contribute interfering magnetic signals that can mask detection of buried metal objects
Applicability	Total magnetic field can be a choice in the project

3.1.3 Ground-penetrating radar (GPR);

“A Ground Penetrating Radar (GPR) responds to changes in electrical properties (dielectric and conductivity), which are a function of soil material and moisture content” (Daniels, Gunton, & Scott, 1988). This is shown in Figure 8. GPR is a commonly used geophysical sensor to detect buried utilities.

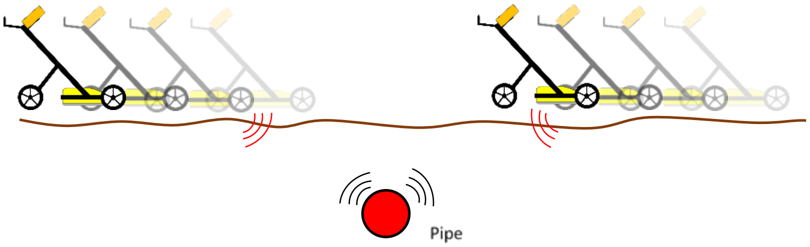


Figure 8 - system representation of a Ground Penetrating Radar (transmitting - left, and receiving, right)

The main advantage of GPR is that it can be used to map and detect both metallic and non-metallic utilities at various depths (Wahab, 2013). At the cost of lowered resolution, the depth of investigation can be increased by decreasing the frequency. However, the accuracy of GPR is considerably compromised at depths of more than four meters (Luís, Boo, Pereira, & Yamanouth, 2012). The applicability of GPR depends significantly on the type of soil on which it is operating. For instance, the radar penetration may be reduced to less than 1 meter in clay materials or high conductivity materials such as those containing salt. It is because the electromagnetic propagation rapidly attenuates in the presence of conductive materials, such as water (Papandreou, Brennan, & Rustighi, 2011). Other parameters influencing the functionality of GPR include, but not limited to, soil density, water content, and environment accessibility, geometry of the subsurface, and surrounding utilities. The main drawback with the GPR is the difficulty in data interpretation and operation complexity. Table 5 summarizes the main characteristics of GPR.

Table 5 - qualitative review of Ground Penetrating Radar

Features	**Findings**
Material type	Metal and non-metal
Movement speed	No problem with the excavation speed
Accuracy	5-10% depth
Depth	Not good in more than 4 meters
Frequency	50MHz to 4GHz
Soil type	Less effective in wet soil and clay
Surface terrain	Problem in rough and cultivated surfaces
Scanning pattern	Should be in grid way
Data processing	Complex data interpretation
Strength	• Flexible and relatively rapid surveying technique • Centimeter scale resolution
Weakness	• High operating costs • Affected by the geometry of the subsurface • Negative effect of water content • Difficulty in data interpretation • Operation complexity • Saline soil has effect on it
Applicability	Inapplicability in high conductive soils

The functionality of the GPR can be improved through the integration of ultra-wideband (UWB) radar (Zhuge, Savelyev, Yarovoy, & Ligthart, 2007), Guangyou 2007). This is because the UWB operates beyond the microwave band of the GPR (300 MHz to 3 GHz), in the spectrum of 3.1 GHz to 10.6 GHz (Lee, 2007). Researchers demonstrated that UWB can detect objects up to 30 centimeters (Guangyou, 2007; Zhuge et al., 2007). UWB has some advantages compared to GPR, which include:

- It can deduce the type of the material based on measured dielectric property of the object (Zou, 2012).
- It returns high resolution 3D images (Amineh & Nikolova, 2010; Kidera, Kani, Sakamoto, & Sato, 2007; Myakinkov & Smirnova, 2010);
- It has a higher sensing accuracy as compared to GPR (Zou, 2012).

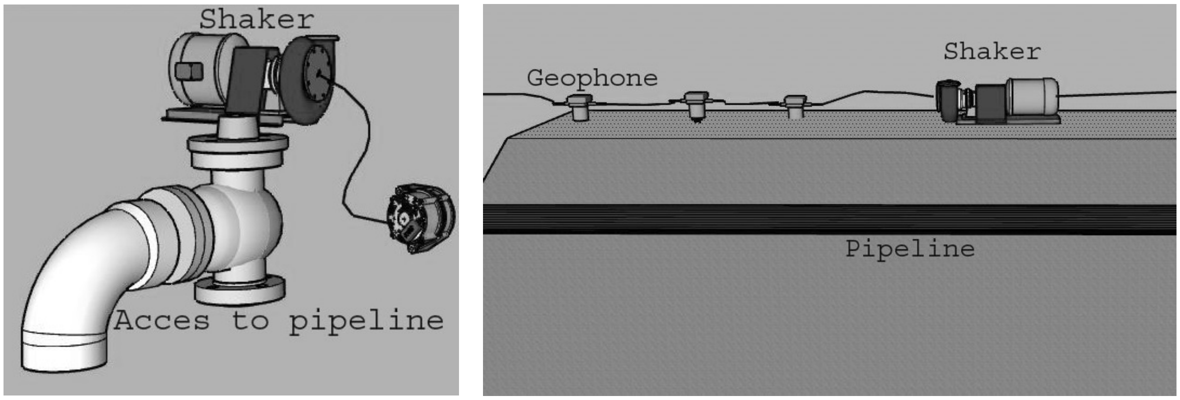
On the other hand, there are some limitations associated with the application of UWB. These include (Park et al., 2004):

- Loss of signal is higher compare to GPR, especially for the wet soils;
- Equipment needs to be installed onsite before measurements can be started;
- More powerful devises are needed with detecting at depth, since an increasing depth by n times needs transmission or 10^n times more energy.
- Wireless communication devices interfere with UWB signals.

All in all, the application of UWB radio waves in addition to a technology such as GPR seems promising to improve the its performance.

