

TRAVISIONS

TRA VISIONS 2024

Final Project Template – This template is to be used for submitting the final version of the project. The final deliverable should be submitted by the 31st of October 2023

Idea Number:

C2024 - 64

PILLAR / TRANSPORT MODE				
ROAD ☐	RAIL ☐	WATERBORNE ☒	AIRBORNE ☐	CROSS MODAL ☐
Project Related to:	☐ RA1: Safe & Inclusive Transport ☐ RA2: Sustainable Mobility of People & Goods ☐ RA3: Collaborative Digitalisation ☒ RA4: Efficient & Resilient Systems			

Project Title:

LOCK-INSPECTOR: A Dedicated Subsurface Inspection Radar System for Increasing Inland Waterway Infrastructure Resilience



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1. Introduction

'Don't Sail in Uncharted Waters.'

The more we know about where we are and will be heading, the safer and more efficient our navigation becomes. This attitude strongly aligns, and continues to ever-increasingly resonate, with collective attitudes towards improving the long-term resilience of Inland Waterway Transport (IWT) networks.

In Europe, applied research into digitalisation and automation technologies have been identified as two primary routes towards increasing the future resilience of high capacity loc, as seen in Figure 1. They are vast reinforced concrete structures, typically spanning hundreds of meters in length and tens of meters deep, designed to elevate vessels of thousands of tonnes across steep, otherwise impassable gradients. Locks therefore are inherent network chokepoints.

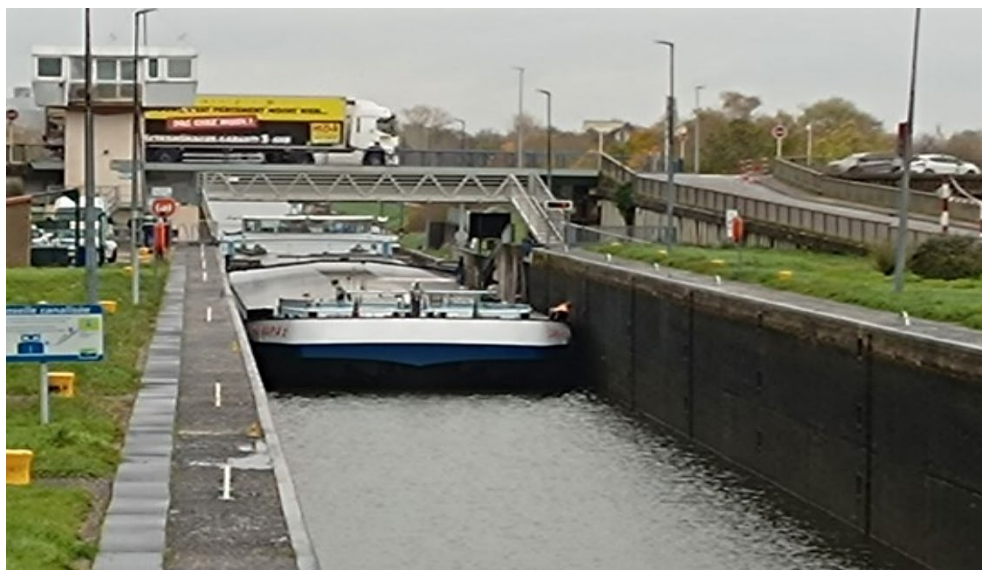


Figure 1: A typical high-capacity reinforced concrete lock in Toul (France), over 150m long and almost 10m deep, is subject to intense displacement forces as water moves to accommodate a 4000 tonne barge. Currently, it is impractical to profile full-wall substructure.

Minimising disruption associated with closures of high capacity locks for essential structural health inspection and maintenance is a key target for today's IWT coordinators. Developing solutions to accelerate the transition from outdated and costly 'reactive' maintenance to more targeted 'predicative' maintenance, in conjunction with design of new dedicated 'digital-twin' locks, are becoming hot topics amongst both IWT academics, development teams and industry practitioners.

Looking to the future of predicative maintenance for resilient IWT infrastructure, project CRISTAL (no. 101069838) was setup by the EU-Horizon under the European Climate, Infrastructure and Environment Executive Agency (CINEA) for 'Climate Resilient and Environmentally Sustainable Transport Infrastructure, With A Focus on Inland Waterways'. A key part of project CRISTAL is development of a pioneering multisensory digital twin lock, to provide a viable basis to inform effective future predictive maintenance.

Effective predictive maintenance mandates we know significantly more about where we are (our lock of interest) and will be heading (pre-knowledge of future defect formation).

Problematically, identifying growing defects early requires comprehensive datasets of lock wall substructural condition... which presently are extremely impractical to acquire on the scale of a full sized structure.

In this report, through technology and knowledge transfer from recent developments in hybrid-rotational Subsurface Inspection Radar (SIR) for railway tunnel inspection, we introduce and examine current development progress of a unique, dedicated system for automated, comprehensive 3D profiling of **Lock Wall Subsurface Inspection (LWSSI): LOCK-INSPECTOR**.

We breakdown the evolution of LOCK-INSPECTOR to date, focusing on the technical design and practical implementation of such an assembly within the confines and restrictions of a working lock site. As project CRISTAL will continue into 2025, attention will turn to project direction in the short and long-term, principally on key upcoming milestones for both the physical subsystems for data acquisition and the virtual data processing workflow for 3D feature volume recovery.

(1.1) Interpreting This Report

To ensure accessibility to both non-IWT and non-radar specialists, we have made an express effort to minimise technical jargon wherever possible in this report. For clarity, acronyms are defined at the point of first use and where necessary, footnotes have been incorporated to elaborate on more technical aspects or clarify any points of potential confusion.

(1.2) Team Background

This group's principal background is in the development of hybrid rotational radar systems for the subsurface inspection of large rail infrastructure, namely tunnels. Expansion of their electrical and digital systems skillset opened their field of research interest, giving rise to an opportunity to contribute as a researcher within project CRISTAL. The student in question is responsible for coordination of the electrical systems and design, testing and validation of the 3D data visualisation workflow for LOCK-INSPECTOR. It should be noted that scientific understanding presented concerning IWT operations, evolution of LOCK-INSPECTOR electromechanical and data systems, alongside longer-term research opportunities discussed within this report is based principally on the students' own PhD research experience to date in literature review, hands-on experimentation and technical design, alongside liaison with industry practitioners in Euromobilita, Railview Ltd and Voies Navigables de France (VNF).

(1.3) Assumptions and Caveats

Project CRISTAL and associated development of LOCK-INSPECTOR is an ongoing research project containing multiple branches, all linking into the design of the multisensory Digital Twin Lock, heron termed the DTL. SIR is one branch specialised in structural health profiling, and will be responsible for data recovery from lock wall substructure, with lock gate condition ascertained from new Acoustic Emission sensors and lock operation status indications (e.g. door failure, vessel occupation, etc.) relayed through conventional alerts schema. Note from this SIR is not the only technology associated with the DTL, but will provide the largest contribution of new subsurface data of the most scale-variable assets of a typical lock, namely the walls.

Additionally, the reader should be aware LOCK-INSPECTOR's formal brief is to operate in locks already drained of water for maintenance and inspection tasks to be performed. This window is for 10 days, scheduled every 10 years. Whilst development of a system cable of submerged deployment presents the ideal commercial state of such a system, as a new proof-of-concept technology it is considered more practically viable to develop the initial version of LOCK-INSPECTOR to function during the

regular decennial drainage periods, and later - with validation trials and refinements completed - augment the established pioneer technology to function in a submergible state to enable more flexible inspection deployment in fully-active, or at least partially occupied, working locks. Further details are provided in Section 3.2.

In a similar vein, LOCK-INSPECTOR's current target is to highlight growing voids in subsurface profiles penetrating outward of 1m behind the wall contact surface, (see Section 2). Exact depths and length scales are however subject to update based on the findings from preliminary testing occurring at time of writing (see Section 4).

