Long-term STability Assessment and Monitoring of flooded Shafts

(STAMS)

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Contact Andrea Gentili
E-mail RTD-STEEL-COAL@ec.europa.eu
RTD-PUBLICATIONS@ec.europa.eu

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Marwan Al Heib, Stéphane Lafortune, Cyril Balland
Institut National de l'Environnement Industriel et des RISques (INERIS) –
Parc Technologique Alata BP 2, 60550 Verneuil-en-Halatte France

Olaya Alvarez, Angel Rodriguez, Alberto Jardon
University Carlos III of Madrid (UC3M)
126, ES-28903 Getafe, Spain

Dagmara Sobczak, Aleksander Wrana, Zbigniew Lubosik
Glowny Instytut Gornictwa (GIG/CMIPL)
Pl. Gwarkow 1, PL 40-166, Katowice, Poland

Klaus Siever; Emma Dawson
DMT GmbH & Co KG (DMT)
Am Technologiepark 1, 45307 Essen, Germany

Michael Bedford, David Gibson
University of Exeter (UEXET)
The Queen's Drive Northcote House, Exeter, EX4 4QJ, United Kingdom

Jacek Dziura
Polska Grupa Gornicza (PGG)
UL Powstancow 30, PL-40039, Katowice, Poland

Adrian Winkler
Spoka Restruryzacji Kopaln SA (SRK)
Strzelcow Bytomskich 207 –PL-41-914 BYTOM Poland

Faouzi Hadj-Hassen
Association pour la recherche et le développement des méthodes et des Processus Industriels (ARMINES)
Boulevard Saint Michel 60, FR-75272 Paris – France

Ramón Terroba, Francisco M. Fernandez Miranda
Hulleras del Norte SA (HUNOSA)
Avenida Galicia 44, ES-33005 OVIEDO Spain

Christopher SATTERLEY
The Coal Authority (COAL AUTHORITY)
200 Lichfield Lane Mansfield, NG18 4RG United Kingdom

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1. FINAL SUMMARY

1.1. Objectives of the project

The main objective of this project is to implement solutions to monitor and to assess the stability and the conditions of flooded shafts, including the non-flooded portions of partially flooded shafts, for long periods of time, including the provision to monitor shafts that will be filled in the future. The objective will be achieved by subjecting a shaft (a) to periodic measurements, and (b) to continuous monitoring. This requires developing new technologies and achieving the following goals:

- Develop and test a **Multi-functional Monitoring Module** that is able to make periodic measurements in order to assess the stability of a flooded shaft.
- Develop and test an **Ultrasonic Inspection Module**, featuring the novel combination of **ultrasonic profiling and ultrasonic imaging**, to both inspect shafts visually and measure possible deformations with high precision between periodic inspections of shafts.
- Develop and test **water dynamics and gas devices** to continuously measure, analyse and asses the stability of shafts for long term monitoring with provision to deploy sensors post-closure that will withstand shaft filling operations.
- Develop and test a **software control and analysis** system to measure, in-situ and in real-time, significant differences that may indicate instability or significant changes in a flooded shaft.
- Develop a **modelling approach** to assess the long-term stability of shafts during and after flooding by coupling the hydro-mechanical behaviour with the chemical reactions which occur between the aqueous solution and the shaft lining components.

For **periodic measurements**, inspection tools will be implemented with multiple instruments to perform measurements of water aggressiveness, gas production and to carry out macroscopic inspection. Most of these technologies need to be developed for implementation in underwater conditions in mining environments. This development not only involves the improvement of the external case of the devices but also to validate their use in underwater conditions. A software control system will be developed to analyse, in-situ, if there are significant changes in the conditions of the shafts acquiring information from the inspection modules and from the continuous measurement devices.

For **continuous measurements** a different approach has to be implemented. The objective is to install newly developed devices in the shaft to monitor the water level recovery dynamics. Additionally, this device could also be used as reference points to make comparisons between periodic images so that significant changes in a shaft can be identified. The numerical simulation will be used to help the design and the interpretation of the in-situ measurements.

1.2. WP0: Coordination & Project Management

The objective of WP0 is the co-ordination and management of the STAMS project. This includes planning, reporting to the partners, collecting and reviewing the deliverables, and transmission to the EU. Technical and administrative management (meetings, management and allocation of budgets) was also performed.

Special attention was paid to the promotion of the project results that have taken the form of conference presentations, paper and a project website.

Task 0.1. Project Coordination

INERIS prepared the GA and the different modifications during the life of the project due to the modification of the list of the partners (AITEMIN replaced by UC3M) and the modification of the status of KWSA, the company becoming PGG with the same role in the project.

INERIS organised the 9 meetings to allow the best interaction between the partners and the coordination of the project.

The first meeting, the kick-off meeting, was organized and hosted by INERIS from 19-20 September 2015 in Paris, with the participation of the partners involved in the project. The objectives of the kick-off-meeting were the presentation of the project and the clarification of the role of partners in the project.

6 progress meetings were organised, each divided into two sub meetings: the first concerned with the development of different technical tools, and the second concerned with the presentation of work done during the previous periods and the planning of work for the next periods.

In addition of the kick-off and the progress meetings, 2 short technical meetings were organized. The objective of those meetings was to discuss mainly the details of the developments and the organization of the future work.

All meetings were reported, and minutes are available in the CERCA and the STAMS website.

Task 0.2. Project Management and Control

The annual, mid-term and final technical reports of the project were prepared with the contribution of all partners. The coordinator presented the reports to the TGC1 and improved them, taking into account the remarks and the observations, of the experts of the TGC1.

1.3. WP1: Selection of Technologies, Sensors and Components for Long-term Stability Assessment

Task 1.1. Definition of Monitoring Requirements for Long-term Shaft Evaluation

The minimal and optimal range of measurements needed for a shaft evaluation were analysed in the framework of task 1.1. Based on the results of the task, the mechanical needs for each device and their functional requirements were defined. In order to achieve that goal, the industrial partners involved in this task (PGG, SRK and HUNOSA) completed a questionnaire prepared by CMIPL. A total number of 23 shafts were analyzed and described. On the basis of the obtained data, a typical and a worst-case scenario were prepared. The two prepared scenarios – typical and worse, due to the large variability of flooded shaft parameter – differ in the shaft diameter, water levels and shaft access limitations. From the point of view of the definition of the monitoring requirements for long-term shaft evaluation, it is crucial to assess the worse conditions during the inspection. The most important parameters are the shaft depth and the water level, which directly affect the rope length and strength parameters of the casing. The next important parameters are the total range of installed sensors (minimal and maximum distance between the sensors and measured objects). It was expected that this is directly connected with the diameter of the shaft, but the obtained data showed that more important is the location of access point in the shaft area. In the worst-case scenario, due to the adverse location of the access point, the range of sensors should be between 1.0 and 6.5 m. The next crucial information relates to size access limitations. Performing of underground tests requires development of the inspection modules with a horizontal cross-section smaller than 0.5 m wide. In turn, the total length of the inspection modules is limited to the possibilities of their mounting on the surface only.

Task 1.2. Sensor and Component Selection for Multi-functional Monitoring Module

Although one main objective is described in the title of the task, an important preliminary decision had to be taken in this task as the first priority. That decision was whether to develop two periodic inspection modules – the Multi-functional Monitoring Module (MMM) and the Ultrasonic Inspection Module (UIM) – or to combine the functionality of both into a single unit.

An analysis of the pros and cons of separate and combined modules suggested that the separate approach had more benefits than the combined approach but that a slight change in the philosophy could provide the “best of both worlds”. Specifically, it was decided to also include a sonar in the MMM. This meant that the MMM would meet all periodic inspection requirements in a single unit for end users with a sufficient budget, and that the UIM would offer a lower-cost option for organisations with more modest requirements and budget. It was also decided that certain parts of the modules could be designed as common sub-modules. These common sub-modules were eventually used in the UIM and the Reference Point Installation Module but, for practical reasons, not in the MMM.

Finally, a study was carried out into the components to be used in the MMM and suitable units were chosen.

This task laid important foundations for the design of the MMM, UIM and Reference Point Installation Module that were carried out in other tasks.

Task 1.3. Definition of Requirement of Ultrasonic Devices

Here, the objective was to decide on whether to develop, in conjunction with a sonar manufacturer, an ultrasonic device capable of both profiling and imaging or whether to employ two separate units. However, as a result of the decision to add a sonar capability to the MMM, made in T1.2, this also applied to the MMM.

Work on this task started with an analysis of the differences between profiling and imaging sonars, not only from the perspective of features and benefits, but also in terms of the underlying technology. Following this, detailed discussions were held with several sonar manufacturers who questioned the benefit of using an imaging sonar in a mine shaft. In particular, it was suggested that the highly reverberant nature of the environment might produce confusing results, given that an imaging sonar has to collect data for a much longer time period than a profiling sonar. However, it was suggested that some, but not all, of the perceived benefits of an imaging sonar could be achieved by producing a waterfall display from stacked profiles. Given the slight change in philosophy made in T1.2, this gave rise to the following decisions.

Because the UIM is now been targeted as users with a limited budget, it was decided to include only a profiling capability. This has resulted in a very significant cost saving. However, the option of showing a pseudo-3D waterfall display would be added in the software. For the MMM, however, a decision was made to use a combined profiling/imaging sonar. In fact, such a unit had become available commercially since the project was first conceived so the issue of how to provide the dual capability did not have to be addressed. As a result of the discussions with manufacturers, it still wasn’t clear exactly what benefits would accrue from an imaging sonar in this atypical environment, if any, so this allowed an element of additional research. In the event that the cost of the dual-purpose scanner could not be justified, the same manufacturer offers a lower cost profiling only sonar of exactly the same size that could be substituted.

The results of this task led into the design of the MMM and UIM in Tasks 3.1 and 3.2.

Task 1.4 Component Design and Selection for Tube Bundle System.

The tube bundle system is intended to sample the air from the dry portion of the shaft, for chemical signatures of lining degradation or other characteristics (for example changes in methane level) that could pose a risk to shaft stability. The use of the system for sampling water in the flooded portion of the shaft was also considered but this was discounted because of the ensuing requirement for submersible pumps, the short lifetime of such pumps, and the requirement that the tube bundle must work for a protracted period of time even though maintenance is not possible. Instead, the electronic sensors that were researched in this project will be used for water sampling, leaving the tube bundle for air sampling, which is undoubtedly the strength of this technology.

The unusual requirement of this system, compared to those used in working mines, is that it must survive the potentially hazardous environment of a non-maintained shaft, and even shaft filling operations, for a long period of time without the option of maintenance. Work in this task involved deciding on a high-level design and the materials to be used in its manufacture. The decision on the materials was made in consultation with materials scientists and manufacturers after compiling a comprehensive list of risks that the tube bundle would need to survive. The novel aspect of the design is the addition of a yielding layer, between the sample tubes and the outer sheath, to absorb the force of any impacts and, in so doing, protect the sample tubes from crushing. Nano materials were studied but discounted because they are not sufficiently advanced and are very expensive, so conventional plastics were chosen instead. A probable definition of materials – namely polyethylene for the sample tubes, a thermo-plastsic elastomer (TPE) probably thermo-oplastsic polyurethane (TPU) for the yielding layer, and PVC for the outer sheath – was drawn up. The work in this task led to the detailed design and prototyping in T4.1.

Task 1.5. Selection and Design of Suitable Technologies for Fixed Reference Points and Installation Device

The selection and the design of the fastening method underwater was the main objective of the task. Different approaches were discussed during the first period, ranging from mechanical to chemical technologies. The initial approach, using drilling machines and hydraulic supports for installing the reference points, was abandoned during the discussion about the different methods. The idea of using a direct fastening technology became the final design approach for the reference point installation device:

A Remotely Operated Vehicle (ROV) carries the direct fastening device. The ROV is launched from a docking station at the operational depth. The docking station is lowered to the operation depth via a winch and wireline, and the ROV is run via a well-balanced umbilical (tether). This tether is managed by an underwater winch system. Due to the possible presence of many obstacles inside a shaft, poor visibility in the shaft water, and a water level far below the surface, this practice is required for ROV operation.

1.4. WP2: Development of Technologies for use in Underwater Conditions

Task 2.1. Design of Stability and Control Methods for the Ultrasonic Inspection Module

The objective was to study methods of stability control for the Ultrasonic Inspection Module (UIM), and also make a decision on a suitable method of obstacle detection.

The UIM will be winched into the shaft but other forms of motion are unintentional and need to be avoided. This is because they increase the risk of a collision between the UIM and obstacles in the shaft, and also because it will be difficult to compensate for large amounts of unintentional motion when assembling a 3D model of the shaft from the sonar data. In this context, however, it should be noted that data on any such motion will be made available to the control and analysis software from the Geo-referencing Sub-module. Study from previous projects showed that the most common forms of unintentional movement are pendulum motion and rotation. However, it became clear that such motion would be much less underwater, due to the damping action of the water, than in air where previously developed instruments have been deployed. Analysis suggested that the wireline to be used will exhibit a low degree of rotation and that pendulum motion can be controlled by the winch operator. Accordingly, a decision was made not to add specific active stabilisation technologies but to keep open the option of passive stabilisation if tests suggested it would be beneficial.

Several methods of obstacle detection were researched, and the conclusion drawn was that no one method would be adequately effective both above and below the water level. A decision was made, therefore, that separate methods should be used in these two environments. Based on cost and effectiveness, the following decision was made. For use in the dry portion of the shaft, a downward-pointing waterproof CCTV camera with integral LED illumination would be used. For use in the flooded portion of the shaft, a downward-pointing sonar altimeter would be used. A sonar altimeter would also be used in the Multi-functional Monitoring Module.

This task laid important foundations for the design of the UIM that was carried out in T3.2.

Task 2.2. Appraisal and Selection of Protective Cases for the Multi-functional Monitoring and Ultrasonic Inspection Modules

Here, the aim was to decide whether to protect each of the instruments in the modules individually, or to use a single pressure-resistant protective case for all the components in the periodic inspection modules.

For the UIM, a decision on whether to protect each of the instruments individually or to use a single pressure-resistant protective case for all the components was simplified by the decision to develop various common sub-modules. In this respect, the geo-referencing hardware and the communications interface and power supplies were developed as separate sub-modules so they would be independently waterproofed to an adequate pressure. A decision was only required, therefore, for the instruments that constitute the Profiling and Collision Avoidance Sub-module and, here again, the decision was removed in the light of the fact that off-the-shelf components were being used, all of which are adequately waterproofed.

The additional element of work concerning the specification of the power supply, and power and data cables and connectors, that was originally scheduled in this task, has been carried out in other tasks because it is closely associated with work on the surface equipment and the Cable Interface Sub-module (CIS).

Task 2.3. Design and Analysis of Mechanical System to Install Permanent Devices in a Flooded Shaft

The goal of this task was the design of the device for installing underwater (in the flooded shaft) the reference points needed for accurately positioning the different inspection modules.

This task was split into the design of the ROV, the Docking Station Submodule (DSS), and the reference point installation device which is carried by the ROV.

For the reference point installation device, two approaches were implemented in the context of the project (deep flooded shafts). The so called “Plan A” is a direct fastening system loosely based on a smokeless-powder-operated bolting gun by HILTI. The HILTI system is composed of a six-barrel “gun”, which fires hardened steel bolts using special (water-tight) blank cartridges. However, the HILTI gun is designed to be hand operated, requiring manual operation.

After a careful analysis, it was decided to use HILTI’s barrels and nail/bolt as the core of the bolting system. To complete the system, the following components were developed:

i) An electrically fired cartridge,

ii) A breech block having electrical contacts, and a watertight connector system,

iii) A remote-control system for firing the cartridges was used for the tests, although it may be replaced in the future by an equivalent system and;

iv) A reinforcement system for the reference points, composed of an aluminum tube and an aluminum “head”, where the bolt is nailed. The head has 6 drilled holes to allow the escape of powder combustion gasses.

As a “Plan B”, studies were made in order to collect some facts for a drilling method. These studies should clarify whether it is also possible to use drilling techniques for the reference point installation, should direct fastening fail. Another point that was clarified was what it would be necessary to drill, should there be the chance to do so.

Task 2.4. Definition of the Specific Requirements of a Software Based Analysis Tool, Data Transmission and Acquisition Needs

The software analysis tool was required to allow the preliminary real-time assessment and subsequent analysis of the conditions of the shaft; and control the inspection process of each of the modules. This means that it not only has to acquire the information from all the sensors – including those on the Multi-Functional Monitoring Module (MMM), Ultrasonic Inspection Module (UIM), fixed measurements, and the Reference Point Installation Module (RPIM) – but it also has to control the process of inspection by the modules and the installation of fixed devices while work is in progress.

Each of the modules was required to have a compatible communicating system with well-defined formats for exchanging messages, defined by rules and conventions, using open communication protocol standards.

It was decided to use open protocols and data formats supported by open-source software, which allowed the development of software with open-source tools.