3.1.4 Acoustic method

The acoustic method uses sound pulses to localize buried utilities. This can be done by excitation of a pipe (see figure 9a) or by excitation of the ground itself (J. M. Muggleton & Brennan, 2008) (see figure 9b). Excitation of the pipe requires that utility operators place a signal on the pipe. Placing the signal to the pipe needs access to the pipeline (J. M. Muggleton, Brennan, & Gao, 2011). The technology therefore is not applicable to the scope of this study. A little more realistic is the excitation of the ground. For this method, no access to the utility is needed since it generates vibrations that go into the ground. Seismic or vibro-acoustic methods are commonly used in geophysical surveys (J. Muggleton, 2012). The UK-based Mapping The Underworld (MTU) initiative demonstrated that buried utilities could be detected effectively using surface mounted geophones if the exciter was in contact with the buried utility. However, the fact that a geophone needs to be placed on the ground makes the detection process rather slow and thus not very suitable for real-time applications. It seems that the method creates data uncertainties and involves complex data proceeding (Royal et al., 2011). Also geophysical properties of the soil impact the sensor's ability to detect utilities (Papandreou et al., 2011). In other words, the more rigid the surface, the deeper the feasible range of the detection. For instance, the detection depth will be greater for frozen ground or concrete cover. It is usually detectable up to 2.5 m in depth for gas pipe and 2m for water pipe based on expert's opinion (Jeong et al., 2003).



(a) (b)

Figure 9 - the setup of the acoustic methods: (a) pipeline excitation, (b) ground excitation

An Acoustic Pipe Locator (APL) is ideal for finding plastic pipes and systems without tracer wires. Natural gas, water and sewer laterals are easily traced using this state-of-the-art acoustic technology. APL gives the locator the ability to accurately locate unmarked underground utilities, even Polyethylene Pipes (PEs), PVC pipes, concrete pipes, and clay tiles and of course metal pipes.

As an alternative to geophones, laser-vibrometry technology is used (J. M. Muggleton et al., 2011). In this technique, a laser is used for ground excitation (by using Q-switched laser pulses). The laser pulse heats a small area of the surface in a nanosecond range of time, and based on that an acoustic pulse is generated. The vibration of the soil is measured by a Laser Doppler Vibrometer (LDV). Acoustic waves generated by the excitation laser reflect back from the utility and the echo is measured by the monitoring laser of the LDV. This device has a range of several meters. As with acoustics, the detection with laser vibrometry is based on the change in surface vibration (Heuvel et al., 2003).

Both acoustic excitation and laser excitation methods could serve as a useful adjunct to the more conventional methods of buried object detection, such as GPR (J. M. Muggleton & Rustighi, 2013). However, while the data interpretation is more difficult compared to the acoustic excitation, laser excitation is potentially a faster technique which can, in addition to size and shape information, provide valuable depth information. Nevertheless, the acoustic excitation technique is much more mature than the Laser Excitation technique (Heuvel et al., 2003). Another difference between the two technologies is that acoustic excitation gives the frequency response of the buried object while laser excitement gives the time response. Time response is convenient to provide depth information and frequency response is convenient for the classification of the buried object. Currently, the main constraints of laser excitation technique is the detection depth, which is limited to a few centimeters. But, this problem can potentially tackled through the modulation of the pulse energy. Table 6 summarizes the review of acoustic methods.

Table 6 - qualitative review of acoustic utility detection method

Features	**Findings**
Material type	Metal and non-Metal, ideal for plastic pipes.
Movement speed	Limitation to move fast. Laser excitation method is faster.
Accuracy	0.1 m-0.2m
Depth	Not good in more than 3 meters.
Frequency	Typically from 132Hz to 210 Hz (LDV method uses laser to transmit and receive)
Soil type	Rigid soils transfer signals better than weak soils
Surface terrain	Less effective in covered soil (pavements)
Scanning pattern	Not easily adaptable to excavation pattern
Data processing	Need time to process the data. Complex data interpretation.
Strength	Complementary to other techniques.
Weakness	Using ground-contacting geophones.
Limitation	Inapplicability to high conductive soils.
Applicability	It can be applicable, but maturity is not enough in this step.

3.1.5 Summary of pull detection technologies

This chapter reviews various non-intrusive and intrusive detection technologies. Table 7 provides an overview of the key features of the detection technologies that were analyzed.

Table 7 - comparison of various detection technologies

Feature	**Conditions**	**Electromagnetic**		**Magnetic**	**GPR**	**Acoustic**
		Inductive	*Passive*			
Detectable material	*Cables*	×	×		×	
	Metal	×	×	×	×	×
	Non-metal				×	×
Functional at excavation speed		Yes	Yes	Yes	Yes	No
Accuracy		~ 0.1 m		~5% depth	5~10% of depth	0.1~0.2m
Depth range		<2m	<2m	3m~6m	<4m	<3m
Frequency		50 ~ 480 Hz	50 ~ 60 Hz		50 Hz ~ 4 GHz	132 ~ 210 Hz
Impact of soil condition on functionality	*Wet soil*	High	High	Low	High	High
	Salty soil	High	High	High	High	Low
	Clayey soil	Low	Low	Low	Low	Low
Sensitivity to terrain conditions		Low	Low	Low	High	Low
Scanning Pattern		Swinging along estimated pipeline location	Swinging along estimated pipeline location	Swinging along estimated pipeline location	In grid	N/A
Data Processing	*Real-time*	×	×	×		
	Post-processing				×	×
Estimated maturity level (scale 1-10)		7	7	6	8	4

3.2 Monitoring systems

Section 3.1. explained the results related to our first category of pipe strike avoidance technologies; the detection systems. This section elaborates which monitoring systems exist in order to avoid damage. As shown in Figure 3, we divided monitoring systems into pipe-centered and location-centered. Pipe-centered systems use sensors mounted on or near pipes to warn the operators about working in proximity of pipes. Location-centered systems, on the other hand, use RTLS or aerial observation to monitor the movement of the operators and warn against dangerous proximities.

3.2.1 Pipe-centered systems

With regard to pipe-centered systems, various types of sensors are available. Infrared thermography and negative pressure sensors, for example, have been used for pipeline monitoring. Constraints still exist for each of them: weather conditions influence the effectivity of infrared thermography. Negative pressure sensors further only help identifying the existence of a pipeline leak or damage but do not help locating the exact location of it. Despite the fact that constraints exist, some technologies seem promising. Therefore, the next sections elaborate acoustic emission and fiber optic sensors.

Acoustic emission sensors

An acoustic monitoring system works by measuring and analyzing the seismic behavior of soil. Acoustic sensing is an emerging technology for pipeline monitoring for the remote detection of third party interference (Bernasconi, Giudice, & Milano, 2012). Various examples of this technology are discussed below.

An acoustic emission sensor converts the surface movement caused by an elastic wave into an electrical signal which can be processed by the measurement equipment. Frequency classification of acoustic sensors can vary based on the application condition: in the presence of background noise (such as produced by machinery), frequencies higher than 100 kHz are better. For wide sensor spacing, lower frequencies are selected (Vallen Systeme GmbH, 2015). Broadband acoustic emission sensors are the sensors that respond uniformly to a very broad band of exciting frequencies.