Coupled with the aforementioned deployment window, timescale and access restrictions must be accommodated. In the 10 day drainage window, all necessary inspection and maintained must be completed, typically by one or more third party contractor teams brought in by the IWT management body. The different tasks (e.g. repairs to walls, replacing gates, etc.) are conducted at the same time where access to specific regions of the lock is available, leading to a busy site. In brief, LOCK-INSPECTOR must be designed in such that:

- i. Installation can be completed by onsite plant machinery and be setup in such a manner that does not significantly limit access to specific quadrants¹ of the lock structure.
- ii. Operation can be completed by a minimal onsite crew from within the lock structure² and with minimal demand for onsite facilities.
- iii. Disassembly and transport offsite also abides (i).

Regarding future deployment logistics, there will be several pre-requisites for an effective survey to be undertaken by LOCK-INSPECTOR. Here for brevity, we'll emphasise that from SIR data, information about the size, scale and geometry of a lock structure can be inferred, however, effective inference will always a degree of pre-knowledge about the expected lock structural composition. Critically such surveys will require specifications concerning lock-design (e.g. internal/external wall dimensions, structural age, lock-side traversal obstructions, etc.) and survey environment metadata (e.g. lock ID, location data, historic site survey records, meteorological forecasts, etc.). This information should be readily accessible from existing IWT management records, where it is not the need for external consultation and preliminary surveys (see Section 4) would be advisable.

Finally, as mentioned in Section 1.2, development of the 3D feature reconstruction is part of an active PhD research project, therefore the specific workflow detailed in Section 3.4 is subject to alterations as experimentation progresses. For this report, the current expectation for workflow steps has been summarised.

(1.4) Subsurface Inspection Radar 'At a Glance'

Whilst we live and breathe all things radar, we appreciate that knowledge of radar systems for subsurface inspection often requires extensive specialist training to deploy and appreciate, which in itself does not guarantee accurate interpretations of complex survey data subject to human error and false-artifacts³. Understandably IWT management bodies seek solutions with non-specialist accessible information

¹ A 'quadrant' is a localised region of the lock undergoing inspection. In this report we are usually referring to the footprint of the LOCK-INSPECTOR positioning system.

² When drained, placement of crew in proximity to the lock edge is considered 'working a height' requiring extensive costly training and added security 'measures for working at height'.

³ 'Airwaves' for example, where a feature above or behind the probe appears below the surface in the readout due to radar waves bouncing back of the contact surface into the operator's surrounding environment. Here, the opposite lock presents a possible culprit.

conveyance schema, opening survey knowledge to other engineers (e.g. utility contractors) and the wider public through community outreach schemes. As will be discussed in Section 3, this motivated pursuit of a more involved 3D subsurface visualisation workflow LOCK-INSPECTOR.

Below we include a brief summary of fundamental Ground Penetrating Radar (GPR) operational theory and key terminology to for the reader's reference. We direct an interested reader to [1,2] for a more detailed breakdown of GPR theory, operational conventions and phenomena.

GPR returns imagery of the subsurface of a structure, here walls, but of usually the ground. The 'contact surface' is the portion of the structure you can touch with your hand, the 'subsurface' is the untouchable region behind. A GPR probe fundamentally emits a radio-frequency pulse from a transmitter antenna (Tx) directed into the subsurface, which partially backscatters at material boundaries, meaning strong reflections indicate features of interest. The return time delay and return intensity of this backscatter measured by a receiver antenna (Rx) and plotted as a 1D 'A-scan', subsequently combined to form a 2D 'B-scan' can allow surveyors to infer the depth, geometry and material composition ($M_1, M_2, M_3 \dots$) of features and the Region of Interest (ROI), often today with the help from data enrichment algorithms. Fitting curves to known targets in ROI helps us determine wave speed (v) and convert return time to a more easily interpreted depth measure. The process is illustrated in Figure 2, with jointed black arrows indicating pulse backscatter.

The above process is termed 'Impulse' GPR operation, which directly measures signal properties in the 'time domain'. Impulse GPR underpins the majority of systems for commercial and research orientated probes, however one can instead directly measure the 'frequency domain' using 'Step Frequency Continuous Wave' (SFCW) GPR systems [3] to return often higher resolution profiles, but with reduced penetration depth, ground-clearance and/or slower acquisition rate trade-offs subject to context. We have needed to consider this, alongside other practical automation factors, in development planning of LOCK-INSEPECTOR's electromechanical systems for data acquisition (see Section 3) and recent preliminary investigation work (see Section 4).

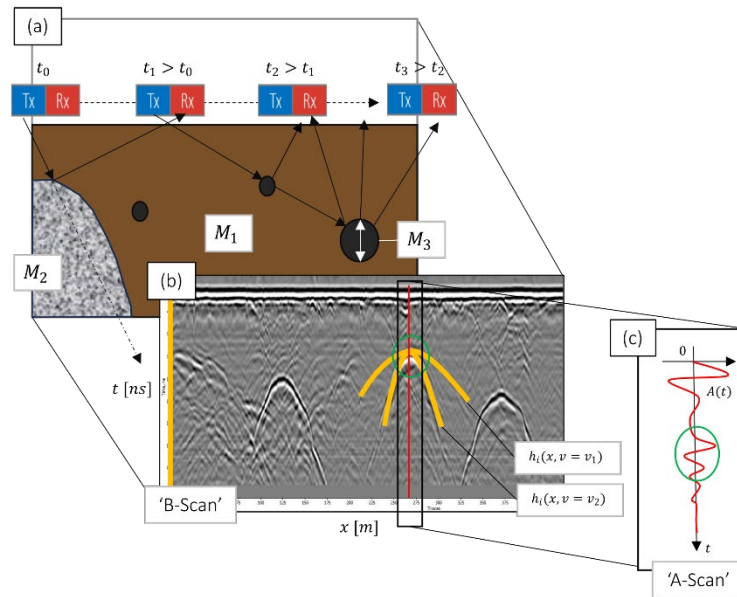


Figure 2: A moving GPR probe (a) recovers 2D images of the subsurface directly beneath the probe (b) by emitting successive radio-frequency pulses. 1D A-scans (c) captured by recording the intensity and delay of returning partially-backscatter signals, which are combined to form 2D B-scans as seen (b). This process of combining profiles lets us also convert 2D datasets to 3D.

For the purposes of this report, first note that the horizontal axis of a B-scan conveys displacement of the probe from the start point, whilst the vertical axis denotes return-time which is proportional to a depth axis⁴ with the contact surface at the top. Secondly, features take the shape of hyperbola because the GPR probe must move (typically in a straight line) as it captures a B-scan⁵. Migration algorithms [4] aid recovery of ‘more faithful’ geometry profiles. Thirdly, where objects are metal or hollow, pulse energy gets absorbed and begins to resonate in a process called ‘ringdown’ as seen in the green circle in Figure 2. The concentric hyperbola this generates makes features like steel reinforcement rods (i.e. rebar) prevalent but also frustratingly masks features behind them. Pioneering research into ringdown suppression algorithms [5] exploiting artificial intelligence is relatively new and lacks testing in real survey datasets. Finally, as 2D B-scans only provide a ‘slice’ of the subsurface, more sophisticated 3D C-scans (i.e. ‘3D volumes’) can be generated by combining 2D B-scans gathered in a 2D grid arrangement⁶ and using 3D-interpolation techniques [6-8] to form 3D visualisations of feature geometry, a process akin to forming 2D B-scans from 1D A-scans.

(1.5) Report Structure Breakdown

The general background motivating this project’s focus on LWSSI is presented in Section 2. We elaborate on the specific innovation gaps within LWSSI, motivating the pursuit of an SIR-based solution and adoption of technology and knowledge transfer from the rail sector. This leads into outlining of the rationale behind system’s design and evolution for LOCK-INSPECTOR in Section 3. In Section 4, we discuss three relevant preliminary tests informing iterative refinement of LOCK-INSPECTOR’s subsystems and 3D visualisation workflow, including current onsite rebar profiling tests at a working lock in Toul, France. We conclude with discussion of short and long-term development prospects of both the LOCK-INSPECTOR system itself, and its associated DTL within EU-Project CRISTAL.