In this task, all these mentioned conditions were considered, plus an analysis of all the sensors used in each module, that the software needed to take them into account. It was decided to have three different interfaces for each of the separated modules: One for the Multi-functional Monitoring Module (MMM), one for the Ultrasonic Inspection Module (UIM), and one for the Reference Points Installation Module (RPIM). Also, a first appraisal of the possible design of the software interface and the operation modes for each module was generated.

1.5. WP3. Implementation of Periodic Monitoring and Inspection Modules

Task 3.1. Prototyping of Multi-functional Monitoring Module

As the decision was to build two systems with different components based on the operational and economic criteria, the objective of this task was to construct a prototype of the Multi-functional Monitoring Module. It was decided that the MMM would include macroscopic visual inspection and ultrasonic geometry measurement instruments. The construction of the MMM consists of underwater cameras with a backlights, that enable examination of a sunken shaft, and a scanning sonar. Despite the potential difficulties with using imaging sonar hardware in the shaft environment, and despite the decision to use only a profiling sonar in the UIM, the option of using both profiling and imaging sonar hardware in the MMM was being kept open at that time.

In this task, the actual MMM, and a car trailer with winch components, were developed. In order to check the possible geometric solutions for the casing of the MMM, an FEM optimisation was performed. The casing takes the form of a steel cylinder with a screwed cover. Inside, power, control, registration and transmission systems are placed, together with their wiring. There is, moreover, a second function of the steel housing: all of the external elements and devices are mounted on it.

The above-ground equipment for the MMM is a trailer with a turnstile and a set of components. The car trailer and winch components were partially based on the existing CMIPL and DMT solutions from the RFCS project “MISSTER”.

The goal of prototyping the Multi-functional Monitoring Module was to develop a complex device capable of being used during on-site testing in T6.1.

Task 3.2. Prototyping of Ultrasonic Inspection Module

The objective of this task was to design and prototype the Ultrasonic Inspection Module in preparation for field trials in Task 6.1. This work built on preparatory work and decisions made in T1.2, T1.3, T2.1 and T2.3. In fact, as a result of the decision to use certain common sub-modules in the UIM, and the fact that these sub-modules have been developed in other tasks, the main work here was the design of the Profiling and Collision Avoidance Sub-module (PCAS) which is used in the UIM and the Reference Point Installation Module.

Off-the-shelf products were readily available to fulfil the needs of the three instruments in the PCAS, namely the profiling sonar, the sonar altimeter and the underwater CCTV camera. Accordingly, an extensive product appraisal was carried out, and meetings were held with manufacturers, before purchasing suitable instruments, after inviting those companies with suitable products to tender.

The mechanical design and manufacture of the PCAS was then carried out. The primary purpose of the mechanical assembly is (1) to provide a firm fixing for the three instruments, (2) to provide a cage type assembly to afford protection to these devices while not impeding their ability to monitor the shaft, and (3) to allow its attachment to the sub-module immediately above it in the UIM, namely the Geo-referencing Sub-module. A stand was also designed and manufactured to assist in on-site handling of the UIM by allowing it to stand on the ground without causing damage to the transducer housing of the profiling sonar, which protrudes through the bottom plate of the UIM.

Following the manufacture of the PCAS, it was integrated with the Cable Interface Sub-module and the Geo-referencing Sub-module to complete the UIM. This was then subjected to successful laboratory testing in a test tank. This paved the way to on-site testing in T6.1.

Task 3.3. Gas and Water Measurements for the Assessment of Shaft Stability

The objectives of task 3.3 were two-fold. First, to assess the long-term stability of flooded shafts using the evolution of gaseous atmospheres as an indicator of the degradation of the shaft support system (concrete and masonry). Second, to develop a device that can measure and monitor, over time, the physical and chemical parameters of water flowing into the mine workings.

Ineris (task leader) ran a laboratory test programme to assess the generation of gasses, when water is in contact with materials used in shaft lining and support systems from GIG and Polish partners. Lab tests showed that degradation of concrete due to flooding could be detected by monitoring changes in gas concentration of the shaft atmosphere. Ineris also identified electrical conductivities measurements tools, for adaptation to shaft monitoring. A review of commercial tools illustrated that the equipment is well-suited to detect water mineralization variations along the water column of a shaft. Those variations could be the consequence of shaft lining degradation linked with hydro-chemical reactions, or to water flow coming from outside the shaft due to damage to the lining.

1.6. WP4 Long-term Continuous Shaft Water, Gas and Environment Monitoring and Modelling

Task 4.1. Tube Bundle System Design: Methods of Lowering, Anchoring and Positioning, Sampling, Observation and Monitoring

The objective was to carry out a feasibility study into several aspects of a novel super-resilient tube bundle, intended for use in the hostile environment of an abandoned mine shaft. Although the prescribed work is, therefore, mainly a scoping study, the work carried out progressed beyond these initial aims by providing a high level of support to potential users as described below.

Following on from the high-level design and a provisional definition of the materials that were produced in T1.4, the design of the tube bundle was finalised, and the materials confirmed following discussions with Colex International, a company with experience of tube bundles, albeit not for use in abandoned shafts. A sample of the tube bundle, containing seven sample tubes, was manufactured and subjected to tests which proved that it has the necessary high degree of resilience to impacts that might occur in the hazardous abandoned shaft environment. It is important to point out that end users can now order production quantities of the tube bundle and such orders would not be subject to the initial setup charges that have been met in this project.

A break-out box was designed and prototyped. This unit is required at those vertical positions within the shaft where atmospheric sampling is required. Its purpose is to allow one of the sample tubes to be extracted from the bundle and exposed to the atmosphere, while maintaining the mechanical integrity of the bundle. A CAD design is available for end users and detailed instructions have been produced for fitting a break-out box.

Support for the tube bundle has also been studied with the recommendation that a synthetic support rope is used with periodic attachments between the tube bundle and the rope. A specific rope and attachment method have been recommended as guidance for end users. Finally, methods of installation into an abandoned shaft, post-closure, were studied and a recommendation made to end users.

Task 4.2 Modelling and Verification of Underwater Transmission Scheme

This task aimed to examine the feasibility of engineering a cost-effective long-term shaft monitoring capability using contactless methods of inductive power transfer and data transmission. As this was essentially a ‘feasibility study’, no equipment was constructed, but the principles behind some of the various concepts were tested and verified. Several results and conclusions were produced regarding the design of such equipment.

Primarily, it is clearly advantageous to eliminate the rechargeable battery from an application such as this, because of the long product lifetime that is required. A super-capacitor would be an appropriate replacement. The shaft monitoring nodes (or outstations) are connected via a single charging line and inductively coupled to it so, in circuit terms, this places them in series. It is necessary to be able to switch their power storage elements out of the circuit and to provide 'line clamping' in order that the system can function as intended. However, this limits the scope for 'soft-failure' of an outstation.

The most practicable design of inductive coupler is probably a ferrite bobbin, because this topology results in a high effective permeability of the ferrite. The performance of the inductive coupler can be assessed by applying a mathematical model of loosely-coupled coils but this is highly dependent on the topology of the pressure-proof enclosure that is to be used.

The communications wire should be implemented as an out-and-back pair rather than as a loosely-constructed large loop. This will aid the stability of the driving amplifier and will also eliminate common-mode noise. A simple data modulation scheme (OOK for outgoing data and FSK for incoming data) is probably enough for this application. The controller functions are probably best implemented in a web-server environment

Task 4.3: Investigation of Long-term Measurement Opportunities

A number of 'measurement opportunities' were investigated for use with the proposed contactless power and telemetry scheme. Two salient points are that, in order to avoid the need for expensive pressure-proof connectors, it was necessary to consider contactless sensors. Additionally, the system needs to be deployed without maintenance for a number of years. These points mean that the range of sensors that can be considered is limited in scope.

The basic parameters that can easily be measured are considered to be water presence, pressure (i.e. water depth), electrical conductivity, temperature and tilt (e.g. shaft displacement). Other measurements, such as acidity (pH) are much more difficult to incorporate into the system.

It is suggested that a two-terminal capacitive type of non-contact type of water conductivity measurement could be attempted but methods of mitigating fouling would still need to be undertaken. The primary mechanism for fouling may well not be biological but could be due to electroless deposition. It was initially conjectured that conductivity might be a useful analogue to pH but this was shown not to be the case.

Task 4.4. Examination of "Value Engineering" Cost Reduction Opportunities

The proposed underwater transmission system (UwTS), described in Tasks 4.2 and 4.3, requires a pressure-proof housing. To reduce the cost of such housings, it was envisaged that submerged sensor nodes operating below a particular depth could be designed with an engineered 'soft-failure' mechanism. Some design calculations were undertaken for a low-cost underwater pressure-proof housing and a prototype housing was designed and tested successfully at depth.

A significant conclusion of a study of failure mechanisms suggests that a reliable soft-failure mode cannot be guaranteed. It is suggested that, in the event of this feasibility study being taken forward and used to design a specific application, a further detailed analysis of a loosely-coupled inductive coupler should be undertaken to try to reduce the unwanted effects of the failure of one of the outstations.

A prototype underwater housing was tested in South Crofty Mine, situated in Cornwall, UK. This mine has recently received a dewatering permit from the UK Environment Agency allowing the discharge of up to 25,000 cubic metres of treated water per day into the Red River. The mine has expressed interest in installing a version of the long-term shaft monitoring equipment. This would allow the mine to track the water depth in two different shafts as the de-watering operation continued. Collaboration between the University of Exeter and South Crofty Mine is envisaged for this operation.

Task 4.5. Hydro-mechanical and Chemical Modelling of Shaft Long-term Stability

The review of shaft failure and risks showed that the lining is the most governing parameter of shaft stability. The assessment of this stability requires, therefore, a detailed analysis of lining conditions, especially after the flooding phase, where the material is exposed to aggressive mine water. As hydraulic, mechanical and chemical loadings are involved in the shaft life, it is necessary to couple them for a reliable assessment of long-term shaft stability.

For the hydraulic and mechanical aspects, coupling the numerical model and an evaluation of stability are made by calculating a safety factor, provided using consistent assumptions in modelling, and reliable mechanical and hydraulic properties. However, for the chemical aspect, full coupling is not easy to achieve due to the complexity of the phenomenon. The proposed modelling approach consists of simulating chemical reactions which occur between mine water and lining material and estimating the degraded width. This altered width is assumed to be totally ineffective and lost, and therefore the lining thickness is reduced from each side by this width. The remaining part of the lining is assumed to preserve the initial mechanical properties of the material without any weakening effect. Hence, stability can be assessed by establishing charts giving the variation of safety factor for a given thickness and strength of lining and shaft conditions.

The modelling approach was illustrated on three French shafts: one lined with cast iron and two with concrete. Furthermore, two cases of shaft collapse from partners mines (Poland) were back analysed to demonstrate the ability of the modelling approach to reproduce observed behaviours.

1.7. WP5: Integration of Technologies and Modelling for Complete Shaft Stability Assessment

Task 5.1. Inertial and Georeference Module and Fixed Reference Points

An inertial measurement unit (IMU) was designed and fitted into the GRS within this task. This IMU does not physically belong to the project, but it was rented to the project. The IMU output data are pre-processed in the CIS. The pre-processed data that are transmitted to the surface unit were these data merged with depth data. This geodetical data set is used for correcting the scanner data from the effects of rotation.

Task 5.2. Software Based Tool for Real-time Control and Post-processing Analysis

The definition of the communication software was defined in Task 2.4 and the software development was carried out in this task. First, the connections were defined, as they were a key issue for driver development in terms of communications management. The main contribution to the STAMS software development in this task of the project, was the development of drivers for the different sensors with open-source software tools, as well as the first version of software interface.

The development of these custom drivers proved the following advantages:

- The possibility to form a waterfall display from the profiling sonar data, for 3D display of the shaft surface.
- The chance to integrate all the measurements in a common user interface, developed with open-source tools.

Task 5.3. Calibration and Application of the Coupled Modelling Approach with the Monitoring Technologies

Four shafts were selected for the application of the proposed modelling approach: one in Spain lined with concrete (Fondón shaft in Nalon colliery, HUNOSA), two in Poland lined with concrete (Shaft 1 in Piast colliery, PGG and Bartosz II shaft located in Katowice, SRK) and one in UK lined with brick and masonry (Downcast shaft in Hartington colliery, Coal Authority). Further to the objective of assessing long-term stability of each one of these shafts, an attempt at calibration of the coupled modelling approach was made using the measurements obtained by the developed monitoring systems. Unfortunately, at the end of the project, the measurements of the new equipment were not quantitative and did not allow a real calibration to be performed. Only a qualitative comparison was therefore made. Besides, due to the lack and uncertainties of data required for modelling, sensitivity analyses were conducted to overcome this difficulty.

Parallel to the field studies conducted in shafts, a testing campaign was carried out in the laboratory to study chemical reactions between mine water and lining material and their effect on the mechanical behaviour. As concrete is the most common lining used in coal mine shafts, tests were run on samples of this material. The major objective of this testing programme was to validate the assumptions and parameters of the modelling approach, particularly at the chemical and mechanical levels. Two water compositions were considered: the first one is a typical mine water instigated from the conditions of Fondòn shaft, and the second corresponds to a very aggressive solution with a high concentration of sulphate and a relatively low pH. Due to the limit of the testing period, a part of the tests was conducted at a high temperature to accelerate the chemical reactions.

The comparison between the results of modelling and laboratory measurements showed clearly that the modelling approach used is reliable, and that the assumptions made for long-term stability assessment of shaft lining are conservative. This lead, therefore, to results with a high security margin.

1.8. WP6: Field-trials, Assessment and Technology Transfer

Task 6.1: Demonstration of Systems and Equipment at Selected Shafts

The Multi-functional Monitoring Module (MMM), the Ultrasonic Inspection Module (UIM) and the Reference Point Installation Module (RPIM), developed in previous tasks, were tested in on-site conditions of shafts. Individual shafts differ in lining, diameter, access, size of shaft opening, installations, organization of the site, etc. For this reason, each test required an individual approach. Conducting multiple tests resulted in recognising multiple issues of various types. This, as a natural stage of the process, helped to adjust the devices to difficult conditions and improve the work carried out. For the MMM test routine, five shafts in Poland were selected from SRK and PGG. Four of those shafts are owned by project partners: three are managed by SRK, and one by PGG. A fifth shaft belongs to Polish mining company Tauron Wydobycie.

Task 6.2. Analysis, Assessment and Equipment Appraisal

The objective of this task was to perform a critical assessment of the developed devices based on results obtained from using the instruments in shaft conditions during field trials in Task 6.1. Moreover, the analysis of the work also led to the recommendations and design guidelines for successful control and support at the test sites (included in deliverable D6.2). Appropriate modifications of existing structures were also suggested.

The results of the underground measurements were analysed in terms of their suitability for evaluation of the stability of flooded sections of shafts. Each of the conducted laboratory and in situ tests ended in drawing conclusions and noting them to improve the device and achieve better results. All of those comments were included in deliverable D6.1, as this built on work in T6.1.

Task 6.3. Results Dissemination

A dissemination workshop was organised in Katowice in Poland, by Central Mining Institute. There were more than 50 participants from 7 mining companies (PGG, JSW, PG Silesia, Tauron Wydobycie, Węglokoks Kraj; LW Bogdanka), state and local authorities, and other organisations related to shaft drivage and maintenance (CSRG, SRK, ‘Bolko’- pumping station; PPG Row-Jas; PBSz, etc.).

The results of the developments and the results of the trial tests were also widely discussed with potential commercial recipients: project partners (HUNOSA, SRK S.A., PGG S.A) and companies not directly involved in STAMS. Included here were participants of the Dissemination Workshop, in particular mining companies, state and local authorities and other organisations related to shaft drivage and maintenance.

Presentations were made and papers submitted to national and international conferences and papers were written to share the results of the developed modules: MMM and UIM.

South Crofty Mine, situated in Cornwall, UK, between Camborne and Redruth, has recently received a dewatering permit from the UK Environment Agency allowing the discharge of up to 25,000 cubic metres of treated water per day into the Red River. The mine has expressed interest in installing a version of the long-term shaft monitoring equipment described in Work Package 4. This would allow the mine to track the water depth in two different shafts as the de-watering operation continued. Collaboration between the University of Exeter and South Crofty Mine is envisaged for this operation.

2. SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS

2.1. *Objectives of the Project*

The main objective of this project is to implement solutions to monitor and to assess the stability and the conditions of flooded shafts, including the non-flooded portions of partially flooded shafts, for long periods of time, including the provision to monitor shafts that will be filled in the future. The objective was achieved by subjecting a shaft to (a) periodic measurements, and (b) continuous monitoring. This required developing new technologies and achieving the following goals:

- Develop and test a *Multi-functional Monitoring Module* that is able to make periodic measurements in order to assess the stability of a flooded shaft.
- Develop and test an *Ultrasonic Inspection Module*, featuring the novel combination of ultrasonic profiling and ultrasonic imaging, to both inspect shafts visually and measure possible deformations with high precision between periodic inspections of shafts.
- Test *water dynamics and gas devices* to continuously measure, analyse and asses the stability of shafts for long-term monitoring with provision to deploy sensors post-closure that will withstand shaft filling operations.
- Develop and test a *software control and analysis* system to measure, in-situ and in real-time, significant differences that may indicate instability or significant changes in a flooded shaft.
- Develop a *modelling approach* to assess the long-term stability of shafts during and after flooding by coupling the hydro-mechanical behaviour with the chemical reactions which occur between the aqueous solution and the shaft lining components.