Recently, efforts were made to produce low cost self-contained alarm technologies that use acoustic sensors without requiring a central computer. These sensors are integrated with visual or audible alarms. Research in the U.S. demonstrated the feasibility of developing a new acoustic sensor that can differentiate between non-threatening sounds and real threatening sounds such as excavation signal (Bernasconi et al., 2012).

In transmission pipeline monitoring and inspection, acoustic sensors can also operate in passive mode. For example, when an impact caused by a third party around the pipe creates acoustic waves, a passive sensor measures the timing and relative magnitude of these waves to determine the impact location and severity. Passive sensors however provide limited functionality and are not always adequate for pipeline inspection. One limitation is that such sensors cannot cover long distances and should be installed in almost every 200 meters (Wang, 2004).

Surface Acoustic Wave (SAW) sensors, which are sensitive to a variety of surface changes, have been widely used for physical sensing. Wireless measurement systems with passive surface acoustic wave sensors offer new and exciting perspectives for remote monitoring and control of moving parts, even in harsh environments. Since they have to be installed permanently – and left untouched - on the surface level, it is however unlikely that these technologies are applicable also for buried pipeline detection (Jin & Eydgahi, 2008).

Another approach in pipeline monitoring with acoustic method is using Multi-point Acoustic Sensing (MAS). In this method vibro-acoustic monitoring stations can be located 30 km away from each other (Bernasconi et al., 2012). This technology was used to monitor 20 inch pipeline carrying natural gas from the Tunisian station in Cape-Bon to the Italian station in Mazara del Vallo with 100 km length (Giunta, 2011).

Fiber optic sensors

Optical fiber communication cables have proven their capability in long-haul applications. They also have some advantages compared to conventional sensors, which include: broader bandwidth capacity, electrical isolation, low error rate, ruggedness and flexibility, and low installation and maintenance cost (Tapanes, 2016). Figure 10 illustrates how fiber optic sensing works.

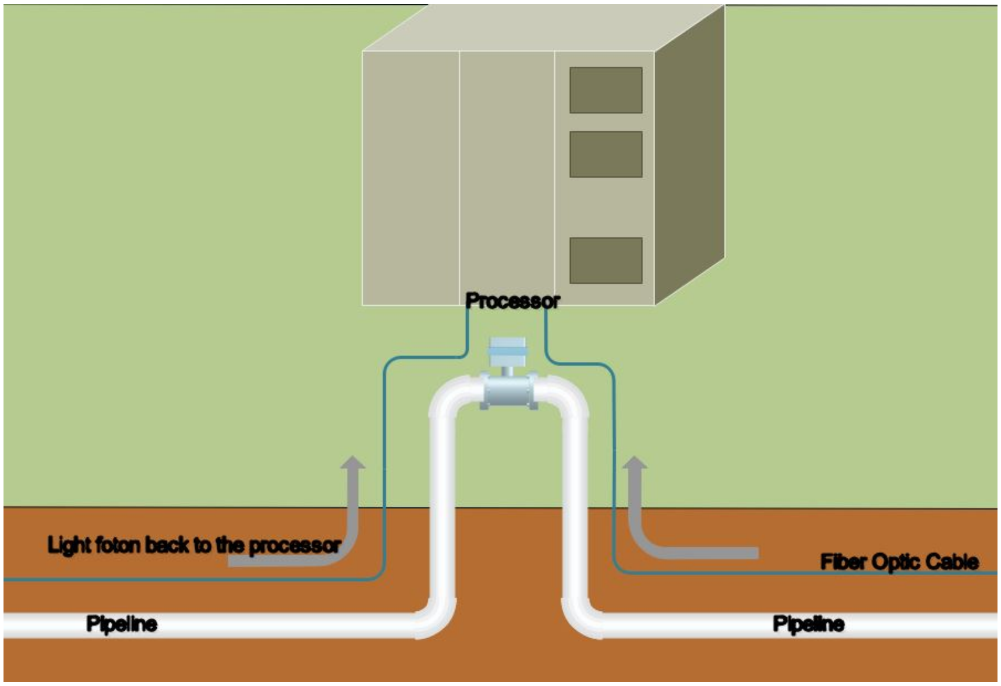


Figure 10 - conceptual visualization of fiber optic sensor system for pipeline monitoring

Fiber optic technology is gaining a wide acceptance for monitoring utilities, and getting to play a major role in real-time monitoring. Fiber optic technology functions by launching light beams through to the core, along the length of a fiber, to identify disturbances to the light pattern. Optical fibers can detect strain-stress, vibration, acoustic-emission, pressure, and temperature. This enables the measurement of a wide range of events and conditions, many of which are useful for monitoring pipelines (Tapanes, 2016). The costs of fiber optic systems are rapidly decreasing, and it is expected that the system will soon be accepted as a reliable and inexpensive measurement tool (Tapanes, 2016).

Monitoring pipelines by means of the fiber optic technology can be done in two approaches: using fiber optic point sensors, and by using distributed sensors installed at tens of kilometers distance. Advantages of fiber optic sensors are that they have a high resolution and work in real time (Tapanes, 2016). Also, they are not impacted by electromagnetic interferences. The good point in using distributed sensors is that they are connected to fiber optic cables. Often existing cables that are buried along pipes can be reused for pipeline monitoring. The US-based company Senstar develops a well-known pipeline centered monitoring system called Fiber Patrol-PL (Senstar, 2016).

3.2.2 Location-centered systems

The second monitoring systems category covers the location-centered systems. These systems use location data to identify the equipment working in the proximity of pipes and warn the operators about the risks. Two main type of location-centered system exist, namely geo-fencing and UAV observations.

Geo-fencing

The point of departure for this system is the assumption that the coordinates of pipelines are known. At its core, geo-fencing uses localization technologies and known locations of pipes, creates a buffer around them, and generates a signal when the buffers are trespassed. More precisely, this system defines a virtual fence in the proximity of a pipeline location. This area is considered as a zone inside which a construction work can potentially cause a damage to pipelines. Geo-fencing systems simultaneously monitor the position of excavators. If an excavator trespasses the virtual fence, it warns the end-user about the potential risks on excavation damage. A visual illustration of the geo-fencing systems and its components is given in Figure 11.