2. Identifying Innovation Gaps in LWSSI

IWT networks are responsible for providing efficient and reliable inland transport options for essential bulk cargos such as fuels, grains ores and construction materials which sustain large numbers of landlocked and coastally-restricted regions of a large portion of Europe. Coastal transports inherently struggle to reach inland regions, whilst bulk cargo transit by comparatively low-capacity roadway vehicles is decreasing as the decarbonisation movement gains traction. Moreover, IWT’s energy efficiency, coupled with its comparatively lower operating costs and increased capacity for oversized cargo can provide significant benefits to equivalent rail-based transport.

Despite these strengths, public and industry interest in innovations for IWT continue to be largely overshadowed by developments in maritime operations and infrastructure, in part due to increased global awareness of concerns over emissions and running costs. From our perspective, modernisation of IWT presents an under-represented field of research in a key infrastructure network, motivating our interest.

Our focus on LWSSI can be subdivided into two main viewpoints. Primarily, a network vulnerability perspective. As mentioned in Section 1, locks are inherent chokepoints of IWT networks, therefore structural health monitoring of lock structure assets is of critical importance to avoid closure delays due to structural failure cascading through the wider network.

⁴ Scaling by the speed of light provides an approximation, however hyperbola fitting (Figure 1c) is most accurate.

⁵ Also because the pulse is emitted as a 3D cone into the subsurface, allowing the probe to ‘see’ slightly ahead and behind its current displacement at any given instant.

⁶ A 2D ‘hash’ (#) grid of ‘longitudinal’ (top-to-bottom) and ‘transverse’ (side-to-side) Bscans is GPR-standard practice when the specific shape of feature geometry is unknown.

Secondly, we adopt a structural vulnerability perspective. In today's digitally-driven approach to intelligent-asset management, large-scale infrastructure is most vulnerable in regions lacking routine, comprehensive structural health data.

To identify associated innovation gaps, we approached the IWT network management body VNF in 2022. We asked, with respect to our network and structural vulnerability viewpoints, where they felt innovation was most urgently needed to boost the resilience of the network. They agreed focus should be on the structural health inspection of locks, being chokepoints.

When considering structural vulnerability, the nature of critical defects informs the nature of critical data inspections must yield. VNF identified 'void-washout' as a primary concern. This process sees a small void form within the wall as forces from shifting landmass and displaced water strain the concrete wall over the lock's operational lifespan. Through continued exacerbation, many voids grow and connect, growing larger. By permeation, ingress and/or surface breaching, water infiltrates the voids, draining slowly as the lock level falls, washing out concrete through hydraulic action, abrasion and solution, causing further growth. The latter can also lead to corrosion and associated weakening of steel reinforcement rods within the walls. Left unaddressed, void growth delaminates sections of lock wall, requiring extensive maintenance and closure time to repair.

Increasing the resilience of locks requires reducing structural vulnerability to void-washout. A recent review of lock inspection technologies [9] explored surface and subsurface profiling lock profiling techniques and identified the use of Terrestrial Laser Scanning (TLS), Thermal Imaging and Multibeam Sonar (MS) as the most practical candidates. TLS and MS do not directly penetrate concrete. Subsurface state can only be subjectively inferred from cracks and bulges in the contact surface. Thermal imaging, despite wide coverage, is highly influenced by ambient conditions, significantly skewing data and limiting times of viable deployment. An alternate sensing basis capable of practically efficient, direct subsurface inspection with comprehensive wall coverage is therefore required.

We have identified GPR as a candidate sensing basis due to its versatility, both from a configuration and data feedback standpoint.

In terms of configuration, we see opportunity for technology transfer from recent developments in hybrid-rotational GPR for rail tunnel inspection, namely the design of dedicated automation systems for GPR data acquisition on otherwise inaccessible large infrastructure. Commercial GPR systems have been recently developed for submerged operation [10,11], however they are positioned by hand and require horizontally level surfaces to operate, making them inefficient and impractical for LWSSI. Therefore, a key innovation for this project is how to develop a scalable GPR system which can automatically profile sheer vertical lock walls.

In terms of data feedback, GPR can distinguish material content, presenting opportunity to develop a system capable of distinguishing metallic rebar from potentially air/water filled void-washout defects. GPR can also return both 2D and 3D visuals of the subsurface. Development of a data processing workflow to render subsurface features in 3D and make feature inspection more accessible to non-radar specialists in IWT management presents a further LWSSI innovation opportunity.

Collectively, these innovation gaps underpin our development of LOCK-INSPECTOR.

3. Evolution of LOCK-INSPECTOR

We are in the design and preliminary experimentation phase of developing the LOCK-INSPECTOR system, which will underpin eventual design freeze and subsequent construction, configuration and capability testing for practical deployment on a full-scale in-service lock.

In this section, we first outline the pre-requisites of system design and operation established through discussion with VNF and our team, then provide an overview of two prospective approaches to mechanical design, followed by a breakdown of the proposed electrical subsystems and man-machine interface for automating GPR data acquisition. Next, the workflow for converting raw data into 3D digital objects is outlined, before finally the practicalities of feeding data to the DTL are explored.

(3.1) System Design: Scoping & Pre-Requisites

In discussion with VNF representatives in November 2022, it was established that LOCK-INSPECTOR's principal aim would be to efficiently return profiles of lock-wall substructure which would aid surveyors in identifying the early onset of void-washout. It was further established that IWT networks lacked detailed records about rebar within the structures. Therefore, any additional useful information LOCK-INSPECTOR could return about subsurface rebar locale and geometry would be considered beneficial for informing structural records and developing targeted maintenance plans.

Regarding functional-ease, it was requested that the developed system should be as assessable as possible to non-radar specialist operators. Therefore the hardware setup, data capture process and returned data output should be streamlined to create a user-friendly Man-Machine Interface (MMI). This respectively motivated: (i) optimisation of hardware setup for simplicity and efficiency of movement and assembly; (ii) automation of the probe positioning and data logging subsystems and (iii) the development of a workflow to return more intuitive 3D feature profiles to surveyors than conventional 2D radargrams.

The need for system scalability was also highlighted. The design of LOCK-INSPECTOR should be in a manner enabling subsurface profiling across the full span of both lock walls, each in excess of 100m horizontally and up to 10m vertically.

VNF also identified several practical considerations development of LOCK-INSPECTOR should consider as a unit operating on working lock infrastructure. From a safety perspective, when a lock is drained, operators are considered to be 'working at height' if they are within several meters of the wall edge. This mandates specialist training and personal protective equipment such as harnesses. Therefore, VNF requires LOCK-INSPECTOR to run with operators to be stationed either at the lock base or on the lock top outside the near-edge region to minimise crew risk.

From a logistics perspective, where apparatus repositioning is required, development should note mooring posts, fences and other physical obstructions close to the lock edge can restrict plant machinery access. This motivates system design to either be full-wall-spanning and fixed or localised and portable. The sheer scale of a full-wall-spanning design would require excessive quantities of materials to fabricate and be extremely heavy, making transportation around Europe hugely impractical. A portable design, which can be repositioned by one (or two) people, is more practically viable.

From a commerce and enterprise perspective, development of LOCK-INSPECTOR should be undertaken in such a manner to return a system which in itself, or reasonably in a future iteration of refinement, can provide a viable basis for a productionable inspection technology, which could practically be deployed to profile the subsurface of an arbitrary lock on the European IWT network in the near future.