The STAMS project is organized into seven Work Packages (WP0 – WP6) including WP0 which covers coordination issues. To accomplish the objectives, a preliminary assessment of the possible combination of solutions was carried out in WP1 and adequate resources was used for the development of the technologies and their validation in underwater conditions in WP2. Using the results from WP1 and WP2, the periodically-deployed modules was developed in WP3 while in parallel; the long-term monitoring devices was developed in WP4. Subsequently, these modules were integrated into the common systems developed in WP5. Finally, in WP6, field trials were conducted to evaluate the consistency of the measurement strategies, and measures were taken for the dissemination of the research results.

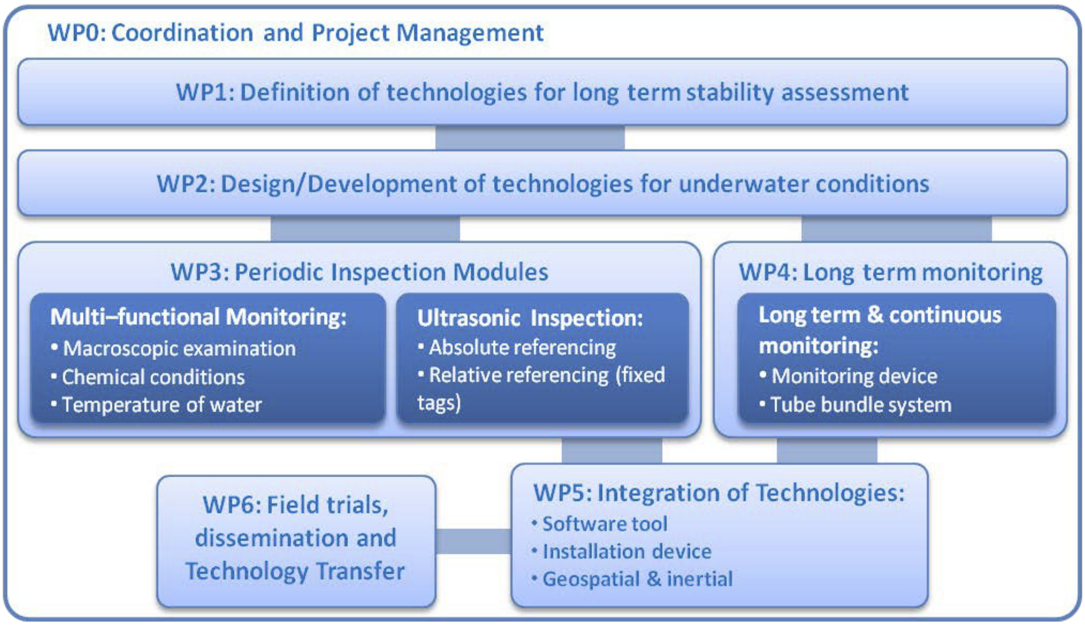


Figure 1 – Interrelation of Work Packages

2.2. Description of Activities and Discussion

WP1: Selection of Technologies, Sensors and Components for Long-term Stability Assessment

The objective of this WP was to define the guidelines of a common platform to develop the different devices and technologies and the logistics to use them in underwater conditions of flooded shafts. The following specific goals was considered:

- ***G1.1.*** Define a common strategy and establish the sensors required within the periodic measurement module.
- ***G1.1.*** Define a common strategy and establish the sensors required for long-term continuous monitoring.
- ***G1.3.*** Specify the functional requirements that will be needed to design the mechanical frame (chassis) and mechanical components required for each module.

Task 1.1. Definition of Monitoring Requirements for Long-term Shaft Evaluation

The minimal and optimal range of measurements needed for a shaft evaluation were analysed in the framework of Task 1.1. Based on the results of the task, the mechanical needs for each device and their functional requirements were defined. In result, a total number of 23 shafts were analysed and described. The analysed parameters obtained from the developed questionnaires allowed assessment following aspects (*Figure 2*):

- General inspection requirements (shaft depth, water depth, maximal length of flooded shaft section, maximal length of dry shaft section in analysed shafts, total water inflow into the shaft);
- Requirements resulting from horizontal section of the shaft (shaft diameter, number of access points in the shaft, distance to the lining resulting from shaft diameter and the location of access inputs on the surface);
- Shaft access limitation (minimal access size and access time limitations);
- Shaft lining (thickness of lining in analysed shafts, type of lining in analysed shafts).

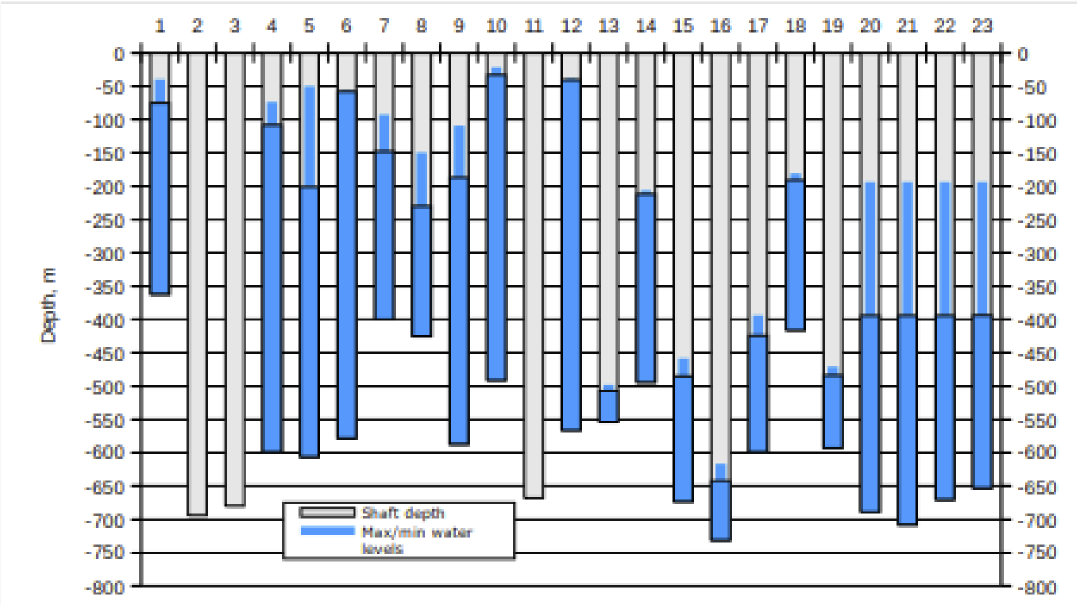


Figure 2 – Characteristics of Shafts, Depth and Max. & Min Water Levels

On basis of the obtained data a typical and worst-case scenario were considered for the development of the inspection tools MMM and UIM: the maximum flooding shafts is less than 1000 m and the water depth is 600 m. The two prepared scenarios – typical and worst – due to the large variability of obtained flooded shafts parameter - differ amount others in the shaft diameter, water levels and shaft access limitations. From the point of view of the definition of monitoring requirements for long-term shaft evaluation it is crucial to assess the worse condition during the inspection.

The most important parameters are the shaft depth and the water level flooded depth, which directly affects the rope length and strength parameters of the casing. The next important parameters are the total range of installed sensors (minimal and maximal distance between the sensors and measured object). It was expected that it is directly connected with the diameter of the shaft, but the obtained data showed that more important is the location of access point in the shaft area. In the worst-case scenario, due to the adverse location of the access point, the range of sensors should be between 1.0 and 6.5 m. The next crucial information relates to size access limitations. Performing of underground tests requires development of the inspection modules with a horizontal cross-section smaller than 0.5 m wide. In turn, the total length of the inspection modules is limited to the possibilities of their mounting on the surface only. More details on the above issues can be found in Deliverable D1.1- Selection of Technologies for Underwater Inspections.

Task 1.2. Sensor and Component Selection for Multi-functional Monitoring Module

<u>MMM Components</u>

The main objective of this task was to select the main sensors and components of the Multifunctional Monitoring Module (MMM) by testing the actual capabilities and performance of each of the candidate technologies in underwater conditions. GIG is currently using different devices for shafts inspection that were developed in the RFCS MISSTER project (Salmon et al., 2015). At the stage of preparing the project proposal it was assumed that it would be possible to adapt sensors and components from previous devices. However, due to the attempt to develop sensors and components that are, at least in some part, compatible with the Reference Points Installation Module, and due to the fact that, in the meantime, new sensors dedicated to underwater inspection have become available, the preferable approach is to develop the Multi-functional Monitoring Module (MMM) based on the following components:

- cameras with 1/3 in CCD Sensor, wide angle and low underwater distortion and light sources working to the depth of 6000 m (producer Deep Sea),
- transmission and power modules compatible with the Reference Points Installation Module,
- car trailer and winch components are partially based on the existing GIG and DMT solutions from RFCS MISSTER,
- other electronic/hydraulic elements are developed in agreement with DMT and UC3M.

<u>MMM / UIM Philosophy</u>

Although the project Technical Annexe refers to the development of two separate periodic inspection modules, namely the Multifunctional Monitoring Module (MMM) and the Ultrasonic Inspection Module (UIM), it also mentions the possibility of combining the functionality of both units into a single module. An objective of this task, therefore, was to decide whether to develop the two modules independently or to develop them as a single combined module.

In order to make a decision on this matter, an analysis was carried out of the pros and cons to the end user, and the implications for the project, of developing (1) two separate modules for periodic inspection, namely the UIM (Ultrasonic Inspection Module) and the MMM (Multifunctional Monitoring Module), and (2) a single module containing the functionality of both the periodic inspection modules. The initial conclusion drawn was that there were pros and cons of both approaches although, on balance, there were more benefits associated with the development of two separate modules. These pros and cons are summarised in *Table 1*.

		Combined Periodic Measurement Modules	Separate Periodic Measurement Modules
End-user Considerations	Purchase Cost	Slight benefit	
	Cost of Ownership		Major benefit in event of loss
	Speed of Operation	Medium benefit	
	User Flexibility		Medium benefit
	Winch Requirement		Possible benefit
Development Considerations			Medium Benefit

Table 1 – Summary of Pros and Cons of the Two Approaches

Although there are very clear benefits, overall, by offering a separate UIM and MMM, it has to be recognised that the speed of operation, which is the most significant benefit of the combined approach, is lost.

On studying the pros and cons for separate versus combined development, it became clear that by adapting the philosophy for the provision of the PIMs, it would be possible to offer the best of both approaches. The solution is to offer both an ultrasonic scanning sonar facility in the MMM and to separately offer a very low-cost UIM. This allows users to select the solution that offers most benefits to them and, at the same time, provide the UIM at a much lower cost than was originally envisaged, for those users with a limited budget. The UIM is also uniquely suitable for use in shafts that do not have a large enough access opening to permit the larger diameter MMM to be deployed. This decision required the method of providing a combination of a profiling and an imaging capability in the UIM to be re-appraised as discussed in Task 1.3. As a brief summary, however, it was decided that it will be possible to provide many of the perceived benefits of the imaging hardware using profiling hardware alone at the cost only of additional software development.

Common Modules

As a result of this analysis of the pros and cons of the two development approaches, it was recognised that some of the functions required in both the periodic inspection modules (which also includes the Reference Point Installation Module – see Task 2.3) could be developed as common sub-modules that could be used in more than one of these modules, thereby reducing the development time.

It was also recognised that if these modules were designed to offer a “plug and play” capability, allowing the end user to swap them between the periodic inspection modules, this approach will also offer a reduction in the cost of ownership for the end-user because an end user would need to buy only one set of common sub-modules, even if they intended to utilise multiple modules.

These common functions include geo-referencing, and communications and power supply, and have been developed as separate sub-modules as described in Tasks 2.1, 2.2, 2.3, 3.1 and 5.1. In the final analysis, it was decided not to use these common sub-modules in the MMM but to use them in the UIM and RPIM. In addition, it was decided that the part of the UIM containing the scanning sonar and the collision avoidance hardware (see Task 2.1) would also be developed as a separate common sub-module. Called the Profiling and Collision Avoidance Sub-module, this has also been used in the Reference Point Installation Module (see Task 2.3). The way in which the various sub-modules form part of the UIM and the RPIM is illustrated in *Figure 3*.

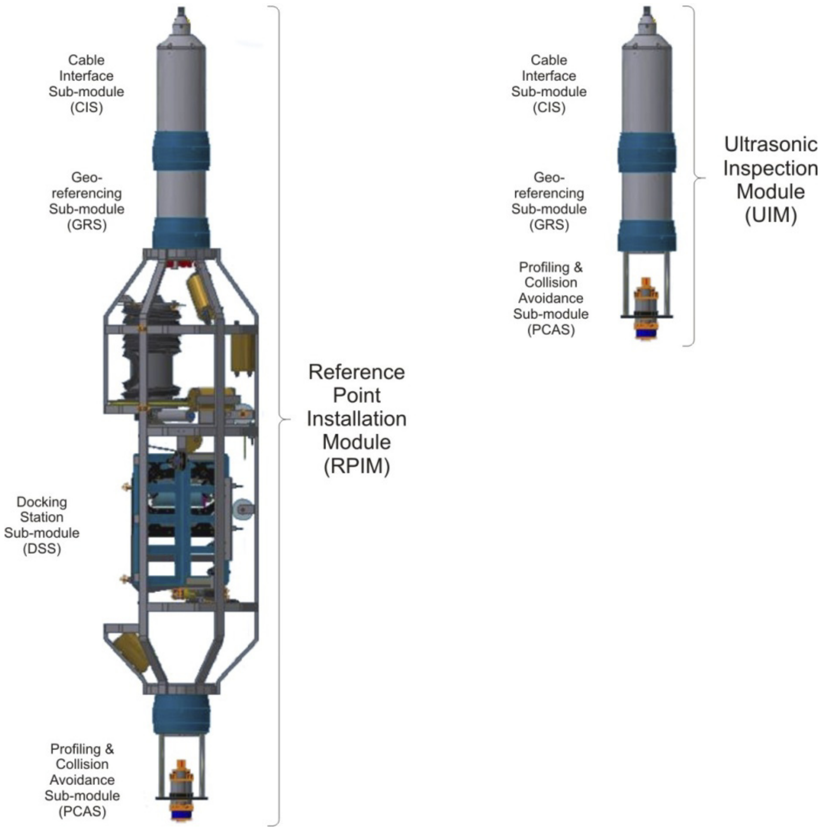


Figure 3 – Arrangement of Sub-modules in Periodic Modules

More details on the above issues can be found in Deliverable *D1.1 – Selection of Technologies for Underwater Inspections*.

Task 1.3. Definition of Requirement of Ultrasonic Devices

Profiling and Imaging Sonars

The specification of the Ultrasonic Inspection Module (UIM) requires both a profiling and an imaging capability. As the name suggests, a *profiling sonar* (Atherton 2011a) is used to generate a profile. In marine use, this would typically be the profile of the sea floor and, perhaps, structures such as pipelines on the seabed, while in the application of this project it would be a profile of a horizontal slice through a shaft. Such a profile is produced using a narrow conical shaped beam as shown in *Figure 4* and recording just a single return signal in response to each transmitted pulse.

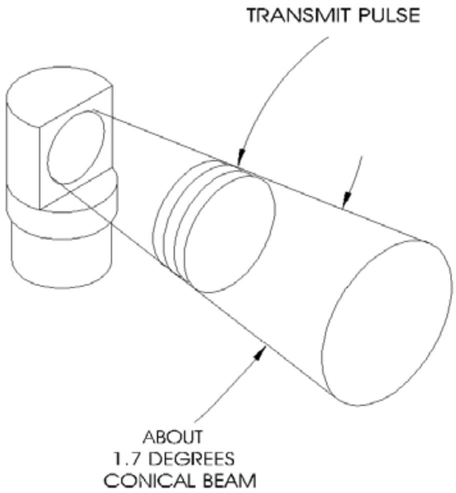


Figure 4 – Typical Beam Pattern of a Profiling Scanner

According to the application and hence the processing algorithm, this single return would normally be either the first return signal or the strongest such signal, bearing in mind that there could be multiple reflection from objects at different distances within the angle of the transmitted pulse. Typical output is shown as *Figure 5*.