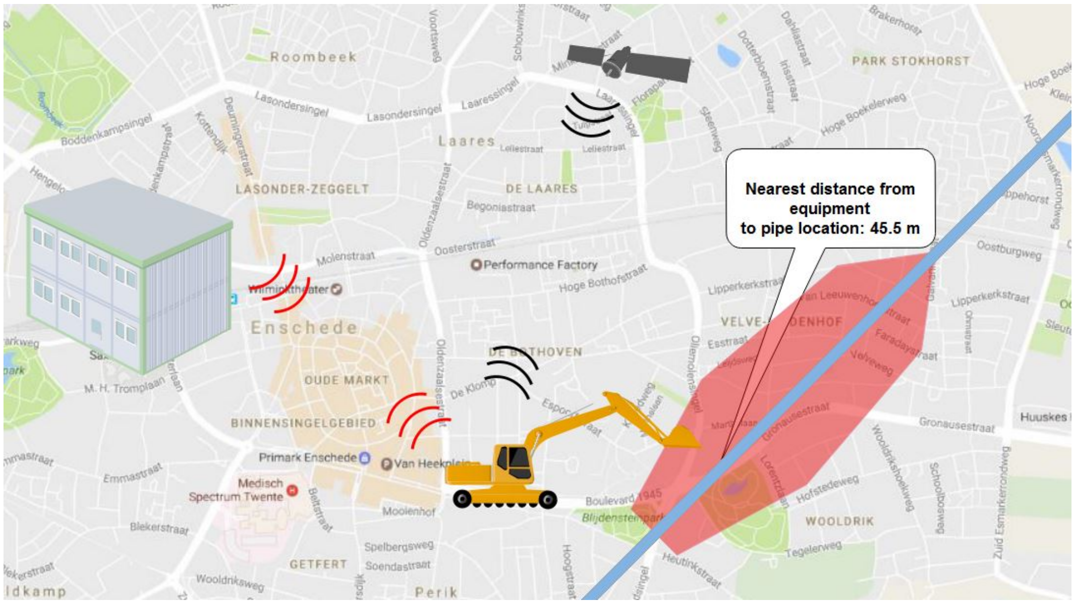


Figure 11- conceptual visualization of the geo-fencing system components

The number of nuisance alarms in this system can be high. As a result, users' trust in the system may wear out over time. To create a more precise geo-fencing system, cross referencing of the position of the excavation bucket with the GPS coordinates can be used. In case a bucket reaches the pipeline location, a warning will be transmitted to the excavator or a safety control center. This approach has been developed in the United States by groups such as the Virginia Utility Protection Services (VUPS), Global Technology Integrator Limited (GTI), and ProStar Company (Prostargeocorp, 2016).

UAV observations

Another method for pipeline monitoring is to use Unmanned Aerial Vehicle (UAV). This method is based on observing the pipeline and detecting threats using aerial images. In this system, an auto-pilot system, which allows the programming of the flight route, and precise GPS positioning, is crucial. Every image is geo-referenced and time-stamped. The final outcome of the stage is a geo-referenced mosaic of images covering the pipeline. The last step in the overall workflow is to identify objects near the pipeline that might represent a potential danger. This method eventually allows detection of threats to the pipeline such as construction work, earth movement, laying utility, preparing building sheds, soil upheavals, planting of new trees, temporary deposition of materials can be monitored in real time using this technique (Kuehnen, Schnur, Rogg, & Schmidt, 2010).

Image analysis can be automated. This tool should identify potential hazards along the pipeline automatically and alarm the pipeline operators.

3.2.3 Summary of monitoring systems

This section discussed various monitoring systems for alerting operators and utility owners about excavation work in the proximity of pipelines. We introduced pipe-centered and location-centered solutions, and we elaborated their advantages and disadvantages. In general, it can be asserted that there is a lack of reliable and durable monitoring techniques that can be readily used for the reduction of excavation damages to the pipelines. This is mainly due to the fact that there are still several issues that need to be addressed by system developers. Some of the most common problems in monitoring systems include, but are not limited to (Wang, 2004):

- The generation of nuisance alarms that lower the value of a system;
- The inability to anticipate damages (rather than detecting them ate the time they occur);
- Training and experience is required to operate these systems;
- Weak signals (such as caused by hand-drilling) cannot yet be detected.

3.3 From detection and monitoring to warnings

This section finally discusses how signals from utility detection and monitoring systems are passed effectively to the user of excavation equipment and owner of pipeline networks.

3.3.1 Filter algorithms

Both detection systems and monitoring systems can be effective in avoiding pipeline damages. One precondition is, however, that systems do not ‘overlook’ a pipeline (false negative), and that true positive warning signals are effectively brought to the attention of excavator operators or the utility owners. Utility mapping technologies may also detect other subsurface objects (e.g. other utilities or debris). Similarly, monitoring systems may detect objects other than excavation equipment (e.g. passing machines or lorries). Such disturbances (false negatives) are generated by many systems, and are called nuisance alarms or false positives. A good system should adequately deal with the true positive and nuisance alarms. An overview of these different alarms is given in Table 8.

Most detection equipment developers have their own filters and algorithms to indicate whether a signal is a true positive or false positive. Although most filters have been developed and tested in controlled laboratory conditions, their effectiveness in outside conditions can be less.

Table 8 - taxonomy of warning signals based on effectiveness

	Warning generated	**No warning generated**
Pipeline present	True positive	False negative
Pipeline not present	False positive	True negative

3.3.2 Alarming systems

After generating a true positive warning signal, the next step in the chain of strike avoidance is to effectively pass this signal on to the end-user (i.e. the excavator operator or network owner). Because of the limited time available for this research, we only enumerate a few basic technologies that are often used to alarm users.

Table 9 shows different ways in which alarms can be triggered. First, the most common are the audio alarms and visual alarms. These generate a sound or light pulse to signal end users. Also, haptic feedback systems exist to stimulate the end users by using vibrations. Systems can use multiple alarming devices to inform the end user about the severity of each alarm. This can be referred to as plurality alarm. Finally, utility operators often have already asset management or pipeline integrity management systems in place. These systems can often also have a user interface to communicate warning signals.