(3.2) Mechanical System Design

A topic of debate put forward by VNF discussed the feasibility of deploying such a GPR-based inspection system whilst the lock is in an undrained state. From an IWT operations perspective, such an approach presents a more desirable use case. It negates the need to empty the lock and opening the possibility of conducting subsurface inspections outside the typical decennial maintenance window, potentially in a lock still open to network traffic. This would require selection of highly specialist submersible GPR hardware [10,11], as would water-proofing of the automated positioning system (see Section 3.3). Although not inconceivable to achieve and a marked benefit for more versatile survey scheduling, the introduction of submersion at this stage introduces added complications to an already electromechanically complex build. As outlined in Section 1.1, such an undertaking would be better realised as a future refinement or augmentation of the proposed proof-of-concept system. Discussions remain ongoing.

For completeness, we will provide a concise overview of two prospective system designs. These designs remain subject to revision at time of writing. In both Figures 3 and 4, the basis is a large vertical XY plotter placed against the lock wall. The GPR measurement probe is mounted to the plotter's carriage to allow movement automation and connected to the control unit via a flexible umbilical. Leadscrews facilitate precise and stable motion of the carriage. Area coverage should be maximised to facilitate scan automation, but the resultant mass of the framework must not compromise repositioning nor risk the apparatus toppling. A sprung mounting mechanism for the GPR probe would also be desirable to allow surface contact⁷ to be maintained, but not cause the automated positioning system to become stuck if the wall exhibits undulation.

(3.2.1) Prospective Approach 1: Wall-Mounted

LOCK-INSPECTOR's framework would mount over the mooring posts on the lock top to serve as strong anchor points. Subject to approval by VNF, studs temporarily welded to the lock-edge metallic protector could be used to assist. With this framework, quadrant span could exceed 10m, reducing time consuming repositioning as the survey progresses.

However, sourcing and supporting leadscrews this long would be a challenge. Limited lock side access motivates apparatus design for repositioning by an individual. To achieve this, rather than fixing the framework to the mooring posts, we could fix a temporary, robust dolly track (with another at the lock base). Akin to ladder rails on a library shelf, the framework could then be pushed along these rails to reposition the apparatus and be locked in position with a pin. Time saved would offset dismantling and reassembly of the equipment on the opposite wall.

⁷ Minimising GPR surface lift-off minimises energy losses and returns better quality imagery.

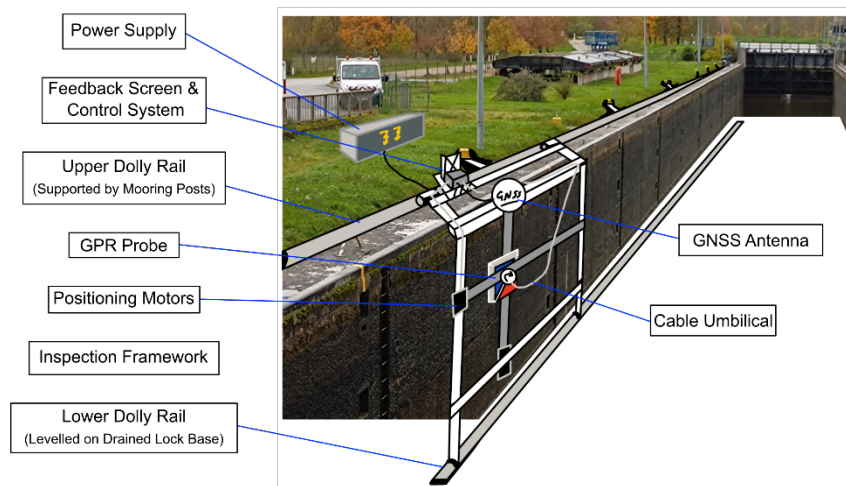


Figure 3: Concept diagram of a wall-mounted setup for LOCK-INSPECTOR. Here, like a library ladder on rails, one can push the apparatus to a new location, locking it in place with a pin.

(3.2.2) Prospective Approach 2: Non-Wall-Mounted

LOCK-INSPECTOR's framework would possess a smaller span between 1-3m to reduce framework weight to the point the assembly can be lifted by a pair of operators to any location on the lock side. Fixture points for dolly track mounting - as in Subsection 3.2.1 - could also be fitted to achieve similar repositioning results by an individual. The XY-Plotter framework would fold open with the base remaining on the lock top and the pivot aligned to the lock edge. A sliding mechanism would be engaged to allow the plotter to slowly descend down the lock wall to the base, serving as the XY-plotter. With water resistant GPR and motor hardware, such a system could be readily deployed in a drained or non-drained lock as no in-lock assembly or disassembly is required.

A key challenge to overcome would be maintaining consistent probe lift off from the wall face. The framework should not flex such that the base of the framework remains parallel with the wall. Moreover, the base remaining on the lock top needs to be sufficiently heavy and well anchored to prevent the apparatus toppling, but must also be made light enough to allow repositioning by the individual.

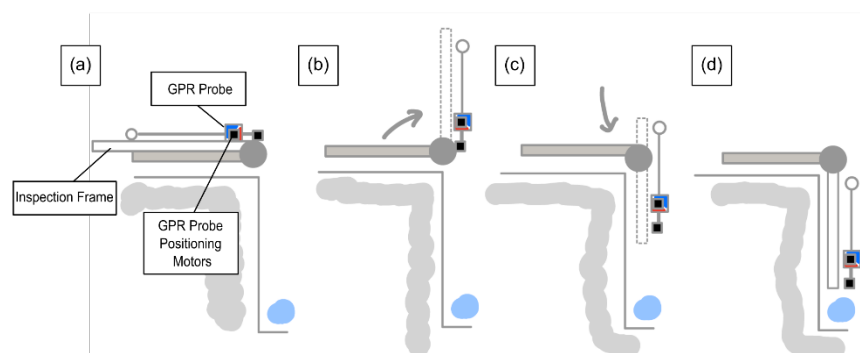


Figure 4: Concept diagram of a non-wall mounted setup for LOCK-INSPECTOR. When placed on the lock side, the inspection frame can be raised and then lowered down the side of the lock (a-d). Note that with suitable water-resistant hardware selection for motors and the GPR antenna, this option could be feasibly deployed in both drained and non-drained locks.

(3.3) Electrical System Design

LOCK-INSPECTOR's electrical systems - shown in Figure 5 - are subdivided into three sub-systems: (i) Power Supply; (ii) Position Automation and (ii) Measurement Automation. All are centrally regulated by a Raspberry Pi 3 'master' module.

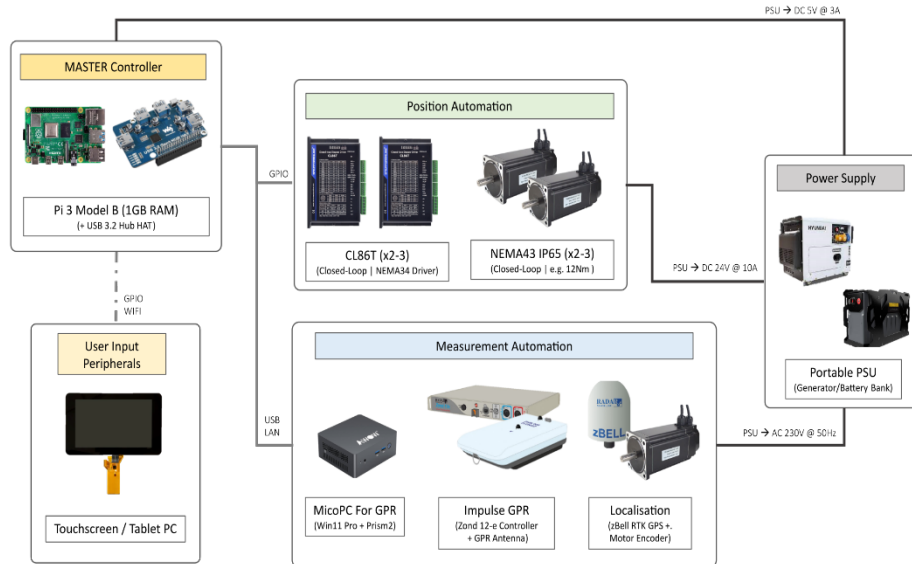


Figure 5: Electrical sub-systems of LOCK-INSPECTOR.