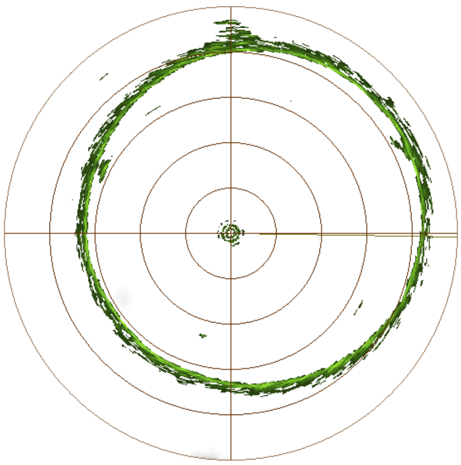


Figure 5 – Profiling Scan of Mineshaft (Image: RFCS PRESIDENCE)

It is anticipated that the primary output of an ultrasonic profiling exercise in a mineshaft will be a series of profiles down the length of the shaft, separated by no more than the height of a single brick (and ideally less) so that single bricks missing from a brick-lined shaft could be detected. This series of profiles allows accurate measurements to be taken, it would permit accurate physical models to be created by 3D printing, and it provides a basis for making comparisons between successive scans so that any further deterioration since the last scan can be identified.

As the name suggests, an *imaging sonar* (Atherton 2011b) is used to generate something that can be thought of as the equivalent of a visual image. Such a profile is produced using a narrow fan shaped beam as shown in *Figure 6*. For imaging the seabed (a typical application), the seabed would be a horizontal plane below the vertical scanner shown in the diagram.

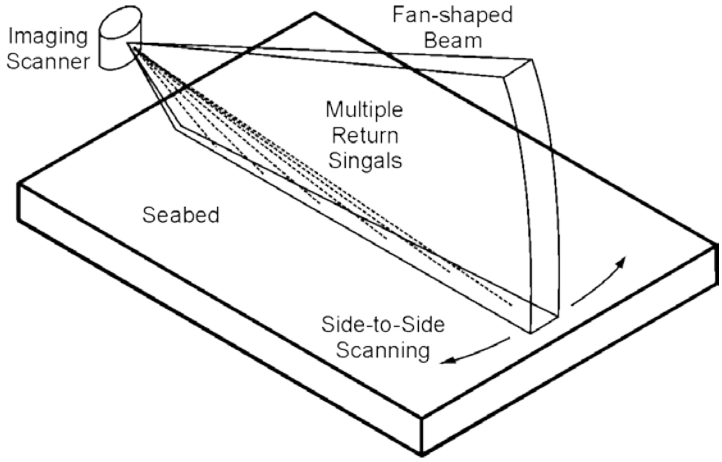


Figure 6 – Typical Beam Pattern of an Imaging Scanner

In contrast to profiling, multiple returns are recorded for each pulse. Because the beam normally scans at a shallow angle, the time of the return signal corresponds to the distance (e.g. along the seabed). The amplitude (which is represented via greyscale or false colour) represents the reflectivity of the target. Typical output, shown as *Figure 7*, is of a wreck on the seabed.

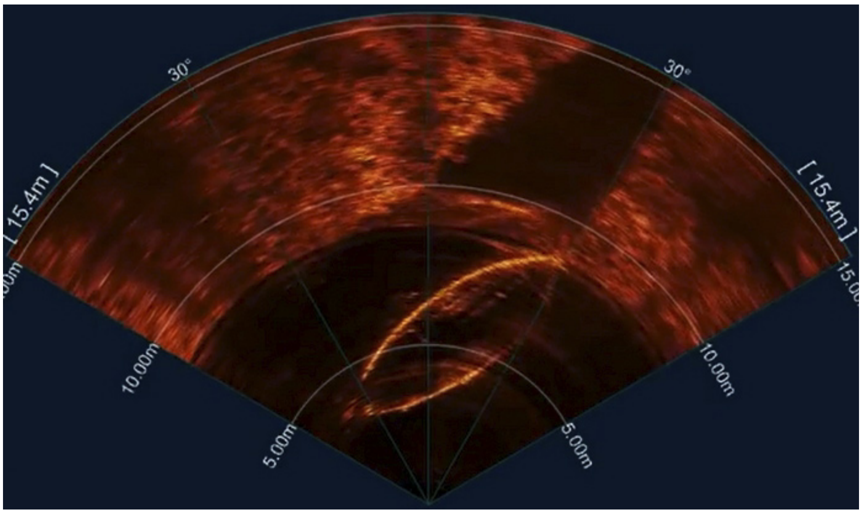


Figure 7 – Sample Output from an Imaging Exercise (Image: Tritech)

The proof-of-concept work carried out in RFCS PRESIDENCE (Herrero et al., 2012) made use of a profiling scanner to obtain cross-sections of a shaft as shown, for example, in *Figure 5*. While this approach provides accurate measurements, a degree of “detective work” was needed to interpret the cross-sectional images and, in some cases, more than one explanation seemed possible for a given feature. Given that one of the commonly cited benefits of an imaging scanner is that it “provides the viewer with enough data to draw conclusions about the environment being scanned”, it might seem probable that such a capability would reduce the ambiguity of profiling. While it is likely that the post-processing of data from a profiling sonar would, in most cases, remove any such ambiguity, it is highly desirable if a clearer picture, of the type offered by an imaging sonar, could be made available in real time to assist the operator. This would allow the operator to adjust the angular resolution and/or the winching speed to concentrate on those areas of the shaft where possible damage is deemed to have occurred.

An analysis was carried out of two approaches for the provision of both a profiling and an imaging functionality. These approaches were (1) the production of a combined scanner in conjunction with a sonar manufacturer, and (2) the use of a third-party profiling sonar and a third-party imaging sonar device.

Recommended Approach

Discussions were held with key manufacturers of profiling and imaging sonar devices to better understand the pros and cons of the two approaches. The most important outcome from these meetings was the suggestion, made by two manufacturers, that a combination of profiling and imaging scanners might not be the best way to meet the objectives of the UIM, and that it's possible that a more cost-effective solution could be achieved with a profiler alone, albeit at the cost of additional software development. Given that such a solution would potentially halve their sales, both to this project and, more significantly, to end-users employing the techniques developed in the project, such a suggestion was taken seriously. To quote Tritech's Mike Broadbent the recommendation was made, "because we're interested in providing the best solution". This, therefore, was an important result which has resulted in an amendment to the approach taken in the UIM for reasons discussed in the following two paragraphs.

First, doubts were expressed, by two manufacturers of scanning sonar equipment, about the feasibility of using an imaging sonar in a confined environment such as a mine shaft which will be highly reverberant. The result of multiple reflections is likely to be a confusion of the resultant image while a possible approach to minimizing multi-path effects would result in ambiguity of the position of targets. Given that a major reason for adding an imaging capability is to help the user interpret the profile data, this was considered a major potential drawback.

Second, as a result of a decision regarding the changing development strategy for the MMM (see Task 1.2), involving the inclusion of full scanning sonar facilities in the MMM, the rationale of developing a separate UIM evolved. The UIM is now being designed as a very cost-effective instrument for use by those end users who cannot justify the high cost of the MMM and only require a capability for surveying shaft geometry. It will also be applicable in cases where the entry into a shaft through the cap is too small to permit the much larger MMM to be used.

As a result of these two considerations, it was decided to use only profiling hardware in the UIM. The following are the implications of this decision.

First, the hardware cost of the UIM will be reduced by approximately £9,000, representing, perhaps, a 30-40% reduction in the total cost of the unit. This is considered a major advantage, given the revised rationale for the UIM.

While the elimination of the imaging hardware might seem a retrograde step, the perceived benefits of this hardware will be provided by generating a waterfall display of the profiling data (i.e. a pseudo-3D image with similarities to the initially perceived display from an imaging sonar – see *Figure 8*) that can be viewed by the operator in real time as well as being available for subsequent review. This will not suffer from the problems of using imaging hardware and the cost will be only that of software development, so it will not impact the end user cost.

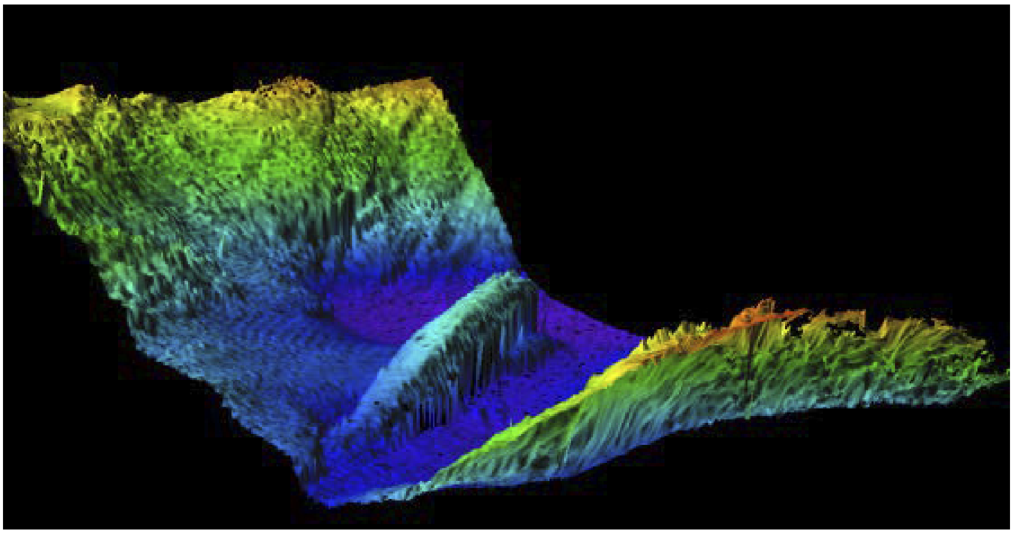


Figure 8 – Example Waterfall Display (Image: Kongsberg)

Despite the decision made in relation to the UIM, a profiling and decision was made to use an imaging capability. As a result of the discussions with manufacturers, it still wasn't clear at this point exactly what benefits would accrue from an imaging sonar in this atypical environment, if any, so this allowed an element of additional research. In fact, such a unit had become available commercially since the project was first conceived so the issue of how to provide the dual capability did not have to be addressed. In the event that the cost of the dual-purpose scanner could not be justified, the same manufacturer offers a lower cost profiling only sonar of exactly the same size that could be substituted.

As a result of decisions made in this task, selection of a specific sonar unit for the MMM and for the UIM could start. This was carried out as part of the design exercise for the two units in Task 3.1 and 3.2 respectively.

Task 1.4. Component Design and Selection for Tube Bundle System.

Overview

Tube bundle systems (TBS) are routinely used for monitoring the atmosphere of working mines. Good introductions are found in (National Coal Board, 1977), (SIMTARS, 2015) and (Zipf et al., 2013). These systems employ a bundle of plastic tubes, encased in an outer sheath, with individual tubes being exposed to the atmosphere where sampling is required. Pumping at the surface draws air to surface facilities where chemical analyses are carried out. The disadvantage compared to the use of underground electronic sensors is that there is a delay, resulting from the time taken for the air to reach the surface from the sampling point – as much as an hour in the case of tubes kilometres in length. There is an additional delay due to the common practice of cycling the outputs from the individual tubes through a single set of gas sensors and the associated purging. However, the advantage provided is that they are less prone to failure than underground sensors. In the case of abandoned mine shafts, however, the disadvantage of slow response times does not apply since changes are expected to occur very much more slowly than in a working mine.

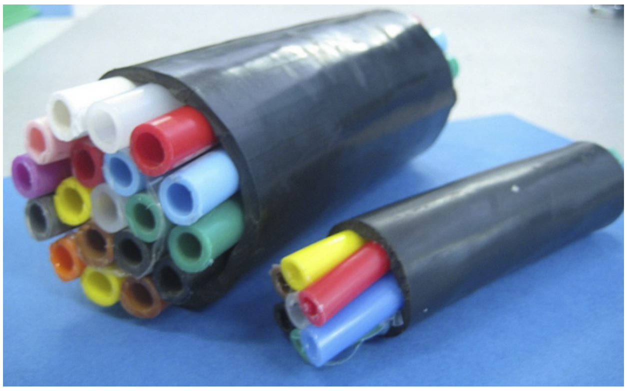


Figure 9 – Typical Tube Bundles in Working Mines

An analysis was carried out of the requirements of a tube bundle system, for sampling air in the dry portion of abandoned flooded shafts and, potentially, water in the flooded portion of the shaft. This analysis led to a provisional specification of the materials to be used in the tube bundle which is being designed in Task 4.1.

Water Sampling

The first area to be considered was the use of the tube bundle for sampling water which is an optional add-on to the primary use of sampling air. Apparently, there has been no widespread use of tube bundled systems for monitoring water in mines. However, such systems have been used in boreholes for sampling groundwater from different depths. This usually involves the positioning of barriers to compartmentalise the borehole in order to prevent mixing of water from different depths. The major differences between this form of sampling and that occurring in abandoned mine shafts is that the placement of barriers would be impractical and probably unnecessary if water sampling is to occur at points that are separated by very large depth intervals.

The other major difference is due to the impossibility of drawing water by suction from a depth in excess of around 10m. Consequentially, submersible pumps below the water level would be required instead of suction pumps at the surface. In view of the fact that one of the main benefits of a tube bundle system is that there is no requirement for electrical or electronic equipment underground, there is an element of doubt as to whether the use of a tube bundle system for sampling mine water would be beneficial. Furthermore, a requirement of the tube bundle is that it would be a “fit and forget” system since maintaining or replacing elements of a tube bundle in an abandoned flooded shaft would be difficult at best and impossible at the worst. Accordingly, a review was carried out into the expected lifetime of submersible pumps. Unconfirmed reports suggest that, within the UK water industry, the accepted MTBF (Mean Time Between Failures) of electrical submersible pumps is 36 months. This appears to be confirmed (or, more accurately is, perhaps, slightly optimistic) by a figure provided by Gould Pumps for their new e-SV Series of stainless-steel submersible electric pumps which, they claim, has been designed to provide new levels of reliability. The quoted MTBF figure is 20,000 hours which equates to 27 months. The above report relates to high quality water.

The very much higher acidity of mine water, in some geographical regions, and the possible presence of solids in suspension, would place much greater demands on a submersible pump. In discussion with the Coal Authority in the UK, it was suggested that the pumps used to control the water level tended to last between a year and over five years although the former was considered particularly poor. It is pertinent to mention, however, that in the case of one colliery, there was a spate of pumps failing after just six months. It is believed that a contributory factor was blockage due to a build-up of ochre – a family of insoluble iron (II) and iron (III) oxides. Water in UK coal mines is generally not acidic, although the Coal Authority is also responsible for pumping at Wheal Jane, a former tin and copper mine in Cornwall where the water is highly acidic. Here, a lifetime of around two years is considered typical for stainless steel pumps.

Because of the poor expected lifetime of submersible pumps, it was decided that the use of the tube bundle system for sampling water was incompatible with the "fit and forget" philosophy. Accordingly, further work on the tube bundle system both in this task and in Task 4.1 has concentrated in its use only for sampling air from the dry portion of the shaft. By way of contrast, the electronic sensors being researched in WP4 would provide the means of monitoring the characteristics of the water in the shaft. Using this approach, each of the methods of continual monitoring will be used for those aspects of monitoring for which they are ideally suited.

Tube Bundle Requirements

The initial design of the tube bundle, as specified in the Technical Annexe, refers to a three or four component construction, as opposed to the two components design that has been used in working mines. The four component variant is shown in *Figure 10*, the additional one or two components being specified to provide additional protection against the potentially severe conditions in an abandoned mine shaft, and even survive shaft filling operations, bearing in mind the fact that there will be no opportunity to replace sections of the tube bundle in the event of failure. It was eventually decided that a three-component design (including the addition of the yielding protective component but not the inner reinforcement covering) would be adequate, while recognising that, for manufacturing reasons, it might be necessary to have a thin layer of material immediately surrounding the sample tubes. It was also decided at an early stage that a design with a single diameter of sample tubes would meet the design requirements while minimising manufacturing costs.

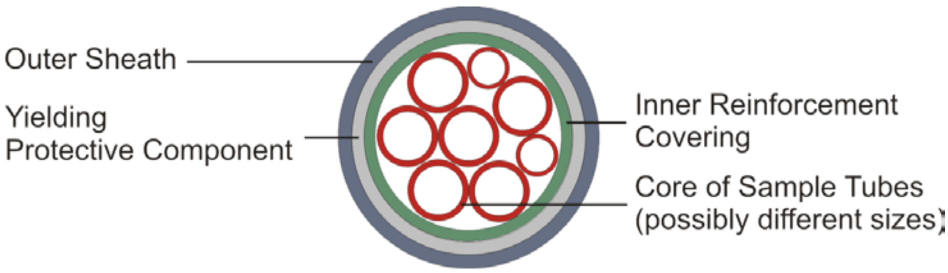


Figure 10 – Initial Design Concept for Tube Bundle

Following a decision about the top-level design of the tube bundle, consideration was given to the properties of the materials required for each of the components, namely the sample tubes, the yielding protective component and the outer sheath. This analysis provided guidance for a final decision on the materials and the design and prototyping of the tube bundle in Task 4.1. The following requirements were considered:

- Static pressure – protection against crushing in the event that the tube is surrounded by compacted filling material.
- Impact strength – protection against falling material and detached shaft furniture.
- Tensile strength – protection against elongation and consequential damage under its own weight, bearing in mind that fixing to the shaft wall isn't feasible although a support rope might be employed.
- Abrasion resistance.
- Chemical corrosion resistance.
- Anti-aging properties.
- Anti-static properties.
- Heat extremes.