Table 9 - examples of used alarm systems

Alarm System	**Function**
Audible Alarm	Sounds are used to trigger the operator/crew. Examples are a whistle, a horn, siren and an alarm claxon
Visual Alarm	Light is used to trigger the operator/crew. Examples are: flashing light, strobe light or screen information
Stimulation Alarm	Vibration or mechanical signs are used to activate the worker. An example is a vibration device
Plurality Alarm	Using primary and supplementary alarms. A first signal device associates with the supplementary device. Using a plurality alarm needs a system to activate supplemental signals in response to primary signals
Pipeline monitoring systems	Some pipeline owners have their own pipeline integrity systems that monitor the operational conditions of the pipeline continuously. Warning signals are generated also in the user interfaces of these computer systems

A plurality alarm supplements primary alarms with another alarm type. This combination can, for example, be (Delia, 2010):

- a primary audible alarm and supplementary visual signal;
- a group of audible alarms such as whistle, horn and claxon;
- a first audible signal can activate a supplementary stimulation alarm;
- a series of wired or wireless transmissions to a remote receiver.

More information about technologies mentioned in this section is likely to be found also in the research domains such as traffic safety systems, human-machine interaction, and user-interface design.

4 Conclusions

This chapter summarizes the outcomes of a review study initiated by the Dutch Ministry of Infrastructure and the Environment (I&M), and the pipeline owner association (VELIN). The VELIN have set the target to reduce damages to high-pressure pipelines to zero, an initiative supported by the ministry of I&M. In particular, these organizations want to avoid damages to buried pipelines. Such incidents are often caused by third parties.

To contribute to the reduction of damages, the University of Twente first explored what technologies exist to help avoid pipeline damages. The project team identified and described the existing underground utility detection and monitoring systems. In specific, their main objective was *to review available systems that help detect potential conflicts between excavator equipment and high-pressure transportation pipelines.*

After a literature review and various expert interviews, we conclude that reducing pipeline incidents caused by excavators is not possible by implementing one single technology only. No single detection, monitoring, and mapping technology is 100% safe and error-free. It is, therefore, most likely that a combination of detection and monitoring technologies should be further developed and implemented to reduce damages. These different technologies were reviewed during this study. Below, we present these conclusions in more detail.

In terms of detection technologies, there are lots of underground utility detection technologies and each of them has some strengths and weaknesses. Our analysis was aimed at identifying constraints and selecting technologies that can be used for the development of strike avoidance systems. It is not possible to generally advise using a technology for each type of utility (such as steel pipelines). Although the performance of technologies are evaluated under controlled conditions, site-specific conditions often have an impact on the effectiveness of a system too. Nevertheless, some technologies seem more promising than others. On this note, Ground Penetrating Radar (GPR), electromagnetic locators (Radio Detection), magnetic locators, and acoustic locators seem more promising for pull detection technologies. They have constraints, however, when it comes to real-time detection. This is because some technologies require special expertise and training or need significantly more development before they can be mounted on excavation equipment. Furthermore fiber optic cables and RFID tags seem to be effective push detection technologies. When considering the abovementioned systems, various factors influence detection and monitoring tools' applicability during excavation work. This leads to a few requirements for detection and monitoring systems:

- Equipment should be rugged enough to be handled during excavation work;
- Equipment should not be disturbed by the (metal) body of an excavator;
- Equipment should function well with the kinematic behavior of an excavator;
- True positive signals should be increased as much as possible;
- False positives/negative signals should be reduced as much as possible;
- Detection should happen in real-time, involving no post processing;
- The output of detection should be understandable for non-professional people such as excavator operator.

Using only detection technology or a sequence of such technologies does not guarantee that all pipelines will be detected. For the most reliable detection technologies - such as GPR and radio detection the issue is not as much the reliability of the detection antennas but rather their limitations when it comes to mounting them on moving excavation machines. GPR and radio detection require fixed movement patterns and are less effective when they follow - more random and varying - movements of excavators.

In sum, although detection technologies can help avoiding damages, we suggest using also monitoring systems. Steel pipeline strike avoidance systems such as fiber optic sensors and acoustic-based monitoring systems exist already on the market for professional and non-professional operators. In the United States, geo-fencing was also developed and tested positively. The reliability of these systems depends largely on the accuracy of available pipeline maps. Based on above conclusions, the authors have made a set of recommendations that can be used to further form long-term and short-term strategic plans for the reduction of excavation damages.

5 Limitations of this study

Decisions made during the research activities influenced what we studied in more detail, what we studied less, and what was left outside our scope. This section elaborates how these decisions impact the reliability and validity of this study. Below we discuss influencing factors such as available time, altering focus, the adopted review approach, and validity of our predictions.

One constraint of this study was the time frame. The actual research was conducted in less than six months. This time was sufficient to thoroughly and systematically analyze the available literature for utility detection. It appeared more difficult, however, to also find different experts (technology users, developer, and researchers) and have an interview with them. In addition, the steering group meetings slightly changed the original scope from evaluating detection technologies to also including global monitoring systems after intermediate results showed that detection technologies are not yet sufficient per se. As a consequence, only the last stage of the research was used to extend the focus beyond studying push and pull detection systems, looking also into real-time monitoring systems. In future studies, it can be helpful to also spend more effort on exploring how global monitoring and local detection systems complement to – and interfere with - one another.

Besides the time constraints, one other limitation relates to the nature of desk-research and review studies. The advantage of our review is that it creates a broad, systematic overview of the state-of-the-art technology. Also, the availability of experts and their willingness to share information with the interviewer impacted the findings. Although we strived to have a complete overview of expert interviews, we recommend for future studies to create a sample of respondents with an equal balance between technology developers, users, and researchers.

Next, this study is based on research work and expert views. This means that no specific hands-on experience was gained by the research team. The findings and conclusions are therefore mostly drawn from second-hand data. Although this should not necessarily decrease the reliability of this study, it is worth mentioning that first-hand experience can be used to strengthen the findings in our study.

Finally, this study reported about technologies and their maturity. To be successful, however, systems need not only to be technologically mature. Implementation of technologies on a larger scale also depends on the adoption. This, in turn, is influenced by factors such as ease of use, legislation, and investment costs. Predictions about most promising technologies, their development process, and uptake should, therefore, be interpreted with a little caution since they are, at best, an educated guess.

6 Recommendations

This final chapter uses the findings above to outline a technology roadmap that should help establishing safer excavation practices nearby transportation pipelines. Based on our research experience, discussions with the steering group, and the development of the roadmap we finally conclude by suggesting possible work packages that could be started on the short term. We successively discuss general recommendations for local detection technologies, global monitoring systems, warning systems, and data. Finally, we conclude by formulating three more specific research and development work packages.