Owing to the remoteness of many lock sites within Europe, it is advisable that LOCK-INSPECTOR be designed to connect to a portable standalone power supply. Subject to survey context, generators for plant machinery already on site may be utilised or brought in, providing multifunctional operation.

LOCK-INSPECTOR's positioning system will feature two weather-resistant NEMA34 closed-loop stepper motors with integrated rotary encoders, each with an associated Microstepper Driver. Closed loop operation allows probe positioning leadscrews to self-correct in the event of unexpected slippage of the probe or motors. Encoders also enable continual logging of probe position relative to the survey quadrant datum. This will be combined with a super-resolution Z-Bell RTK GNSS antenna connected to a dedicated 4G wireless router for probe geolocation data recovery to within 100mm, accurately tracking measurement position with redundancy. We note the 2D grid scan must initially track horizontally along the top of the lock when collecting GPR measurements. This ensures as the probe descends into the lock (and GPS becomes less reliable) that only the vertical displacement coordinate of measurements changes, which can be extracted directly from the encoder log files.

For measurement automation, we utilise Impulse GPR from Radar Systems Inc. instead of SFCW GPR to enable higher speed data acquisition (in excess of 1.5ms^{-1}) at potentially greater lift off⁸ (up to 250mm vs 8mm). A Zond 12e Advanced GPR controller will connect directly to a 1GHz antenna capable of 3.75m penetration (unobstructed). The Zond 12e is connected to a MicoPC running its dedicated Prism2 GPR data logging software in Windows. To enable automated control by the master Pi, software REMMINA links to the MicoPC via ethernet, using SSH protocol to automate cursor movement. This occurs in the background.

⁸ The probe must clear natural undulations of the lock wall to avoid collisions were the automated positioning carriage to rigidly set the lift-off of the antenna (i.e. if sprung mounting is not viable).

The operator will use either an inbuilt touchscreen or tablet PC to pre-set the data acquisition mode, access advanced settings in Prism2 (if desired) and begin the automated scan. It is key for end-user accessibility that if required, the full measurement process can be initiated from a single button press. If development time permits, it would be desirable for feedback to display a real-time update of recorded B-scan profiles to the touchscreen interface as the survey grid is populated with data.

(3.4) 3D Feature Reconstruction

A 2D grid scanning trajectory has been adopted for the GPR probe to ensure optimal data coverage for 3D feature reconstruction is achieved. The combination of A-scans in both longitudinal (parallel to lock edge) and transverse (orthogonal⁹ to the lock edge) orientations enables features with previously unknown or spatially complex footprints (such as void-washout) to be most-accurately captured (i.e. no one direction of scan dominates the dataset). In addition, selection of a 2D grid also exhibits the best practical trade-off between return dataset density and survey runtime, which can be further improved if the antenna is configured to advance in a first iteration Peano space-filling curve¹⁰ (see Figure 6a). This removes wait-time associated with retraction of the antenna between B-scan passes. Resultant B-scans can be aligned in 3D space to form a cube of horizontally and vertically aligned B-scans to form a 'data cube' as in Figure 6b. Alignment is based off the respective GNSS coordinates of each B-scan, alongside relative local positioning data recovered from the encoders within the closed loop stepper motors of the positioning sub-system.

The data cube can be regarded as a collective of A-scans aligned in 3D space, which can be further deconstructed as a series of individual datapoints in 3D space, each with an associated amplitude (i.e. the local level of GPR backscatter). This constitutes a 3D point cloud encoding the subsurface geometry of the lock wall. Note at this point there will always be regions where no data has been directly observed between neighbouring B-scans because the GPR antenna takes a finite time to record a measurement, by which time the system has already moved to a new location.

We perform initial pre-processing techniques to suppress noise within B-scans and increase the spatial resolution (i.e. sharpness) of key features. For the former, techniques including band pass filtering, background subtraction and parametric gain are applied, whilst for the latter we apply the more experimental technique of Combined Processing Methodology¹¹ (CPM) [12].

3D interpolation 'fills in the gaps' within the point cloud to return an effectively continuous 3D response field, meaning at an arbitrary point within the dataset the subsurface GPR response amplitude can be estimated based off the value of datapoints in the local vicinity in 3D. We are in the process of conducting an optimisation study to establish the most effective 3D-interpolation strategy for subsurface point cloud data from Nearest Neighbour, Kriging [6] and Radial Basis Function [7] approaches. This work is being conducted as part of the technology transfer from SIR for rail tunnel inspection described in Section 2. The study is underway and involves adaption of the open source GPR processing tool GPRPy [13] to integrate tools for 3D feature recovery and visualisation, in collaboration with its developers at The University of Alabama (USA).

⁹ Orthogonal in this report means 'at right angles to'.

¹⁰ This does require the data processing workflow to flip every second B-scan horizontally to ensure each B-scan advances in the same direction.

¹¹ This technique combines the amplitude precision of an A-scan's response profile recovered by Inverse Fast Fourier Transform with the increased spatial resolution of the same A-scan profile recovered using the MUSIC algorithm.

Feature segmentation follows, which subdivides the resultant point cloud into distinct regions with 'similar' content. Principally these are regions suspected to contain features (e.g. voids, rebar, etc), however regions containing unwanted artifacts (e.g. ringdown, noise/signal-clutter artifacts) may persist despite pre-processing, warranting the comparison of region densities to identify abnormally low density regions - likely associated with ambient noise - or specific periodicity in amplitude variation across the region, a hallmark associated with ringdown artifacts. Metrics for similarity call upon spatial proximity of like-for-like datapoints and low amplitude differentials, alongside the generation and cluster analysis of normal vectors. For the latter, Principal Component Analysis [14] can be trailed to generate local normals, which undergo clustering to form locales of points likely belonging to the same body¹². Fitting of a shared 3D plane to segmented points informs the collective normal, representing the 'outward' surface of the suspect feature, to which application of iterative region growing [15] expands the locale into a full surface.

The next candidate region, corresponding to another suspected feature in the dataset, can be subsequently selected and the segmentation process repeats until the dataset is fully partitioned. Application of Delaunay Triangulation [16] to each segmented region in turn can generate a 3D digital mesh. A primitive rendering would assign a fixed colour with point-source lighting to all meshes as in [17]. A more advanced rendering, capable of feature colouration based on suspected material type (i.e. concrete, air, water, metal, other) would require a more sophisticated segmentation procedure, likely conducting a second pass to estimate feature¹³ material properties.

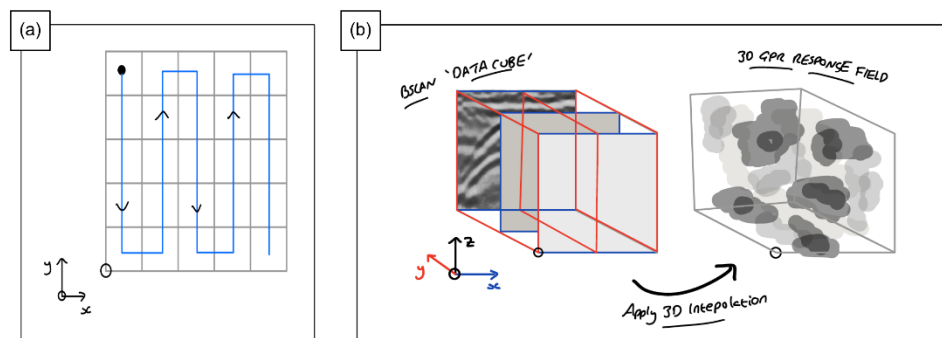


Figure 6: A Paneo Curve scanning trajectory (a) improves data acquisition efficiency. Through alignment and interpolation of returned B-scans in 3D space (b), suspected features of interest are isolated during segmentation for mesh generation to return 3D feature visualisations.