Choice of Materials

To meet these requirements, candidate materials for each of the three components were considered in conjunction with a plastics manufacturer with experience of tube bundles for the mining industry (Colex International) and materials scientists from the University of Exeter. In view of reference in the Technical Annexe to consideration being given to newly developed nano-materials – commonly based on new allotropes of carbon such as graphene, and carbon nano-tubes – an initial analysis considered the state-of-the-art. The first conclusion drawn is that although several polymer-nanomaterial composites are available commercially, and have been for some time, they tend to use “conventional” nanomaterials rather than the more recently fabricated nano-materials such as the newer carbon allotropes. Several recent research projects were appraised and while some of these are moving towards small-scale manufacture, the resultant materials are still not available in large volumes and are, therefore, prohibitively expensive for this application. Consequentially, and at the advice of materials scientists, nano-materials were discounted in favour of more conventional materials, most notably polymers. The following analysis discusses the requirements for each of the components and the recommended materials.

Sample Tubes – Because they will be protected by the novel combination of a yielding protective component and an outer sheath, the core of sample tubes might be considered the component that is least challenging. However, because these tubes might be expected to provide reliable service for many years or decades, their requirements in terms of long-term stability is probably more stringent than in the conventional tube bundle systems that are used in working mines. The most obvious requirements are as follows:

- Impervious to the water and air.
- Adequate structural strength, i.e. resistant to crushing, taking into account the fact that they will be protected by the inner reinforcement covering, the yielding protective component, and the outer sheath.
- Related to structural strength is the requirement that the tubes will not become brittle in low temperatures, and hence liable to damage by cracking, something that could occur, in some geographical areas, above the water level, close to the surface.
- Resistant to acid mine water given that the possibility of rupture to the three outer layers would have the consequential effect of ingress of mine water where the shaft intersects with galleries.
- Long-term stability, especially in the elevated temperatures that may be encountered in the deepest sections of the shafts, the operational lifetime being measured in decades.
- As light as possible while achieving the primary requirements.
- As low-cost as possible, while achieving the primary requirements.

Material scientists suggested that PTFE exhibits excellent chemical resistance, UV resistance etc. so is probably the ideal material from a technical perspective but is probably more expensive than is justifiable for this application. Low density polyethylene (LDPE) and nylon (PA12) are used for the sample tubes in most currently produced tube bundles while the options of PE and polypropylene (PP) have been suggested by material scientists. As a cheap plastic, commonly used by manufacturers of tube bundles, LDPE would appear to be a good choice.

Yielding Protective Layer – The following requirements were identified:

- Yielding (compressible) to protect the inner components of the sample tubes and their inner reinforcement covering from crush damage in the event that the outer sheath suffers a degree of crushing.
- Not liable to become brittle and thereby unable to meet its main requirement of being yielding, in low temperatures, something that could occur, in some geographical areas, above the water level, close to the surface.
- Adequate structural strength although, in this case, unlike the other components, given that the material is required to be yielding, the specific requirement here is resistance to tearing in the event of pressure being exerted on the outer sheath.
- Resistant to acid mine water given that the possibility of rupture to the outer layer would have the consequential effect of ingress of mine water where the shaft intersects with galleries.

- Long-term stability, especially in the elevated temperatures that may be encountered in the deepest sections of the shafts, the operational lifetime being measured in decades.
- As light as possible while achieving the primary requirements.
- As low-cost as possible, while achieving the primary requirements.

Some materials can be foamed by injecting gas while manufacturing. However, particular attention has been given to materials that have the required properties inherently. According to material scientists, a fluororubber would meet the above technical requirements while also achieving a good bonding with the sample tubes. However, the cost would probably be too high. Thermoplastic Elastomer (TPE), otherwise known as thermoplastic rubber, and Thermoplastic Polyurethane (TPU) in particular has been suggested. Colex have no experience of the addition of this layer to a tube bundle so they were not able to make any recommendations.

Outer Sheath – The following requirements were identified:

- Good structural strength, i.e. moderately resistant to crushing, taking into account that the primary requirement is to prevent the sample tubes from being crushed and that the properties of the sample tubes themselves and the yielding protective component may be sufficient to achieve this.
- Related to structural strength is the requirement that the sheath will not become brittle, and hence liable to damage by cracking, in low temperatures, something that could occur, in some geographical areas, above the water level, close to the surface.
- Abrasion resistant, perhaps assisted by reduced friction with shaft filling material.
- Resistant to acid mine water.
- Long-term stability, especially in the elevated temperatures that may be encountered in the deepest sections of the shafts, the operational lifetime being measured in decades.
- Anti-static properties to prevent static build up because the potential for initiating explosions in the case of methane build-up. In discussion with tube bundle manufacturer Colex International, it was suggested that it is generally only necessary to provide an antistatic outer sheath in order to meet regulatory constraints although a few customers also specify anti-static sample tubes.
- • As light as possible while achieving the primary requirements.
- • As low-cost as possible, while achieving the primary requirements.

Material scientists suggested that a metal armoured outer sheath would provide the ultimate in strength although there is severe weight (and hence handling/installation) and cost disadvantages. Alternatively, nylon was suggested for its strength and chemical resistance but, because of its tendency to swell in water, resulting in dimensional changes and reduced mechanical properties, PVC was deemed to be a technically better and lower cost option. Similarly, Colex suggested PVC which is the material used in their current products. This is available both as standard grade, flame retardant and anti-static, all three variants having been used previously.

Task 1.5. Selection and Design of Suitable Technologies for Fixed Reference Points and Installation Device

The initial approach using drilling machines and hydraulic supports for installing the reference points was abandoned during the discussion about different models of realisation. The idea of using direct fastening technology became the final design approach for the reference point installation device: A **R**emotely **O**perated **V**ehicle (ROV) carries the direct fastening device. The ROV is launched by a docking station at the operation depth. The docking station is lowered to the operation depth via winch and wireline, and the ROV is run via a well-balanced umbilical (tether). This tether is managed by an underwater winch system. Due to the possible presence of many obstacles inside a shaft, bad visibility in the shaft water, and a water level far below the surface, this practice is required for ROV operation.

The Docking station (Docking Station Submodule – DSS) has to ensure the safe transport of the ROV and installation device through the shaft. The shaft may be partially or fully flooded. The docking station must also manage the ROV operation during the journey to and from the shaft wall. This requires a permanent interaction between the ROV and DSS and several navigation aids.

The docking station comprises the tether winch including 10m ROV tether, a thruster set with 4 thrusters in a 45° arrangement, latches for securing the ROV, several limit switches and junction boxes which comprise different electrical control modules.

The ROV is designed from several commercial ROV components as well as some components tailored to the application. The main pressure cylinders and the thrusters are manufactured by “Blue Robotics” while the buoyancy control device, the bottom junction box and all switches are designed and manufactured by DMT. The underwater connectors are made by “Subcon” micro circular series. The control electronics is also made by DMT.

For test purposes, the payload frame of the ROV is equipped with a dummy installation device, which attaches a reference point using a pneumatic cylinder as an actuator and a magnet for installation.

The DSS operation requires the CIS for power supply, telemetry and control. It requires the GRS for orientation and the PCAS for navigation around obstacles within the shaft.

WP2: Development of Technologies for use in Underwater Conditions

The objective of this WP is to define the guidelines of a common platform to develop the different devices and technologies and the logistics for use in underwater conditions. In a first instance, it has been determined that the power supply and data transmission will be wired with the devices tethered from the surface. The following specific goals have been defined:

- G2.1. Design the mechanical protection (mainly using CAD/FEA tools) of sensors and devices for their use in underwater conditions (protection cases, connectors, etc.)
- G2.2. Test and validate sensors and devices in laboratory and real conditions.
- G2.3. Test mechanical actuators and power supply systems for the underwater installation process.
- G2.4. Implement prototypes to develop sensing techniques.
- G2.5. Define the needs for monitoring and control modules.

Task 2.1. Design of Stability and Control Methods for the Ultrasonic Inspection Module

<u>Stability Analysis</u>

The UIM will include a geo-referencing capability which, in conjunction the cable counter on the winch, will be able to determine the vertical depth in the shaft plus the module’s horizontal position within the shaft’s cross section and the rotational angle of the module. These measurements of the UIM’s position should be able to allow for a compensation of any unintentional movement of the module that might occur during lowering operations, when measuring a shaft cross section using the scanning sonar. However, there was a concern that it might prove difficult to compensate for excessive unintentional movements, should such motion occur. It was also a concern that large amounts of uncontrolled motion, in particular pendulum motion, would increase the likelihood that the UIM would collide with obstructions in the shaft such as pipes, cables, shaft furniture etc. Such a collision could cause damage to the UIM and could even result in its loss if it becomes irreversibly entangled. For this reason, a study was carried out into the likelihood and magnitude of such movements with a view to designing methods of stabilising the module (i.e. reducing the magnitude of these movements) if it was considered that they posed a risk to the accurate and safe deployment of the UIM.

Initially, results obtained in RFCS PRESIDENCE (Herrero et al., 2012), which involved the surveying of dry abandoned mineshafts using instruments deployed using a winch, were reviewed. Four types of unintentional movement were identified, namely rotational, pendulum, spring and “wobble” and the magnitude of these were measured using a test rig. The conclusion drawn was that only rotation and pendulum were significant and the magnitude of these was sufficiently small that pendulum motion wasn’t sufficiently great to pose a risk to the module and adequate corrections to the data could be made using inertial sensors. Similar sensors will be present in the PIMs’ Geo-referencing Sub-module.

Despite positive indication from this earlier project, there are two main differences to the current project. First the PIMs will be deployed in water instead of air, and second, geometric measurements will be made using sonar instead of laser. The relevance of the second difference is that a 360° scan will take longer to complete which, perhaps, places greater constraints on the required level of stability. On the other hand, it is anticipated that damping of unintentional movement motion will be significantly greater in water than in air.

Because of these conflicting differences, a study was carried out into the properties of logging cables, in the light of the fact that the most significant cause of rotational motion is the increasing tension during winching operations. *Figure 11* shows the rotation of a well logging tool during cavern survey, operated at low speed (approximately 2m/min). In this specific case, the logging cable was guided approximately 1300m through an inclined casing. Beginning from the 1300m point, the tool was able to rotate without additional friction. The discontinuities of the rotation may be explained by the friction between cable and casing in the upper part of the borehole. Each cycle of the displayed curve represents a full rotation. There were about six revolutions per 300m (150min). No damping fins were installed at this tool. The tool had a length of 24m, and the tool diameter was 130mm. It can be assumed to have very low forces, acting against the tension of the logging cable.

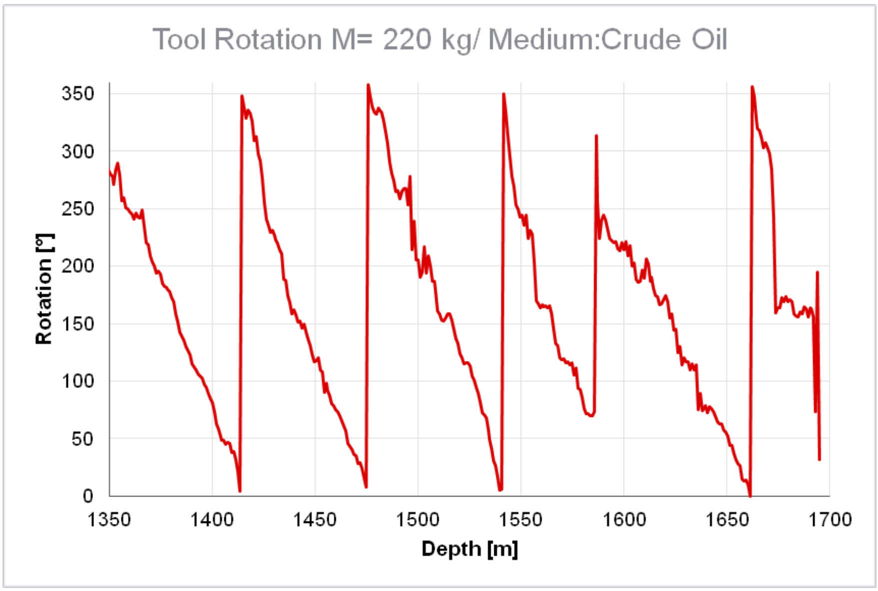


Figure 11 – Rotation of a Well Logging Tool During Cavern Survey

The situation related to the UIM should be much better because this instrument does not have a smooth surface and will, therefore, cause a lot of turbulences which will slow down the rotation. The resulting rotation speed < 0.04 revolutions per minute is very low compared to the profiling scan speed of approximately 4 seconds, so the disturbance of the acquired scan is less significant.

<u>Stability Recommendation</u>

In the light of this study and the fact that a degree of passive stabilisation has resulted from the choice of the most suitable logging cable, it was decided that further stability control methods – especially active techniques – were unnecessary. This decision was influenced to a large extent by the amendment to the rationale of the UIM, namely that it should be designed to offer as low-cost solution as possible. In this respect, if the geo-referencing hardware indicates that unacceptable levels of pendulum motion are occurring, rather than having previously invested in expensive active stabilisation hardware, it is a more cost-effective solution to suspend winching for a short period of time until the motion has subdued. It is also planned to study the degree of unintentional motion experienced during the early phases of the field trials with a view to adding some form of passive stabilisation such as fins or baffles, should it be deemed necessary.

<u>Obstacle Detection</u>

Although the likelihood of the UIM coming into contact with debris in the shaft increases with the magnitude of any unintentional movement, such a risk exists even if no such motion occurs. In particular, the module will be at risk from collisions into obstructions immediately below it while it is being lowered into the shaft. Accordingly, it is a requirement that the UIM is able to detect obstacles immediately below it so that the winch operator can suspect winching.

Study of this subject started with an appraisal of the type and amount of material that can be expected in abandoned mine shafts. CCTV footage of inspections of dry mine shafts in several countries was reviewed as shown, for example in *Figure 12*. The presence of cross members and horizontal sections of cables and pipes were identified as areas of particular concern because of the threat they posed to entanglement.

Figure 12 – Stills from Footage of Shaft Inspections

Although the main purpose of the STAMS project, and hence also of the Periodic Inspection Modules (MMM and UIM), is to monitor the flooded sections of abandoned shafts, some of these modules will also make measurements or observations in the dry portion of the shaft above the water level. Irrespective of which portion of a shaft a module is intended to monitor, though, that module will have to pass through the dry section of the shaft before it reaches the flooded section. Accordingly, methods of collision avoidance were studied that were applicable to both the dry and flooded sections of a shaft.

Several candidate methods of obstacle detection were identified and studied. Included here were optical methods, metal detectors, mechanical “feelers” and sonar devices. Note should be made, however, of the fact that the scanning sonar device to be included in the UIM is not suitable for obstacle detection because it faces horizontally in order to collect shaft cross-sections. Devices for obstacle detection, on the other hand, must face vertically down to detect obstacles below the module which could pose a risk if downwards winching were to continue. Note should also be made of the fact that it is considered unnecessary to detect obstacles above the module. This is because the option of suspending winching does not exist as it does with downwards winching if the module is to be removed from the shaft.

Of the methods investigated, none were considered effective in both the dry and the flooded portions of the shaft, indeed some were not considered suitable at all. Accordingly, a decision was made to employ two obstacle detection devices.

For the dry portion of the shaft, a decision was made to use a visible light CCTV camera with an integral white or monochromatic light source. The camera will point vertically down the shaft. Although this will only be used above the water level, the instrument will, of course, be submerged during the operation of the UIM so it is necessary to choose a marine grade instrument which is waterproof to an adequate depth.

For the flooded portion of the shaft, a decision was made to use a sonar altimeter which will point vertically down the shaft. Unlike the scanning sonar which will be used in the UIM, a sonar altimeter’s transducer points in a single direction, thereby giving a signal, which is interpreted as the distance to the closest object within its field of view.

Task 2.2. Appraisal and Selection of Protective Cases for the MMM and UIM

<u>Multi-functional Monitoring Module (MMM)</u>

At the stage of considering protection measures against water and pressure, it was assumed that several components, due to its commercial purpose, will be adequately waterproofed and won’t need protective cases. Super Wide-i Seacam cameras, SeaLite Six LED backlights and Kongsberg Mesotech scanning sonar, which are instruments that MMM is equipped with, can operate up to 6 000 m depth. Other devices must be included in casing to protect it from the ingress of water and moisture.