6.1 Technology roadmap

This section presents a technology roadmap containing suggestions for further development of local detection and global monitoring systems. This conceptual map gives an outlook to what actions are possible to improve the state of the art technology. It purposefully does not prioritize one technology over the other and does not spell out precise steps for future research. Instead, it uses existing technological constraints and knowledge gaps to demonstrate what has to be overcome in the coming years. For each step proposed on the roadmap, we suggest various stakeholders be leading. By and large, the success of passing steps along a roadmap trajectory depends on the ability of stakeholders to improve a technology and its adoption. Tracks are not mutually exclusive, and it is likely that progress on all tracks are required to significantly enhance safety.

The roadmap distinguishes trajectories that are related to (1) detection technologies, (2) global monitoring systems (3) warning signals, and (4) data improvement. Within detection technologies, we differentiate between further development of: (1.1.) local pull detection systems, (1.2) local push detection systems, and (1.3) the integration between detection systems and excavation machines. Monitoring systems can be distinguished between location-centered and pipe-centered systems. For each of the categories, we address the current limitations and suggest next steps needed to make progress. On the roadmap, we also add anticipated targets and the constraints related to the feasibility of trajectories. Below, we discuss the different roadmap trajectories.

6.2 Local detection technologies

There are four local pull detection systems (1.1) considered relevant for further development. Each of these systems has limitations. We recommend pursuing development of four mature systems. The first is the GPR system. Its ability to detect pipes in different soil and surface conditions is limited nowadays. High water tables and wet soil currently disturb the signal received by the GPR. Also in clay soil, it is difficult to detect pipelines. Since signals need to be sent into the ground located, the void between the GPR antennas and surface needs to be small. It is, therefore, hard to use GPR on rough surface areas. Besides the effectiveness of the systems in detecting, the GPR creates radar grams that are difficult to interpret. The output of a radar should, therefore, be improved by developing an end-user friendly interface. Companies in the Dutch industry – such as GT Frontline – are already quite advanced in addressing these issues.

Secondly, it is worth pursuing further development of active detection technology. This technique requires a transmitter to be connected to pipelines to activate signals on a pipes. This makes it more difficult to mount the technology on an excavator. Passive technologies do not have this constraint but seem less reliable since not all buried pipelines generate an electromagnetic field that has a current which is strong enough to be detected. We therefore suggest to use adjacent utilities in favor of pipeline safety by creating a magnetic field to the pipe, or installing fiber optic along the pipeline to create magnetic field.

A third existing detection technology is the acoustics systems. Although acoustics can help detecting pipelines it takes significant setup time and effort to use them. They are more useful currently for mapping the underground rather than for strike avoidance. To map pipelines acoustic systems need to be installed on the field to send and receive signals. This installation and calibration should be simplified to make the technology more user-friendly. Also, the penetration depth of acoustics could be enhanced. Moreover, the technology is sensitive to background noise and ambient noise. Simplification of detection procedures and output information are therefore needed.

Fourth, magnetic systems can be further improved to detect pipelines by using the total magnetic field method. This would be reliably functioning on excavators. Also, just like with passive radio detection, a useful application for magnetics systems is their ability to detect cables that are buried close to pipelines. If utility owners bury a cable close to a pipeline, then this can be used in the field to predict pipeline locations.

Also local push detection systems (1.2) could be established to enhance safety. These systems are pipeline-based (on pipeline, or near pipelines). The technologies are relatively mature. It may take, however, decades to implement them on the full (22.000 km) length of all transportation pipelines. Operators cannot yet rely on push systems unless they know which network parts they cover. In this light, it would also be interesting to develop experiments that compare detectable metal lines and RFID tags as on-pipe push systems. Also burying physical markers (such as multiple tape layers) near pipes would make pipes more detectable. Similarly, network owners could install fiber optic acoustic sensing systems for permanent safety monitoring. Some utility cables that are buried close to pipelines (either existing or new cables) can be re-used for detection as well. We suggest exploring which locations can make use of such existing networks.

Integration of local detection systems and excavator machinery (1.3) is another important development trajectory for the usefulness of detection systems. This means, for example, that detection systems should be tailored to the specific kinematics of excavation machines. A mounted detection system can only work effectively if it is capable of detecting pipelines while it moves along with the path and operation speed of the excavator. It is impractical for an excavator operator to adapt his excavator’s movements precisely along the path of GPR survey gridlines. GPR should, therefore, be further developed to also identify pipelines if less structured paths are followed. Furthermore, a local detector’s antennas and sensors should be ruggedized and mounted at an optimal position on excavators to be able to detect pipelines. Further research can be executed to find out whether sensors should be mounted on buckets, close to caterpillars, or both. Another step to be taken is that some detection devices, such as magnetic localization, receive disturbed signals when being placed close to the metal body of an excavator. Solutions for this need to be found too.