(3.5) Digital Twin Integration

At time of writing, for the SIR branch of Project CRSIATL, return data from LOCK-INSPECTOR to the DTL is anticipated to primarily take the form of 'images' and 'text-based' files encoding the 3D feature geometry generated during volume reconstruction. Here we describe information associated with an arbitrary quadrant of a future full lock survey conducted using LOCK-INSPECTOR.

Data passed to the DTL is anticipated to include:

¹² This is because points close to each other, belonging to the same object, are effectively 'geometrically locked' together by the objects structure, thereby typically 'point' in the same direction as their immediate neighbours. Where strong discontinuities exist, these are indicators of close proximity to the object boundary.

¹³ Iterative curve fitting is a common approach scalable to 3D datasets, often used 2D by programs such as GPRPy. The coefficients of a 'fitted' hyperbola can be related to the dielectric constant, which effectively 'defines' the material.

- **Metadata for Quadrants** - ASCII text uniquely identifying the lock surveyed and the specific quadrant inspected, which could be subdivided into specific B-scans and individual A-scans if required. Data fields may include: lock ID number; measurement start/end timestamps; GPS coordinates.
- **Metadata for 3D Features** - ASCII text detailing characteristics of each 3D reconstructed feature in a quadrant of interest to surveyors. Data fields may include: a unique feature ID number; centroid coordinates; feature volume estimate; a complexity metric¹⁴; material classifier; classifier confidence level.
- **3D Feature Geometry** - ASCII text, Polygon or Stereolithography files subject to desired universality of data format compatibility¹⁵, encoding the geometric properties of meshes defining 3D objects for rendering. Data fields may include: a unique node¹⁶ ID number; node lateral, penetrative and vertical node coordinates; node GPR intensity value; RGB colour indexes; opacity metric.
- **Multimedia** - Vectorised image files or videos of individual A-scans, B-scans or other elements of the survey quadrant GPR response profile.

A surveyor or lock operator using the DTL would have access to the 2D and 3D subsurface profiles within the DTL. As a 3D model itself, visuals from LOCK-INSPECTOR would be overlaid on the DTL model, enabling end-users to view subsurface features behind the walls (which may in the future be textured using data from LiDAR scans), therein enabling their use them to inform operations and design of targeted maintenance approaches where required.

Subject to development, functionality for the end-user to assign annotations may eventually be added, facilitating the first steps towards remote structural surveying. In the future this could also include historic survey results, particularly in the event elements of the submergible system proposed in Section 3.2 enters into future refinements of LOCK-INSPECTOR, enabling LSWWI surveys to be more frequently conducted, perhaps as often as annually.

4. Experimentation and Capability Investigation Work

Development and refinement of LOCK-INSPECTOR's design and data processing workflow has motivated several preliminary experiments to date to better inform hardware selection, algorithm structuring and identify any previously unforeseen challenges. We remark that all investigations we discuss are ongoing at time of writing, therefore emphasis has been made on any observations and/or insights achieved to date. In this section we discuss three recent practical investigations, where we look into how we can assess the accuracy of subsurface profiling achieved by LOCK-INSPECTOR during development. Here, we are specifically focused on determining the influence of rebar on LOCK-INSPECTOR's measurements.

A particular challenge we face is the lack of available pre-knowledge concerning the nature of rebar geometry, as although subsurface structural plans of locks are available, documentation does not detail the specific locations, layouts or dimensions of individual rebar within the subsurface.

¹⁴ Complexity of a feature could be associated with the roughness of the 3D features surface, which can be quantified using estimations of the fractal dimension of the object.

¹⁵ ASCII text files are a preferential data export option because of their simplicity, which more readily enables their use in other applications than more niche file formats. They are also human readable, which aids debugging.

¹⁶ A 'node' here is an individual datapoint linked by a connecting 'edge' to other nodes to form a 3D object mesh.

As explained in Section 1.4, GPR has limited resolution behind rebar layers, making it difficult to resolve features. To reliably inform our selection of GPR hardware, design elements of the apparatus such as probe lift-off from the contact surface and eventually relay to IWT management bodies of the size of features resolvable and depth of penetration we expect LCOK-INSPECTOR to consistently achieve, we must determine the 'typical'¹⁷ shape, structure and form of rebar in high-capacity European locks.

These investigations are further complicated by the lack of access we have to lock walls during the design phase, as there can be many months between closures on the network for which site access for our team is not always guaranteed. As such, the most direct option of scanning multiple sample quadrants of lock walls across multiple different locks with our candidate hardware options is not practically achievable.

The three investigations described below adopt three independent approaches for assessing rebar influence on measurements:

- **Onsite Alternative Quadrant Sampling** - GPR scans are taken of an alternative, more readily accessible section of a full-sized lock on the network, possessing a comparable substructural composition to the walls of a typical lock.
- **Offsite Alternative Structure Sampling** - GPR scans are taken of an alternative structure to a lock also composed of reinforced concrete, possessing a comparable substructural composition the walls of a typical lock.
- **Numerical Simulations** - GPR scans are simulated numerically on a computer of a virtual model of a reinforced concrete structure, possessing a comparable substructural composition to the walls of a typical lock.

(4.1) Onsite Alternative Quadrant Sampling - Wall Top Profiling at Toul Lock

The top of a lock wall is a more readily accessible section of the structure than the lock walls themselves. We would expect rebar in a conventional cubic lattice layout to extend throughout both the horizontal and vertical extend of the lock wall.

We can exploit lattice symmetry to profile individual rebar, which we can also reasonably assume to be the same type used throughout the lock. We reiterate that at this stage we are interested in the geometry of the rebar (i.e. rod diameter, spacing between latticework) and its location relative to the lock wall contact surface (i.e. starting depth).

To achieve this, in October 2023 we performed a 2D grid GPR scan of a sample quadrant of lock-wall top at Toul Lock on the Moselle River (France). The scan quadrant¹⁸ measured 1m by 1.5m and consisted of 53 individual B-scans with 50mm separation, yielding 32 profiles advancing in x (parallel to the lock wall) and 21 profiles advancing in y (orthogonal to the lock wall). The survey area exhibits geometry displayed in Figure 6. A metallic grate spans the quadrant area in x , offset from the centreline to facilitate orientation of the dataset. The grate is metallic, therefore serves as a strong reflector, providing an amplitude reference for any buried metal within the subsurface, which we expect the rebar to resemble when suitable post-processing is achieved. Note the quadrat must be set back from the lock edge to comply with health and safety regulations, therefore we focus on results in the section between the lock edge and metallic grate.

¹⁷ By 'typical', we are referring to an arbitrary high-capacity lock on the existing European IWT network.

¹⁸ Onsite access lasted 4 hours, requiring 1.5 hours for equipment setup and pack down. Scanning one quadrant at this resolution required 2.5 hours. We elected to scan a single quadrant accurately rather than scan multiple quadrants inaccurately. Although not an ideal large sampling size, it is reasonable to assume the result can be generalised owing to the expected consistency of structural design for both construction time and cost efficiency.