In order to check the possible geometric solutions for the casing of MMM a FEM (Finite Element Method) optimisation modelling was performed. To perform such optimisation a parametric computer model representing the analysed geometry was build using the Ansys numerical modelling software. The model was used to investigate the influence of input parameters on the total mass, internal volume and maximum stress level in the examined model.

Chosen casing has a form of steel cylinder with a screwed cover. Inside, power, control, registration and transmission systems are placed with its wiring. There is, moreover, second function of the steel housing. All of the external elements and devices are installed on it. All the connectors, cable glands and contraction floats are installed on the lid. The steel cylinder is enclosed by the frame that hangs under the cable clamp. Moreover, there are three arms connected to the frame, on which cameras, backlights and sonar are mounted.

Ultrasonic Inspection Module (UIM)

For the UIM, a decision on whether to protect each of the instruments individually or to use a single pressure-resistant protective case for all the components was simplified by the decision to develop various common sub-modules. In this respect, the geo-referencing hardware and the communications interface and power supplies have been developed as separate sub-modules so they will be independently waterproofed to an adequate pressure. A decision was only required, therefore, for the instruments that constitute the Profiling and Collision Avoidance Sub-module and, here again, the decision was removed in the light of the fact that off-the-shelf components have been used. Two of these instruments – namely the profiling sonar and the sonar altimeter – are intended exclusively for use underwater so are adequately waterproofed. This leaves only the CCTV camera for which there is a modest price premium associated with using a marine grade instrument which has its own in-built waterproofing.

The work concerning the specification of the power supply, power and data cables and connectors that was originally scheduled in this task has been carried out in other tasks because it is closely associated with work on the surface equipment and the Cable Interface Sub-module (CIS). This, therefore, is reported elsewhere.

Task 2.3. Design and Analysis of the Mechanical System to Install Permanent Devices in a Flooded Shaft

Different technological approaches were considered (RFID tags, EM propagation, ultrasound transmitter) for the fixed reference points (RP). Initially, the most attractive technology was the RFID, as it is passive and does not require batteries. However, it was proved that this technology is not suitable for underwater conditions due to scattering of the signal: it would require large Reference Points and antennas.

The alternative suggested was the use of easily recognisable 3D shapes that can be detected by an ultrasonic sensor like the used by the other modules. The design of the mechanical system was critically conditioned by the design of the reference points.

The design of the mechanical system was also highly changed respecting the original design. The original concept design suggested a commercial underwater hammer drill, with a camera and a LED system (*Figure 13*), with the counteracting (neutralizing the reaction forces) of the percussion being based in passive stabilization plates. However, this presented many disadvantages, like the design of the counteracting system, which would not be compatible with all shaft diameters. Also, the forces caused by a hammer drill would be difficult to compensate, so this alternative was also discarded. The proposed design was the use of an underwater robot (which could freely navigate through the shaft water), carrying a direct fastening tool for fitting the reference points. Direct fastening presented many advantages like the power consumption and the counteracting forces, which are much lower and easier to compensate by the underwater robot (*Figure 13*).

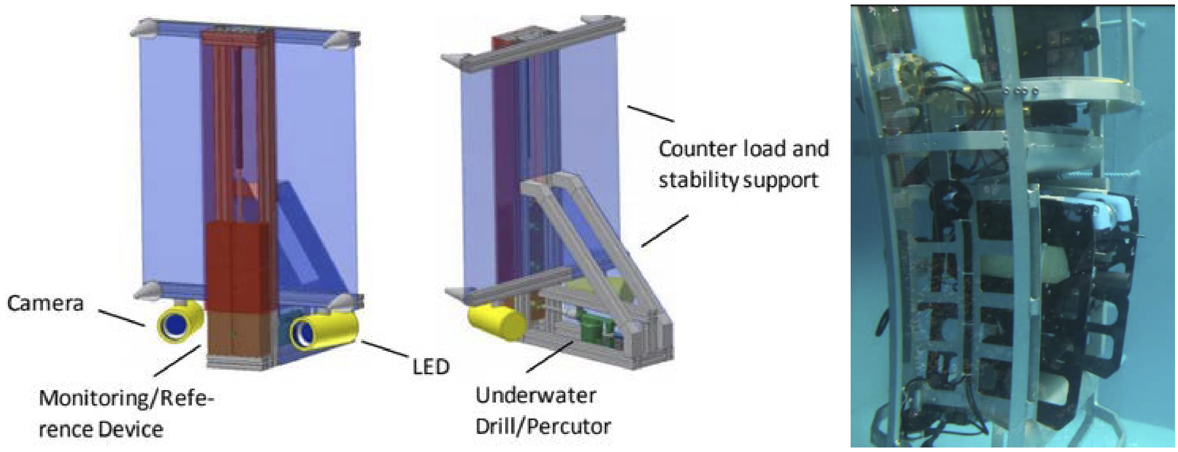


Figure 13 – Original vs. Final Design of the Installation Device

The direct fastening system for installing reference points in STAMS is loosely based on a smokeless-powder-operated bolting gun by HILTI (*Figure 14*). HILTI system is composed of a six-barrel “gun”, which fires hardened steel bolts using special (water-tight) blank cartridges. However, HILTI gun is designed to be hand operated, requiring manual arming, manually pushing it against the target and then firing by pulling the trigger, being very difficult its remote operation. On the other hand, the basic idea was interesting, as the system do not require a long drilling time, where continuous force is applied, as when using standard drilling machines.

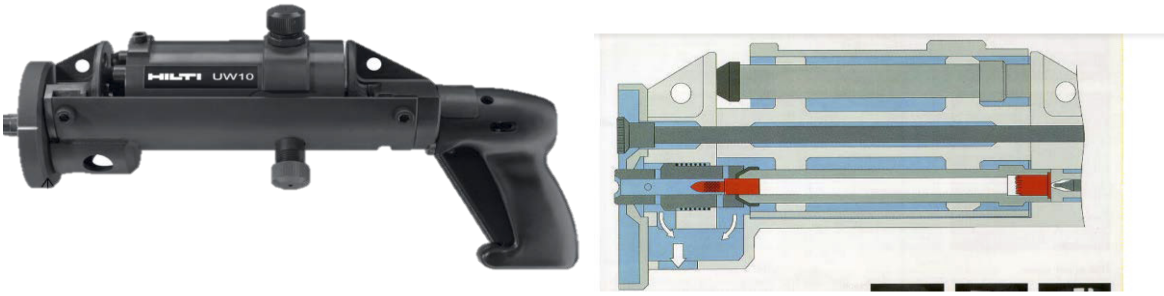


Figure 14 – HILTI Gun and Internal Diagram

After a careful analysis, it was decided to use HILTI's barrels and nail/bolt as core of the bolting system. For completing the system, the following components had to be developed:

1.- An electrically fired cartridge.

2.- A breech block having electrical contacts, and a watertight connector system.

3.- A remote control system for firing the cartridges was used for the tests, although it may be replaced in the future by an equivalent system. It is composed of a base master unit and a remote slave unit, which apply energy to the ignition elements of the cartridges. Communication between master and slave units is made using a Power Line Communication (PLC) modem. The unit selected, a commercial OFDM PLC, 2-wire modem implementation by BlueRobotics, allows to extend the operating range of an Ethernet link to about thousand meters across cat5/ cat6 cables.

For DSS and ROV operation this connection has to be exchanged to a separate power- and RS485 connection, because the commercial Blue Robotics modem cannot communicate across the wireline due to the facts described under Task 3.1.

4.- A reinforcement system for the reference points, composed of an aluminum tube and an aluminum "head", where the bolt is nailed (*Figure 18*). The head has 6 openings drilled to allow the escape of powder combustion gasses.

The **cartridge** layout and some pictures of its manufacturing process are presented in *Figure 15* and *Figure 16*. It contains a printed circuit board (PCB) with the ignition device, soldered to case. The central point is connected to a wire, exposed in the back of the case, and is sealed with epoxy glue. Then, the ignition device it is smeared with a priming compound, powder is measured and loaded, and the mouth crimped. Finally, the front of the cartridge is sealed with epoxy glue.

Figure 15 – Cartridge Design and Manufacturing

Figure 16 – A Hilti Nail/Bolt with Brass Sabot, a Sealed Cartridge and a Barrel with Breechblock

The operation of the system is like that of HILTI gun. A bolt is loaded in the barrel, a cartridge containing the propellant is placed in the chamber and then the breechblock is used to close the device (*Figure 17*). The reference point with the reinforcing tube is placed in the barrel, electric connectors pushed in place, and the system is ready for firing by the remotely operated control system.

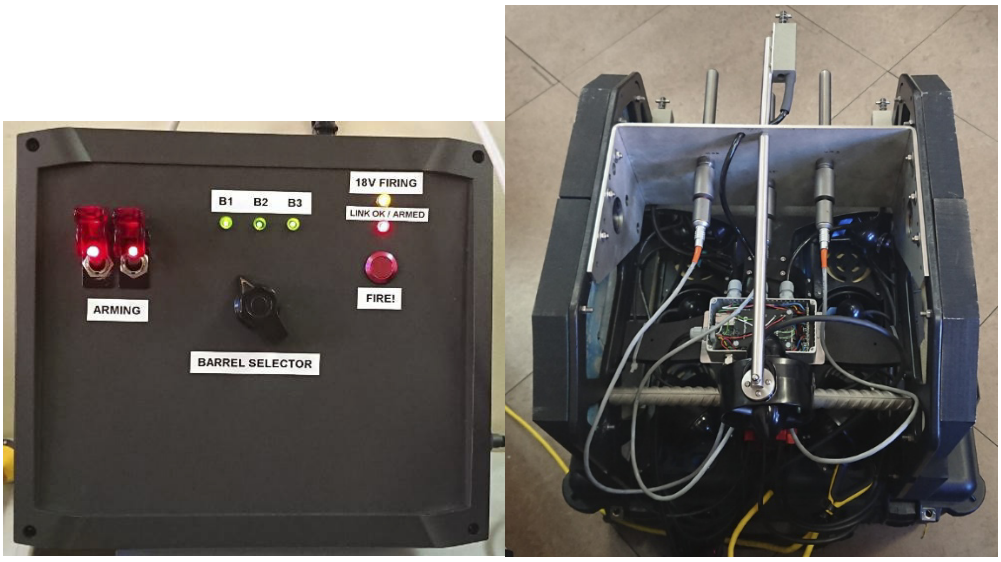


Figure 17 – Master firing control unit (left) and bottom view of the ROV (right), with the slave firing control unit (centre), barrels, limit switches (far side), the additional thruster (near side) and buoyancy panels on the sides.

The slave unit also has interfaces for reading the state of three limit switches (provided by DMT), used to verify that the position of the ROV is correct (that it is close enough to the wall) before firing. All circuits are enclosed in an aluminum box and potted in silicone gel for waterproofing.

Feedback on the state of firing control outputs and limit switches is provided by the slave unit. This information is presented visually through LEDS and forwarded by a serial link to the control computer. Finally, several dry nailing tests were successfully performed in the lab, in preparation for underwater tests (*Figure 18*).

Figure 18 – Lab ("dry tests") setup. The RPID barrels and firing system have successfully nailed several RPs supports on a solid concrete surface. Left upper image: two RP fixed in the concrete. Left down: details of the head and internal cylinder that reinforces each RP. Right image: video capture of the frame just at shooting time.

The ROV technique, described above, was used for installation device tests without the docking station and the corresponding ROV which differs from the Blue Robotics one. The following describes the ROV and docking technology, developed within the STAMS project:

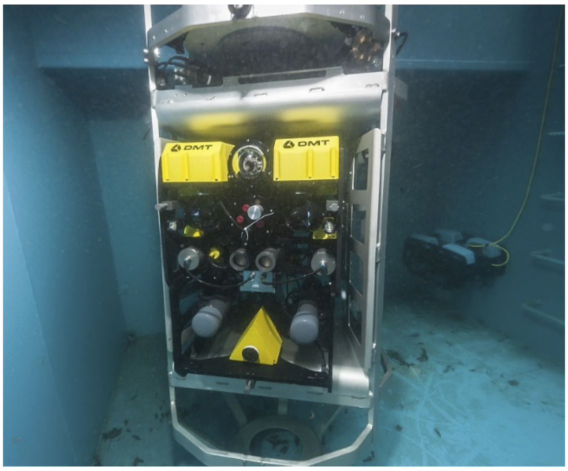


Figure 19 – ROV Inside the Docking Station

The ROV- DSS combination, was developed within this project in order to achieve an optimal performance for shaft wall marking or investigation. Due to the CIS telemetry technique, it is possible to lower the RPIM by a wireline with minimal horizontal movement. The winch operator has to watch to the GRS and the PCAS data and must stop the winch before a potential collision occurs. Autonomous functions are not currently implemented for the run in or run out procedure, but such a function may assist the operator in the future. Once the RPIM is below the water level, the horizontal position can be corrected by the DSS thruster set, but it is not recommended to use this option to pass obstacles.

Devices for autonomous ROV operation in marine environments cannot be used in shafts, because the conditions are very different. Because of the bad visibility, high-resolution sonar systems must be used in shafts for online localization and online mapping. But these systems will not work properly in shafts. The shaft wall will generate multiple reflections from the sonar pulse, which will disturb the sonar image. It would be possible to develop a specific system, but that is time consuming and expensive. For that reason, a different technique was applied for semi-autonomous ROV operation, aided by a docking station, depth gauge and a sonar displacement indicator. Using the DSS technique avoids operating the ROV within a full 3D environment. If the DSS is lowered to a working area that is scanned beforehand using the PCAS – scanner, the ROV has to operate in a depth range of +/- 1 m related to the DSS face and in a small horizontal range related to the DSS face. The DSS is always rotated autonomously to the planned working direction of the ROV. The ROV pilot has only to initiate the single processes:

- Set and stabilize DSS direction
- Launch the ROV
- Initiate autonomous trimming
- Start the mission to the shaft wall
- Set the reference Point
- Return to the DSS
- Finalize the docking procedure by closing the Latches

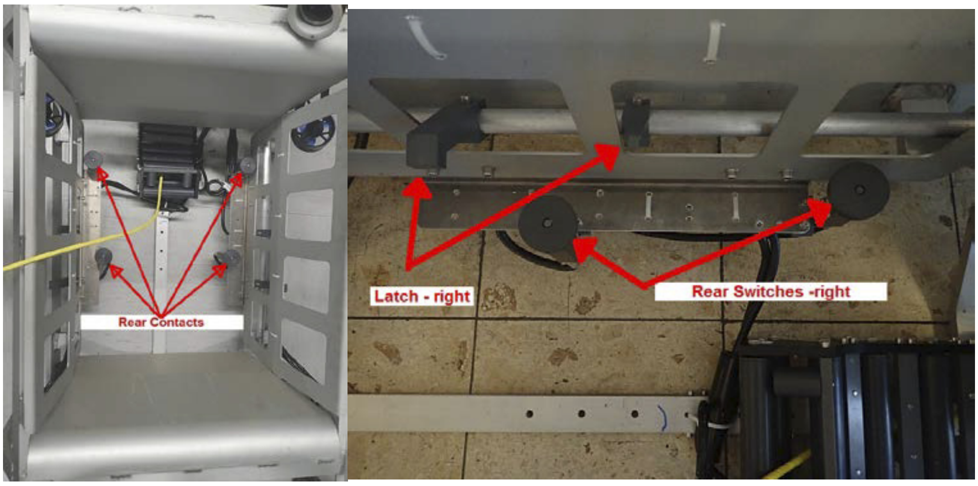


Figure 20 – Left Side DSS Face & Rear Contacts; Right Side Latches and Switches

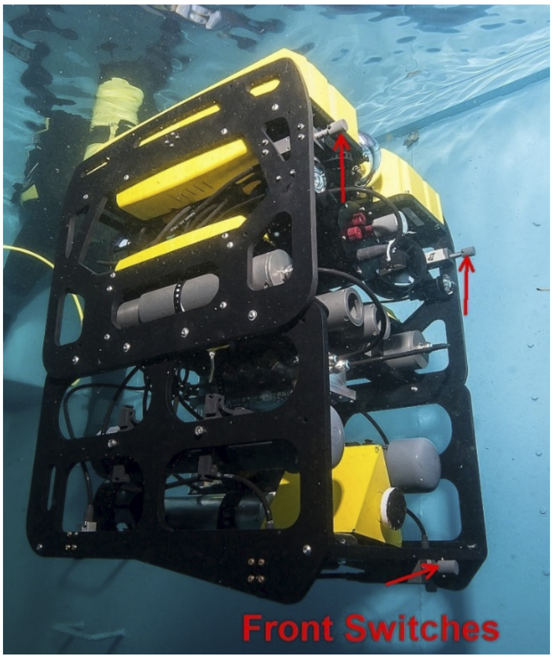


Figure 21 – Location of Front Switches on the Floating ROV

The necessary information of the ROV status and the DSS status are generated by different sensors/ switches. The ROV front switches detect the contact to the shaft wall. These switches can indicate weak contact and full contact. The ROV bottom switches are used for the buoyancy adjustment as well as the docking procedure. If the ROV is back in place or if it is fully docked, this will be indicated by the rear contacts of the DSS. All this information is displayed on the common control interface (*Figure 22*).