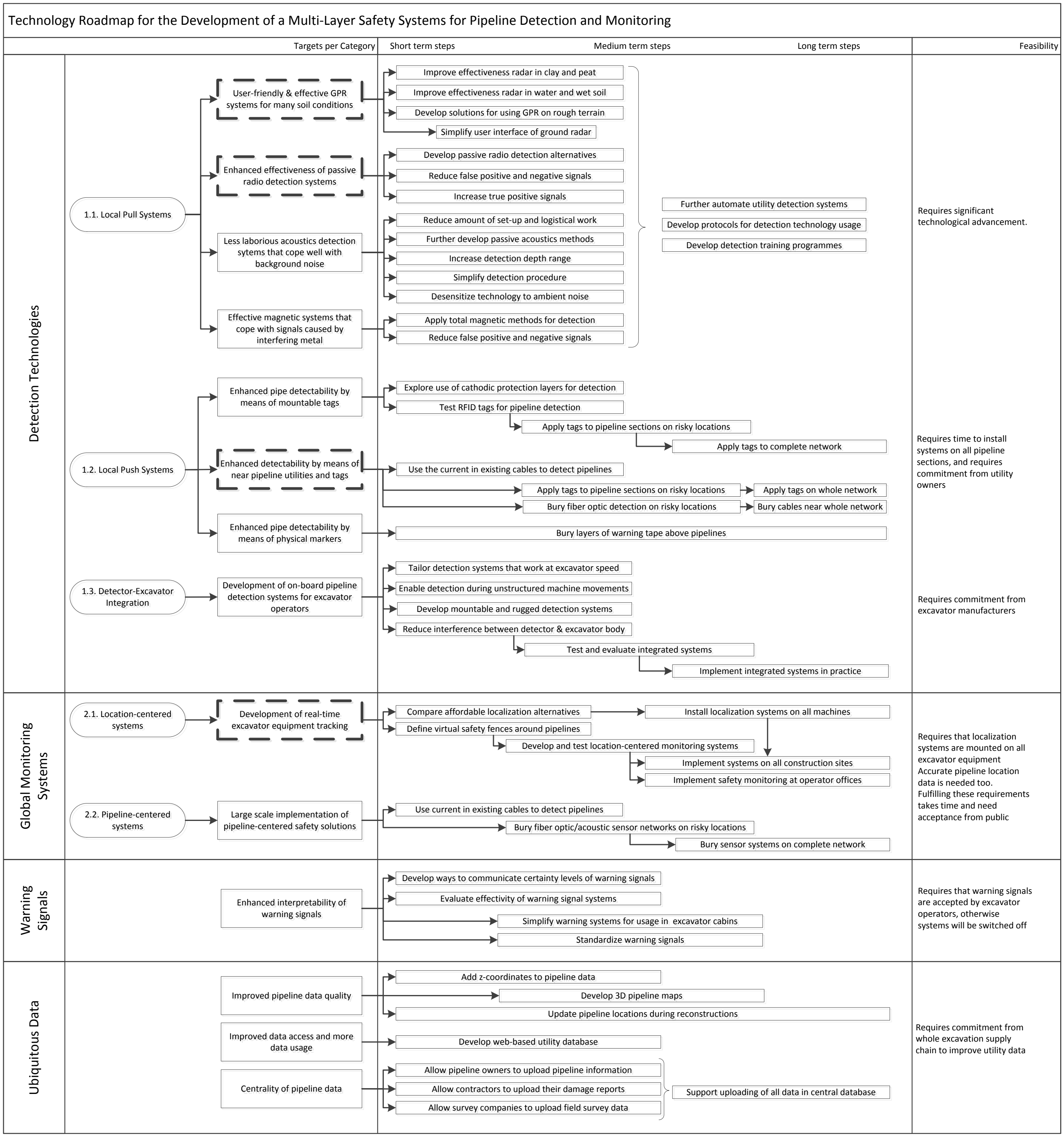


Figure 12 - proposed technology roadmap for pipeline strike avoidance

Another step toward more integration relates to the state of push and pull technologies that require advanced logistic preparation and set up before they can be used for detection. Acoustics and active radio detection, for example, require that signals are placed on a pipe, or that signal generators are pierced into the ground. It could be further investigated whether these less portable solutions could be made more mobile and flexible. Finally, the effectiveness of excavator-mounted development depends also on the user-friendliness of detection systems. Detector operating instructions, training, and user-friendly interfaces for excavator operators therefore need to be developed.

6.3 Global monitoring systems

A system complementary to local detection is the use of global monitoring. These have been explored in this study to a lesser extent due to time constraints, and due to the fact that there exist only a few examples of such systems for pipeline protection. We found however, that the elements of global monitoring system are used already in industry. Required elements, such as real-time localization systems (RTLS), geographical information systems (GIS), and accurate pipeline data are already existing. Combining these elements into affordable monitoring systems is, therefore, an expected step on the roadmap. Global satellite navigation systems with various precision levels could, for example, be tested for their use in equipment tracking. In addition, equipment manufacturers, machine owners, and rental companies could together develop an open source system for equipment localization. As a next step, a system can be developed that integrates location information with pipeline data and anticipates possible clashes between equipment and pipelines. An example of such a system is geo-fencing. Testing various GNSS, the large scale installation of GNSS on excavation equipment, and the continuous improvement of pipeline maps are key steps toward achieving reliable monitoring systems.

6.4 Warning signals

The third track to be followed relates to the development of effective warning systems. Just like the last track, this track supports the first two roadmap trajectories. Still too often, local detection systems generate false negative (i.e. detecting no pipe while there is actually one) and false positives (i.e. detecting a pipe while there is none). Too many of such alarms will make detection systems unreliable and considered obsolete by practitioners. It would therefore be useful to investigate what types of signals can be used to distinguish between warnings from different levels of certainty. Developing a unified warning system that uses a combination of audio, visual and stimulation alarms is likely to contribute to the acceptance of detection equipment.

6.5 Data

The quality excavation safety planning, as well as the utility of global monitoring systems, depends heavily on the data on which they are based. Although location information of steel pipelines is considered quite accurate currently, this information is still stored in 2D schematic plans that contain only lines, nodes, colors, and annotations. The depth information is not always available and accurate. A continuous process of upgrading 2D schematic maps into 3D maps, therefore, is necessary. Furthermore, access to pipeline information can be improved. Nowadays, only dial-before-you-dig (KLIC melding) services can be used to request maps. These maps are valid for 20 days. After that, the contractor should file another KLIC request. Development of a ubiquitous access to pipeline maps, for example via a central database, would lower the threshold to collect and use pipeline information for excavation work. The new KLIC-WIN systems already is a first step in this direction. Besides storing the official utility maps, a ubiquitous utility databases may also help to store more information. Damage reports and historical survey information can, for example, be shared to facilitate learning and exchange.

In sum, the proposed technology roadmap addresses the different trajectories that are worth further exploration and development. We outlined possible steps for improving the effectiveness of detection technologies, and the steps required towards their integration with excavation equipment. A complementary path to follow would be the realization of global monitoring systems that use pipeline maps and real-time equipment location information to detect potential clashes. The last two branches supplement the first to trajectories and relate to the improvement of warning systems and utility data. It is considered as a role for industry to step onto the various trajectories; consider their targets and constraints, and to make decisions about what technology combinations will further developed in nearby future.

6.6 Work packages for the short term

Ideally, our suggestion would be to start development along each of the trajectories mentioned on the roadmap. Since this is capital intensive and time consuming, only a selection of the activities can be started on the short term. As requested by the steering group, this last section proposes three work packages (WP) for short term development. WP 1 relates to the further development of local pull detection systems, WP2 covers the development of local push systems, and WP3 focuses on global monitoring systems. The recommended scenarios below can help to reduce the number of excavation damage to the pipeline but none of them guarantees absolute zero damage.