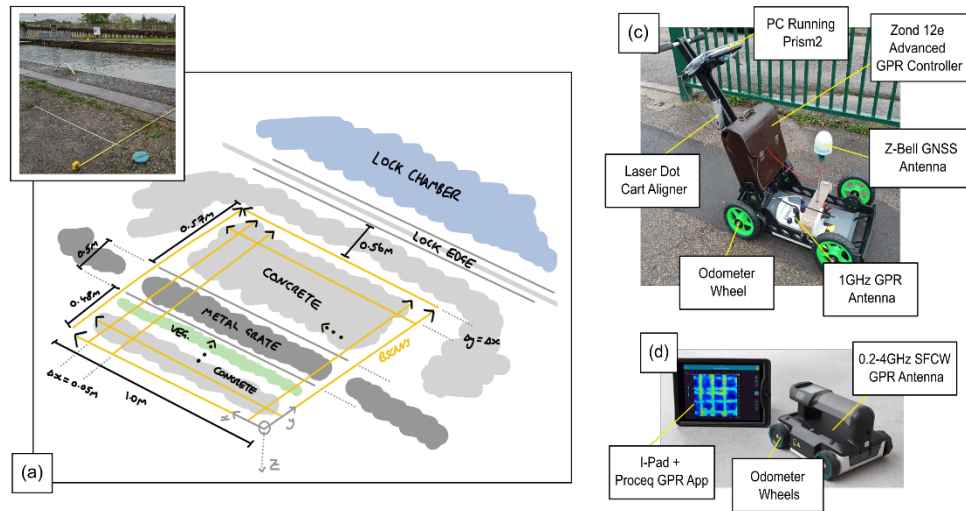


Figure 7: Survey design of Toul wall-top profiling. Scan trajectories (a) and observable surface-level geometry (b) alongside location of nearest to the wall face B-scan 48. Note the metallic grate, included deliberately as reference for a ‘strong’ reflector. Impulse GPR is a Zond 12e Advanced GPR system from Radar Systems Inc (c) and SFCW GPR is a Proceq GP8000 (d).

As mentioned in Section 3.3, we are basing LOCK-INSPECTOR on Impulse GPR measurement hardware. We deploy these hardware elements in a push-cart configuration across the Toul survey quadrant. For performance comparison, we also trailed a specialist concrete survey probe (Proceq GP8000 SFCW GPR), which is less versatile but optimised for rebar detection. Without available pre-knowledge of expected rebar characteristics, data from the Proceq GP8000 provides our ground-truth¹⁹ dataset for comparison.

The extraction and data processing of the Impulse GPR is a more involved process than the Proceq GP8000’s in-app toolkit, which remains in progress at time of writing. Here we examine results from the SFCW visuals for provisional insight into rebar characteristics. We add time-gain compression of 1.9dB/ns to increase feature clarity, alongside background removal with a reference plane of 0mm to reduce prevalence of the metallic grate and enhance nearby rebar.

Inspecting Figures 7 and 8, we observe a top-down XY profile consistent with our initial expectations, as the metallic grate dominates in the region between 0.3-0.7m in y and spans the full x domain. Low intensity straight line artifacts can be observed for $y > 0.1$ m across the x -domain. We estimate rebar diameter between 5-10mm based on cross-sectional profiles observed in Figure 7c. Inter-rebar separation (i.e. pitch) varies between 100-200mm. The first rebar layer is identified at 27mm behind the contact surface. Layers at 73mm and 120mm are also present, however vertical alignment with signal peaks in the first layer are suggestive of ringdown artifacts. We suspect these artifacts have been merged by the Proceq App in generation of its 3D visual output shown in Figure 7b, hence the indication the first distinct layer is approximately 32mm deep. Assuming pitch and first-layer depth are consistent throughout the structure, we would expect the first layer of rebar in the vertical wall to be within 25-100mm of the contact surface.

¹⁹ ‘Ground truth’ is the ‘true condition’ of the subsurface, sometimes referred to as ‘target geometry’.

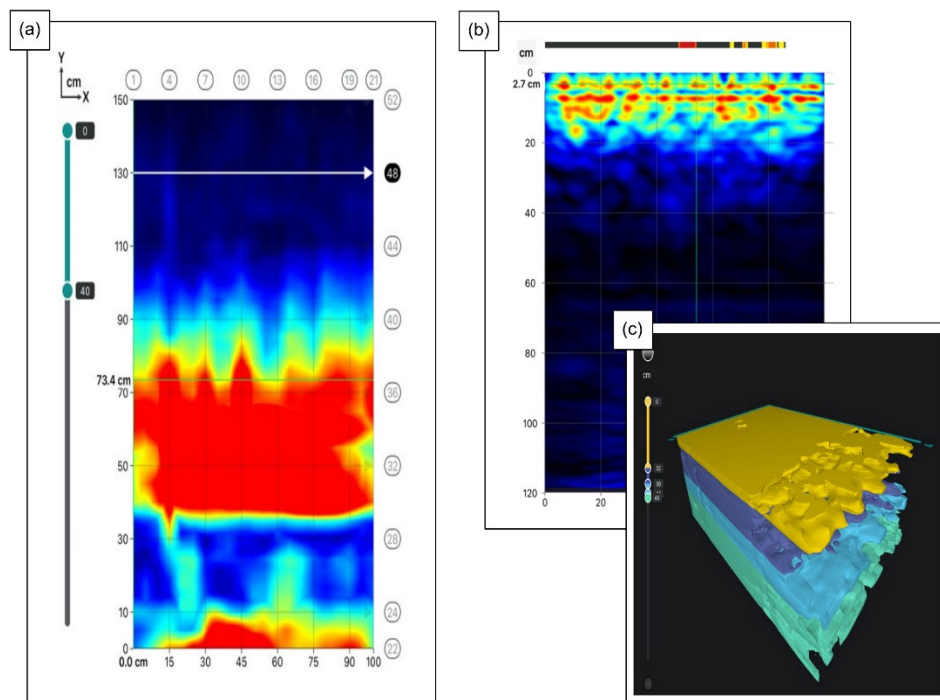


Figure 8: Proceq GP8000 wall top-down profiling of Toul Lock on the Moselle River (France). Red denotes more prevalent features. The metallic grate dominates full-quadrant XY profile (a) as expected. 3D profile estimation by Proceq App (c) appears to merge individual layers of rebar at 27mm and 73mm with ringdown phenomena at greater depths, more readily distinguished in XZ B-scan 48 (b), with a rebar cross-sectional profile highlighted.

From this work, we would be interested in assessing the clarity of a realistic void-washout defect both with and without the presence of rebar. We would vary the pitch, diameter and starting depth of the rebar and compare defect clarity to a control dataset featuring the defect with no rebar. Ensuring precise control of these variables, and replicating defects consistently would be most effectively achieved through simulation (see Section 4.3). If void-washout is clearly identifiable, design freeze of LOCK-INSPECTOR would follow, else, the application of more sophisticated deep-learning methods for ringdown suppression [5] will be explored.

(4.2) Offsite Alternative Structure Sampling - Rotation at Test Wall, Barrow Hill (UK)

Conducting tests on an in-service lock has its limitations for experiment design. Logistical complexity for transport requires tests to be large-scale to justify costs. Moreover, introducing defects to an in-service lock is not permitted nor wise, but will be necessary for future defect profiling assessments.

As a more practical option for smaller-scale tests of system performance, we repurposed a standalone reinforced concrete wall at our test facilities at the Barrow Hill Roundhouse in Chesterfield (UK) to serve as an analogue of a small section of lock wall. The wall contains a mixture of non-reinforced and reinforced sections. The reinforced section we consider is approximately 0.8m wide (x), 0.8m tall (y) and 0.3m thick (z) and contains rebar mesh approximately 5mm in diameter with approximately 100mm spacing. As in the case of the lock, records of structural composition at our disposal lack some details on rebar placement. Here for instance, the number of layers is undocumented. Therefore we again have used the Proceq GP8000 to provide 'effective' ground-truth data for us, as shown in Figure 8, indicating at least 2 layers of mesh are present at approximately 0.1m and 0.2m respectively.

An inherent challenge with this approach is justifying that the test-wall and lock wall are 'comparable' in terms of rebar composition. We expect the lock wall to contain thicker diameter rebar due to the increased load bearing requirements. In the coming weeks as data from Section 4.1 is processed, we can compare scan results from the Proceq GP8000 of both structures for a formal answer. However, regardless of the specific nature of the rebar, if performance of the GPR is affected by the finer rebar present in the test wall is it a strong indication the same would be true in the lock. This can provide a quick and effective test to debug our experimental design setup, but we must acknowledge confirmation of system capability always requires onsite testing.