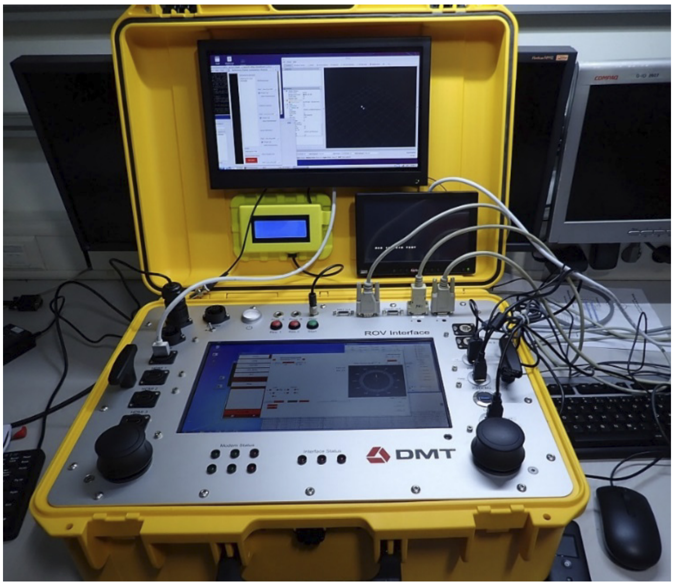


Figure 22 – Common Interface

Figure 23 – Screenshot: Control Menu

Figure 23 shows a screenshot of the common control menu for RPIM operation. All status information and main control functions are available on this screen. The autonomous ROV control may also be invoked at this menu (heading and depth stabilization). This interface, including the software for DSS and ROV control, status display, and autonomous functions, was also developed during the project, below, demonstrates the functionality of the system features. The ROV is launched and straightens the tether whilst the tether winch spools out the tether in pre-set intervals until the ROV reaches the shaft wall.

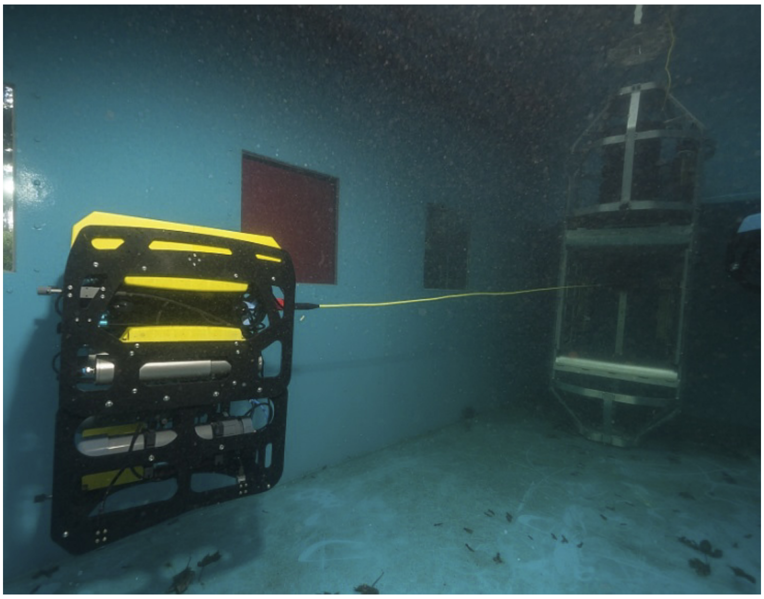


Figure 24 – ROV Launched, En-Route to the Shaft Wall

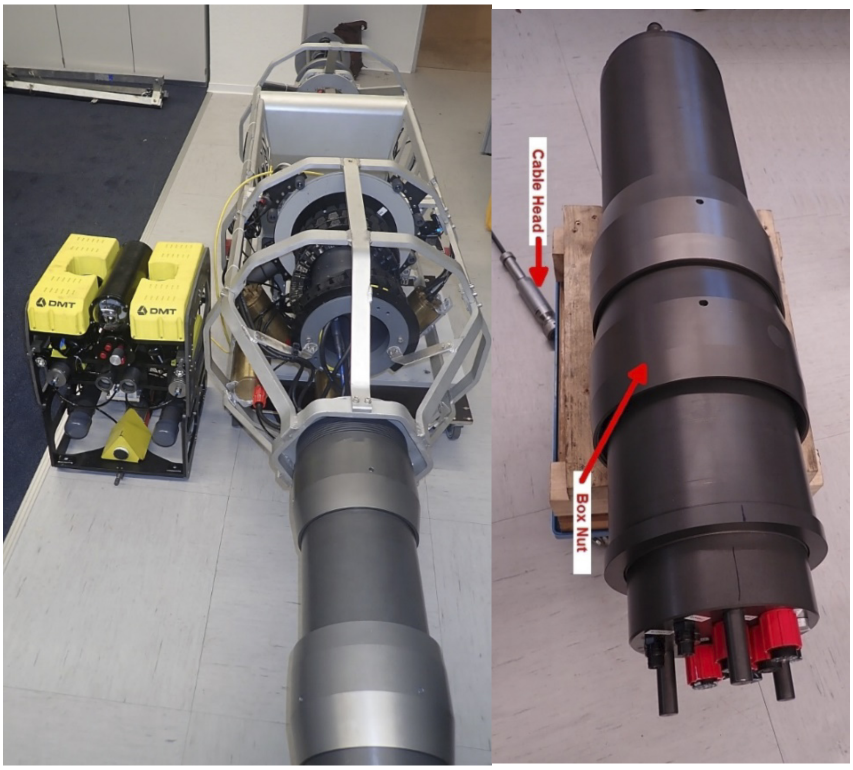
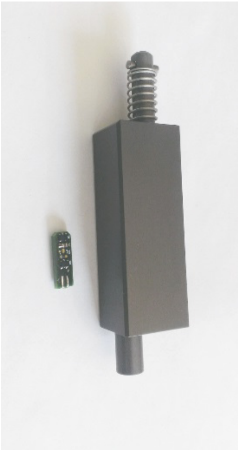


Figure 25 – RPIM complete *CIS & GRS*

These tasks also included several special developments, like the design of pressure feedthroughs, limit switches, magnetic pickups for position control, high pressure junction boxes and a tether winch without slip rings, all for operation depth up to 1500 m.



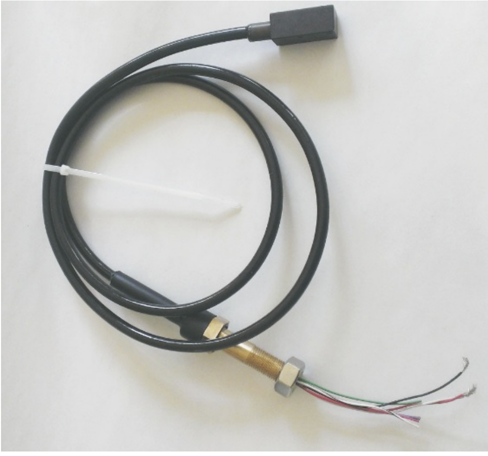


Figure 26 – Left: 2 Stage Switches; Middle: Magnetic Pickup; Right Pressure Feedthrough

The main design aspect of these components was the reduction of seals. Each seal increases the risk of leakage. For that reason, the limit switches (*Figure 26* left) are designed as electronic Hall –sensor switches, where the electronic components are molded directly to the connection cable within the switch block. The piston for position detection has a magnet inside which passes the molded sensors inside the switch block. These switches can be configured either as 2-stage switches or as linear sensors for precise position monitoring. These switches are installed in the ROV as Front contacts and tension detector, inside the DSS as rear contacts and inside the DSS as tether tension detector.

The magnetic pickups (*Figure 26* middle) are constructed in the same manner: a small Hall- sensor PCB molded to the connection cable inside the detector block. The open ends of the connection cables are molded directly to the high-pressure feedthroughs or cable penetrators (*Figure 26*; right), which are fitted to the penetrator plates of the junction boxes.

All high-pressure components are pressure tested at 200 bar, to ensure a safe application within the 1500 m Range. For small items the test equipment, shown in *Figure 29*, was used. The side indicated by the red arrow is the pressurized side. As the 200-bar test was finished with positive results (200 bar – 15 min.) the penetrator was tested up to the maximum allowed pressure of the test equipment, which is 550 bar, in order to determine the maximum working pressure of the penetrator. The penetrator was still ok at 550 bar. It was not possible to destroy the penetrator with the available equipment.

A further special development for the ROV shaft application was the static buoyancy control system. Four motor driven units can adjust the ROV volume by 250 cm^3. This buoyancy is realized by 4 motor driven pistons, which compress the air at the drive side and take water into the cylinder at the outer side. The arrangement (*Figure 28*) also allows the ROV to be trimmed in its pitch axis. The drives are fitted to the pressure range of the other ROV components, and they can operate up to 20 bar external pressure, corresponding to 200 m of fresh water. This buoyancy control is required, because the salinity of the shaft water may vary between the different shafts and the ROV cannot be trimmed manually if the water level is not at the ground level. It would not be possible in accordance with safety criteria.

Figure 27 – Motor Piston Combination

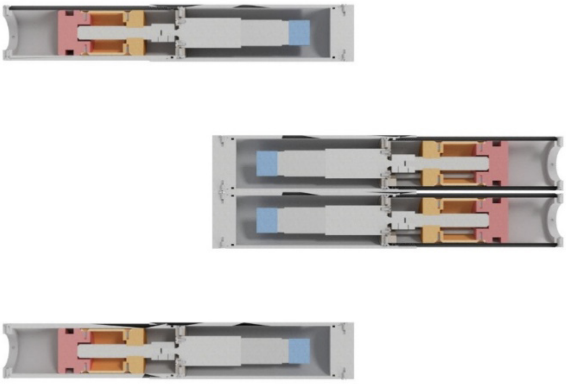


Figure 28 – Buoyancy Control Cylinder Arrangement

Figure 29 – Pressure Test Equipment

A “chassis / sleeve” design, like the CIS and GRS housing was used for the junction box construction. This design allows the full installation of the junction box interior on junction boxes with penetrator plates on both sides, before it is closed by the outer pressure sleeve. Other housing designs require a preinstallation of the interior and extended connection cables to the second penetrator plate. The cables must be stuffed into the box, before the housing is closed.

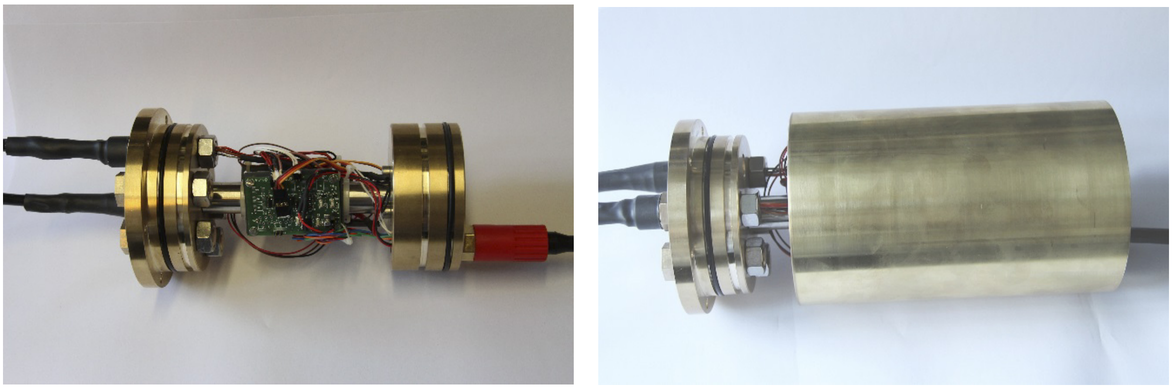


Figure 30 – Junction Box, Two Penetrator Plates

Figure 31 – Junction Box Set, Manufactured in the STAMS Project

Another sophisticated item was the tether winch design with a minimum number of seals. The aim is to allow as many moving parts as possible to be operated without pressure tight penetrators. First, DMT selected special water-resistant tether guide “Twister Band” from the IGUS Company, which allows a double drum technology. One drum is for carrying the tether connected to the ROV, and the second drum is for carrying the tether section which is wound in the opposite direction. *Figure 32* shows the prototype tether winch at the first underwater test. This test was essential for the development process, because the Twister Band was used beyond the normal specification. Normally the Twister Band has to be used with a lower number of turns, and in a standard application the “Twister Band” is not floating. The test has demonstrated perfect performance under these very special conditions. This kind of spooling allows the inner tether to be connected to a fixed connector, instead of connecting it to slip rings.

For driving the drum, a special water-resistant worm gear was selected, which can be fully flooded. Thus, no seal was required here either. The only O-ring sealed item is the winch drive motor axle. On principle, a magnetic coupling could be used here in order to avoid a seal at rotating parts. However, the commercially available magnetic couplings did not fit into the design, because of the required torque value.

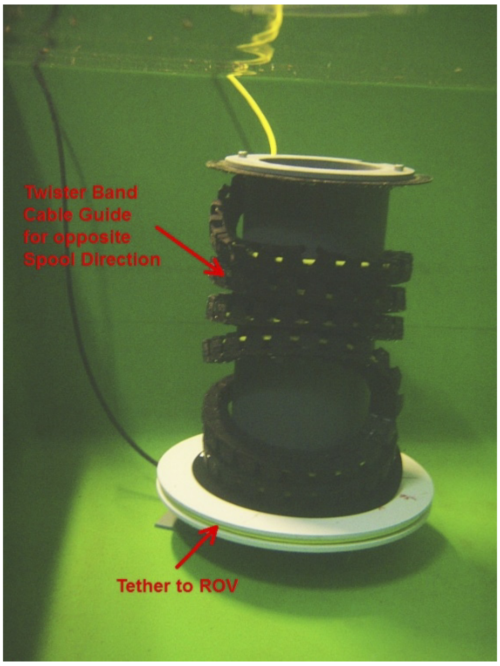


Figure 32 – Tether Winch Test

Designing the latch drive was less complicated. The latches have to hold the ROV in place during all spooling operations of the wireline winch. No high forces will appear here, so the torque values are low for the latch movement. DMT selected as a latch drive the M200 motor from the Blue Robotics Company. These motors are external rotor motors, and they are brushless DC motors. This motor type doesn't need any seal at rotating parts, because the rotor is a ring of magnets and the stator carries the coils. The coils are coated with a special resin and are molded to the connection wires. Due to bearings made of synthetic material, the M200 motor can be flooded.

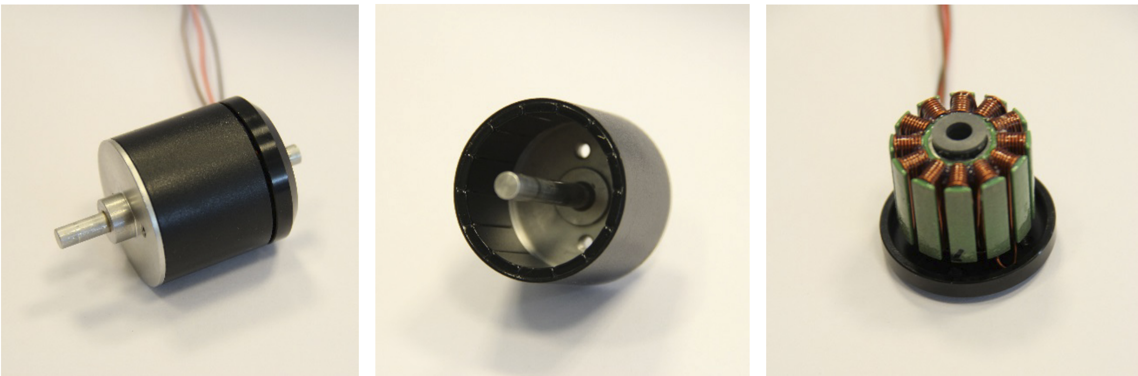


Figure 33 - M200 Motor

The output torque of this motor type is enough to drive the floodable worm gear, which was also used for the tether winch design. This led to the latch design, shown in *Figure 34*.