It is suggested to start develop packages in parallel. This eventually helps developing a multi-layered safety system. In figure 13 we visualize the three work packages in a triangular shape. We suggest that at least two from the three packages are addressed to develop such a multi layered system. The advantage of such a system is that the typical weaknesses of one system can be overcome by using another system as a backup. For example, a combination of a local push systems (that essentially make pipes more detectable), and monitoring systems (that give proximity warnings) helps to still have a functional safety system in case either the push system's transmitters break or when the monitoring system's positioning system fails.

6.6.1 Work package 1 pull detection with GPR and radio detection

This work package is about development the further development of local pull systems. In our results and conclusions we state that GPR and radio detection are the two most common and functional techniques at this moment. We recommend further developing the use of GPR – to explore the excavation site upfront and, later, also during excavation – because: (1) the device seems to have a good range of true positives; (2) it is likely to be functional on a moving excavator; and (3) has an acceptable depth range, resolution and accuracy. Some experiments have been undertaken that integrated a GPR on a moving excavator. Currently, the largest challenge seems to make the GPR adaptable to the less structured movement patterns of the excavator. In addition, widening the electromagnetic spectrum, for example by using Ultra-Wide Band as a complementary to GPR, can help to reach larger depths. Having accurate positioning systems and utility plans (KLIC-data) available on the GPR will also be a step forward.

Radio detection also is suggested for application and further development. The multi frequency radio detection has been tested and seems most promising for direct application. Also, specific types such as an EM-61 and EM-31 device have a high resolution and can be useful for radio detection. Radio detection already demonstrates its use for mapping purposes since it can detect metal objects, has a simple output and acceptable depth range. One next step would be to investigate to what extent the technique can be used during the excavation (without generating too many false positives).

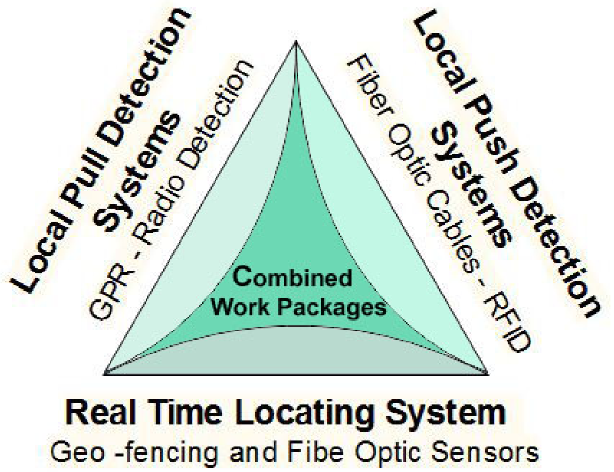


Figure 13 - three core work packages for development of a multi-layered safety system

6.6.2 Work Package 2: push detection with fiber optic cables and RFID tags

Another work packages is be aimed at making pipes more detectable. Local push detection systems can fulfill this objectives. However, they do require changes to the pipeline or pipeline surroundings. Excavation work is needed to install such systems – which in itself enhances risk on pipeline strikes. In addition, push systems are only effective if they are completely cover a pipeline section. On the short run it would be beneficial to identify the pipeline sections that are most prone to damage, and to install fiber optic detection systems there. An advantage of the fiber optic system is that often already existing cables can be re-used. Although we investigated this to a lesser extent, we also believe that RFID tags mounted on pipes will be a possible push technology in future.

6.6.3 Work Package 3: monitoring by implementation of fiber optic sensors and geo fencing

This third work package includes relates to using known locations (of pipes, cables or sensors) to monitor interference between pipes and excavators. One way to go here would be to use fiber optic or acoustic emission sensors. Fiber optic sensors need to be installed every 70 km (they have a reach almost 35 km on each side of the sensor). The system is promising but, just like in WP2 it needs to be cover the full length of a pipeline section to be functional. As positioning systems become cheaper and more accessible, the second technology that is worth further application in the field is geo-fencing. It is therefore suggested to improve localization systems, equip machines with them, and develop a real-time system that anticipates conflicts based on excavator locations and their estimated pose.

In summary, the work packages above alone will not be able to reduce pipeline incidents to zero. A combination of at least two of the three pipeline safety work packages is therefore recommended to create a multi-layered safety system. Also it is worth noting that to reduce the number of pipeline incidents, additional efforts are needed. These trajectories have been mentioned in the roadmap and examples of them are: improving available databases, educate and train people who are involved in excavation chain. Such efforts are captured in the Veiligheid Voorop/VELIN application for the I&M Safety Deals. These deals defined, for example, the necessity to developing safe excavation technologies, develop safe excavation apps, and development of a training for excavator operators, pipeline supervisors, and owners.

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Appendices

Appendix 1

Sample of interview questions

Interview Questions:

1. Would you please explain some facts about the Acoustic and Magnetic technology?
    a. How does the technology work?
    b. What are the key components of the technology?
    c. For which kind of material/utility the technology work?
    d. Frequencies for different materials?
2. Can you explain some detail about the effectiveness criteria? (depth, accuracy, resolution, …)
    a. What is the Depth range in which technology works properly?
    b. How is the Accuracy range in general?
    c. What is the Accuracy, Depth trade off?
    d. How soil condition affect the accuracy, depth and other effectiveness factors?
    e. How mature (scale 1-5) would you rate the technology for steel pipelines?
3. What are the constraints in using this technology?
    a. Does the Weather condition (Rain or snow) disturb the technology effectiveness? If so, please explain.
    b. Does the technology work properly in very low (e.g. frozen surface) or very high Temperature?
    c. Does the surface terrain affect the technology effectiveness? If so, please explain.
    d. How to carry the device? Does it need special equipment?
    e. What are the application constraints for the steel pipelines?
4. What is the potential to improve the effectiveness of the technology?
    a. Is there any possibility to integrate the technology with other technologies?
    b. Any mounting possibility on the excavator?
    c. How we can utilize this technology in approach of alert excavator about the availability of pipeline in proximity?
    d. What are the latest development and latest models of that?
5. What is the time efficiency of technology application?
    a. How the speed of movement and tilt of the device can affect speed of the detection?
    b. How long does it take to process the data gathered by technology?
6. What are the human matters related to the technology?
    a. How is the adaption of people who are involved? (complexity of use leads to less adoption)
    b. What can disturb the effectiveness of technology from workers side?
    c. What is the negative point of the technology in terms of human matters?
7. Are there any people you know that we should interview?
8. What is your advice in terms of using Acoustic or Magnetic technologies for detection of the high pressure steel pipelines?