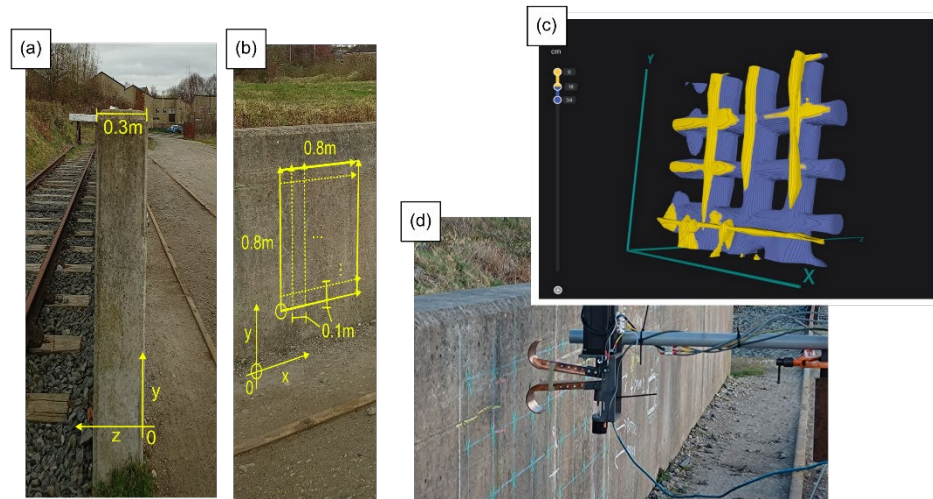


Figure 9: Concrete wall at Barrow Hill (a, b) profiled by Proceq GP8000 in 3D (c) aids investigation into the direct application of hybrid rotational GPR for lock-wall inspection (d). Whilst rotation of the antenna uniquely provides profiles of the structure from multiple viewpoints, a more rapid data acquisition rate is required for practical LWSSI deployment.

Our first use of the test wall shown in Figure 9 was to appraise the feasibility of direct application of an early rotational GPR setup (based on SFCW GPR) for LWSSI. This motivated our subsequent pursuit of Impulse GPR hardware for LOCK-INSPECTOR for time-efficiency. Rotation through 11 orientations in a single antenna location took approximately 1-2 minutes, not restricted by air-launching distance as in tunnel inspection, faster Impulse GPR was selected to ensure two lock walls over 1000m² could be scanned in full across a 10 day inspection period.

(4.3) Numerical Simulations - GprMax & GPRPy

Simulations - as in Figure 10 - present the most time and resource efficient approach for small scale GPR investigations, however can be computationally expensive, especially for survey regions in excess of 0.5m³ from our experience. GprMax [18] is the state of the art in open source simulation of GPR forward-modelling, allowing the user to specify a geometry configuration in 2D or 3D and generate resultant B-scans. Similarly GPRPy [13] represents state of the art in open source GPR enrichment and inversion, which allows the user to clean and enhance GPR B-scans, with provisional capabilities to reconstruct 3D feature profiles²⁰.

²⁰ This functionality is not a directly integrated feature in the base program, but can be achieved with advanced programming of an included experimental add-on.

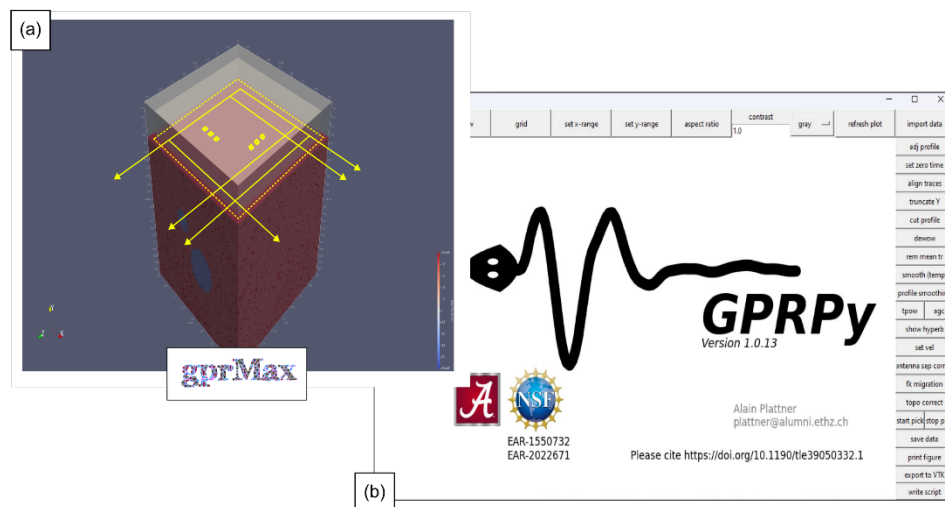


Figure 10: Open source development platforms GprMax (a) and GPRPy (b) provide state of the art tools for forward-modelling and inversion of GPR surveys respectively. Yellow lines denote B-scan trajectories. With upcoming analysis of the Toul survey, characteristics of concrete reinforcements will be modellable as GprMax input geometry. Together, these tools will allow simulation of survey data and 3D reconstruction to refine systems design.

As in Section 4.2, validity of rebar simulations prior to the onsite survey at Toul have been challenging due to the unknown properties of the rebar in the real lock structure. However, with findings examined in Section 4.1 we can now transfer these properties directly into to our future simulations, with GprMax simulating the physical response of the lock wall and GPRPy recovering the 3D profiles of subsurface geometry (once augmented with our 3D reconstruction workflow - Section 3.4). Of immediate interest is trailing the performance of recently developed ringdown suppression algorithms based on deep learning to more clearly reveal void-washout within the lock wall, alongside optimising the speed of probe advance and displacement between successive B-scans in the 2D scanning grid against the survey runtime, in order to minimise data acquisition runtime whilst maintaining reconstruction accuracy.

It should be noted, we have achieved three significant advances with GPR simulation for LWSSI to date. In brief, these include:

- Creation of a unique conversion program, allowing GprMax output to be directly imported to GPRPy for enrichment and inversion, linking the forward and inverse modelling tools for what we believe to be the first time.
- Construction of a bespoke program for geometry randomisation in heterogeneous subsurface media based on Voronoi cell tessellation, which can form a basis for the randomised generation of defects in simulation data alongside introduce a degree of randomised variation to the periodic nature of rebar latticework, akin to real-life construction imperfections.
- Development of a dedicated program to automatically generate 2D grid scans of 3D survey environments in GprMax, a feature previously unavailable for 3D forward modelling but essential for simulating a scan by LOCK-INSPECTOR.

5. Plans For Future Development

In the short-term, our immediate focus at time of writing is analysis of the Toul survey datasets to confirm the expected characteristics of rebar within a typical lock wall. This will inform comparative performance of the Zond 12e Impulse GPR hardware compared performance of the Proceq GP8000 SFCW system, allowing hardware selection to be finalised and confirm the expected penetration and spatial resolution capability we can anticipate for 3D reconstruction. Integration of the 3D reconstruction workflow into GPRPy is also a priority to ensure the full inspection cycle (from data acquisition to finalised data output) can be run and refined in future onsite trials, alongside the integration of complementary advanced processing techniques such as CPM. In conjunction, freezing of LOCK-INSPECTOR's electromechanical design approach will mark the start of full-scale apparatus construction. During this time, simulation to jointly optimise the speed, separation and interpolation techniques associated with B-scan acquisition and processing will be undertaken. Incorporation of biasing towards higher speed or higher density data acquisition would be a natural progression to increase the versatility of LOCK-INSPECTOR in practical survey deployment, which we hope to achieve on a full-scale lock by late 2024.

In the longer-term, we would be interested combining subsurface point cloud generation from GPR with surface point cloud generation from LiDAR and Close Range Photogrammetry. Accurate alignment of datasets will require attention, but if achieved may enable the transplant of the DTL into a mixed reality environment. Hybridisation with Augmented Reality hardware such as the HoloLens [19] would be a significant innovation for survey practitioners, allowing onsite teams to see directly behind walls, potentially even watching replays of defects forming if the DTL eventually stores historic SIR datasets.

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