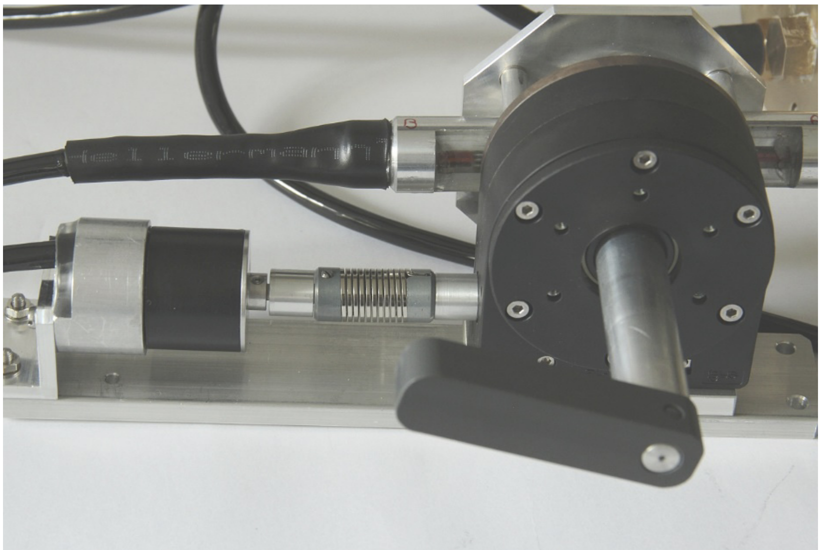


Figure 34 – Latch Detail

The back plate of the worm gear is equipped with two magnets, which are detected by the magnetic pickups as described before. This sensor / magnet arrangement is used for latch position control. The control electronics are placed inside the winch – latches junction box. This junction box (*Figure 35*) receives its commands directly from the CIS.

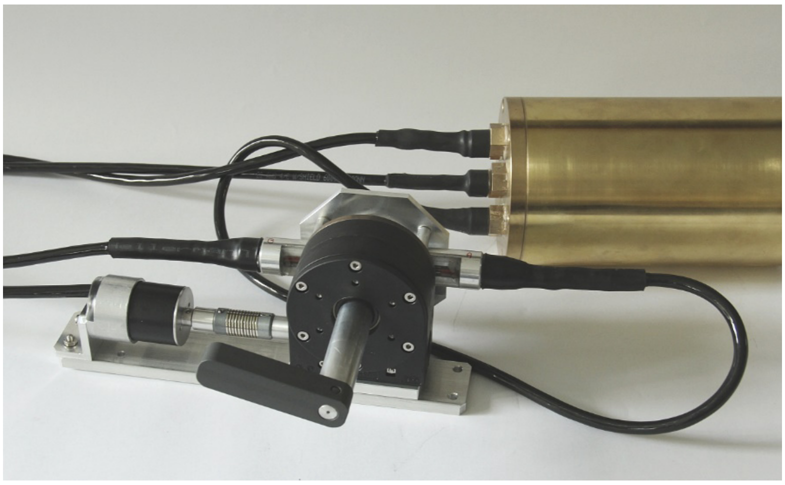


Figure 35 – Latch & Junction Box

The integration of the components described above into the overall system is shown in *Figure 36*.

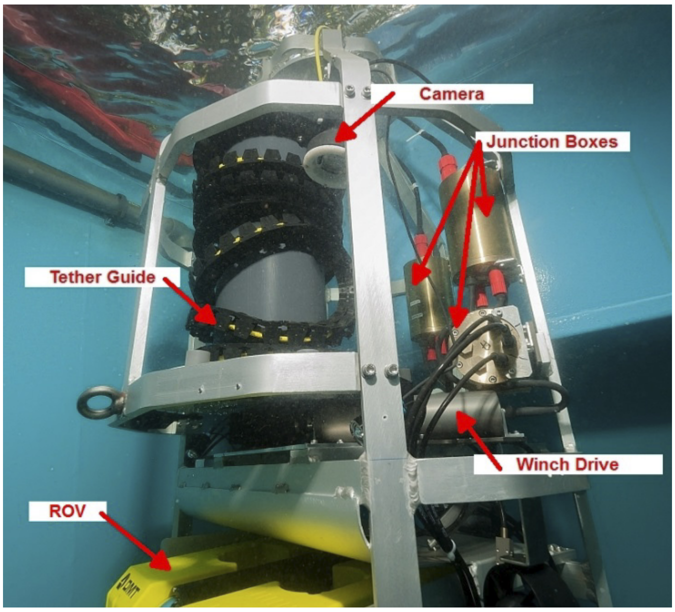
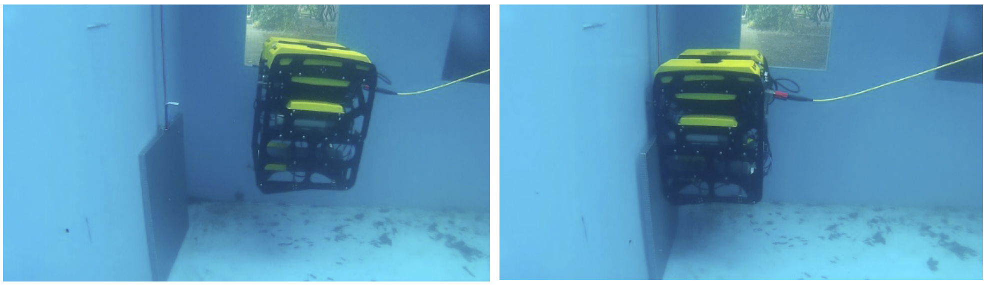


Figure 36 – DSS Top

The overall function of the RPIM was tested, using the dummy installation device, shown in *Figure 37*.



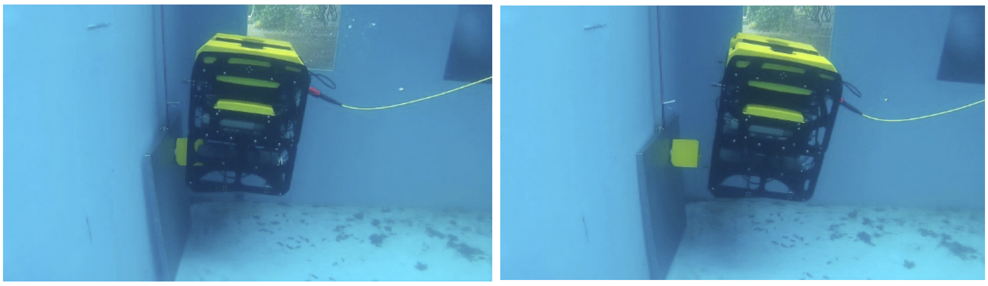


Figure 37 – Installation Procedure (Screenshots from latest Movie)

<u>Alternative fastening method, plan “B”</u>

As a “Plan B”, studies were made in order to collect some facts for the drilling method. These studies should clarify whether it is possible to use drilling techniques for the reference point installation, should direct fastening fail. Another point to be clarified is what would be necessary in order to drill, should there be the chance to do so. The initial question is about the necessary propulsion for a drilling process using a hammer drill, if drilling in concrete. Next is the question of centring the hammer drill. First, a “dry” test facility was installed in a DMT laboratory (*Figure 38*). The test bench was equipped with a pneumatic cylinder for applying a constant force to the hammer drill, a load cell, a position sensor and a pressure gauge. The accumulator powered hammer drill from the Hilti Company was fixed on a liner guide for the first test. At the end of the linear guide, a concrete block in the 100 kg range was installed.

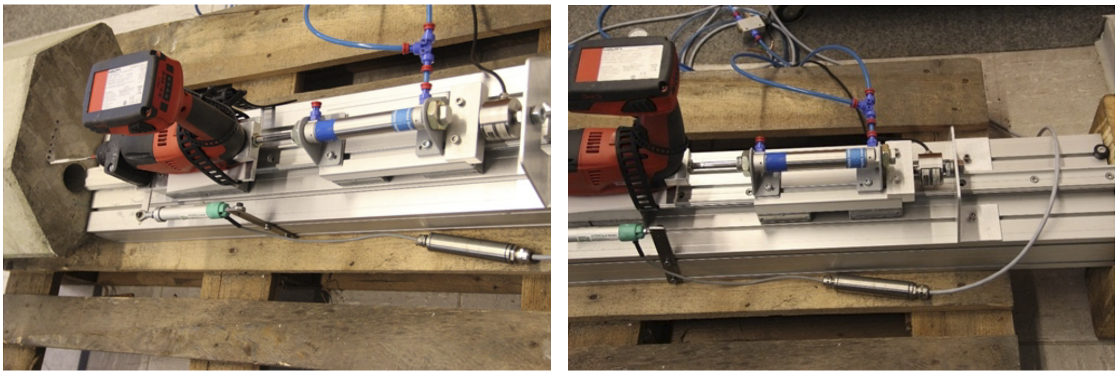


Figure 38 – Test Bench

Figure 39 shows a required force of about 50 N before the drilling process starts. Later on, it was demonstrated that the drilling performance is better if the pressure is applied as a sharp pulse. Several experiments led to the diagram shown in *Figure 40*. Applying a sharp pulse of about 80N delivers a repeatable performance. As explained above, the propulsion was generated by a pneumatic cylinder. An additional test was executed to ensure that the planned thrusters perform as well.

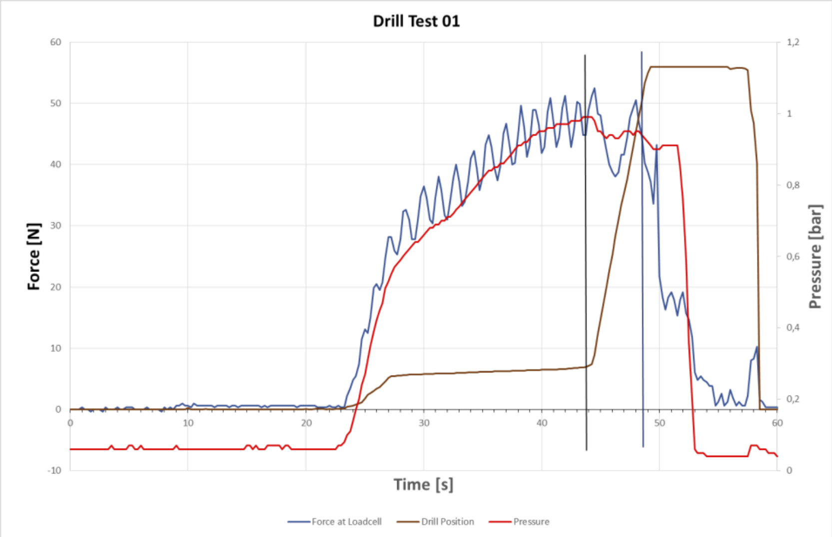


Figure 39 – Linear Increasing Pressure

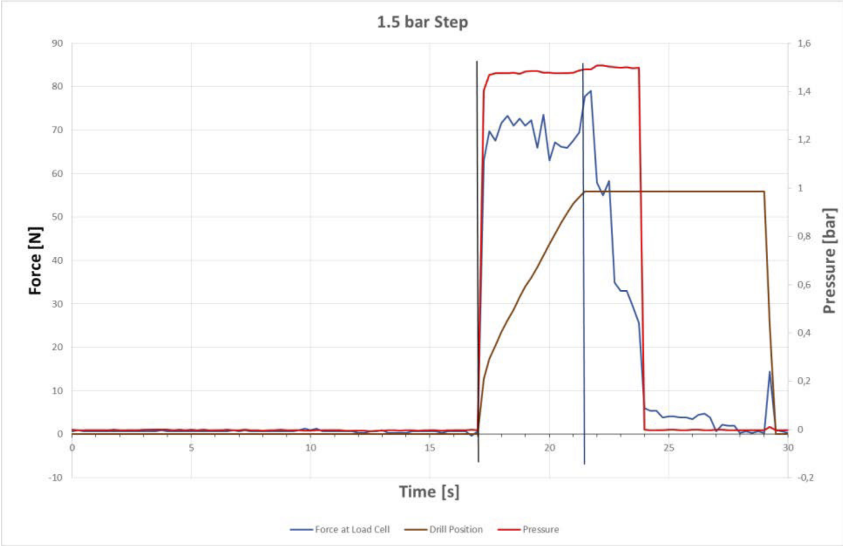


Figure 40 – 80 N Step

The hammer drill was mounted inside a watertight enclosure, the drill bit was extended by a seal zone, and a cover penetrator with integrated seals for rotational and axial movement was designed and built, for a thruster drill test.

Figure 41 – Hammer Drill Encapsulated

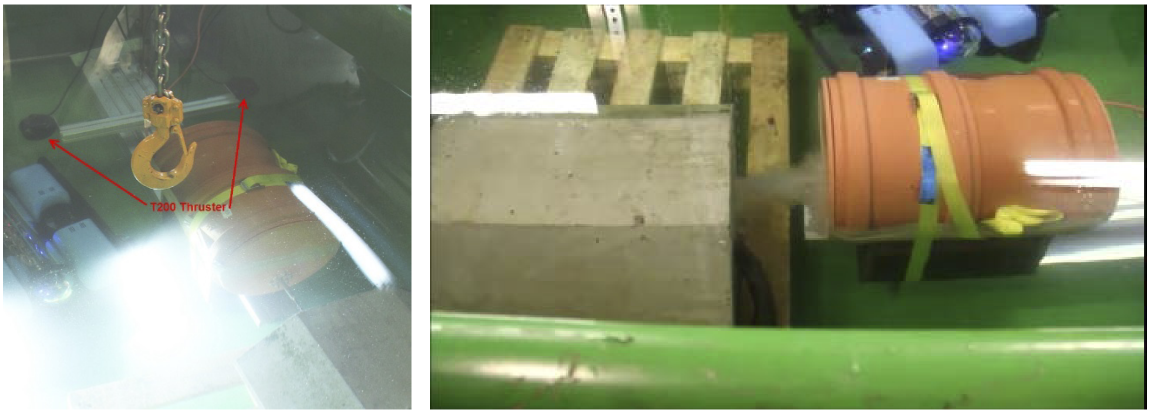


Figure 42 – Underwater Drill Test

The tests were performed with about 70 % thruster power from two T200 Thrusters. It took about 8s to drill 50 mm into the concrete block. The drill bit diameter was 6 mm for this experiment.

Figure 43 – Misaligned Concrete Block

The question of centring could be answered by repeating the experiment with different angles between test bench and concrete block. Acceptable drilling results could be achieved between +/- 5 ° and +/- 10° of misalignment. These results were not really repeatable, since depend heavily on the tip of the drill bit. A self-centring method has to be applied for repeatable drilling results.

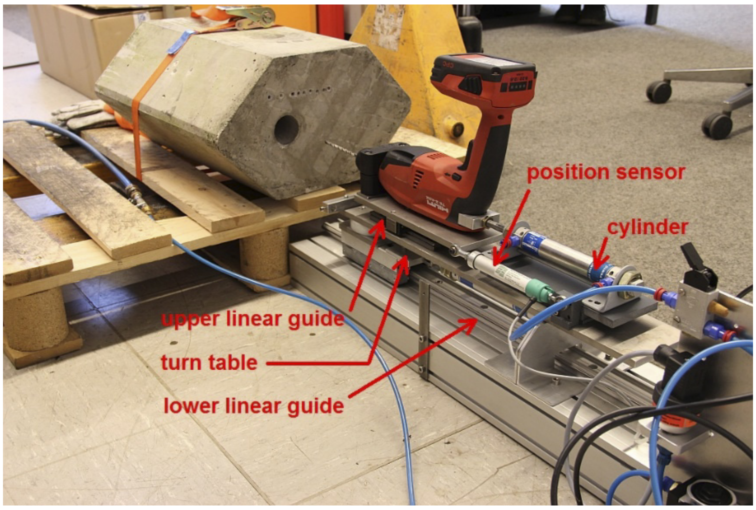


Figure 44 – Self Centring Test Setup

In order to test self - centring of the hammer drill, the hammer drill was installed on a second linear guide on top of a turn table with two guiding pins. The pneumatic cylinder which supplies the propulsion for the hammer drill is also installed on this upper linear guide. The lower linear guide simulates the ROV movement. This linear guide can also turn, and shift left and right. If an axial force is applied now to the lower linear guide towards the concrete block, one of the guiding pins will touch the concrete block first and the turntable rotates until the opposite guiding pin touches the concrete block, too (*Figure 45*). This set up forces the hammer drill always into a perpendicular direction with respect to the concrete surface.

Figure 45 – Self-Centring Process (Screenshots from Movie)

This experience led to the final ROV design. The ROV has three of these guiding pins; they are realized as spring loaded front contacts. If one of these contacts touches the shaft wall, the ROV operator must initiate the installation procedure. The first ROV action is to execute a forward shift by increasing the thruster power to 80% and to activate the bottom auxiliary thrusters. This strong forward propulsion forces all front contacts to touch the shaft wall. If all contacts are indicating full contact, the bolt can be steed, or the drilling process can start.

The next task was the identification of a hammer drill technology for under water drilling. There are two basic principles available: pneumatic hammer drills and hydraulic hammer drills. Some hydraulic ones are already designed for underwater applications, but these are heavy machines with external hydraulic power supplies. These machines exceed the ROV size and payload.

The pneumatic hammer drills are very common and there are some on the market which can be used up to 50 m of depth, which is again not an option for the project. Thus, an investigation of the hammer-drill performance in pressurized situation was started.

The tests were carried out in the laboratory in a dry condition. The setup was similar to the former drill tests, except for the hammer drill housing. The hammer drill was installed inside a pressure chamber (*Figure 46*).

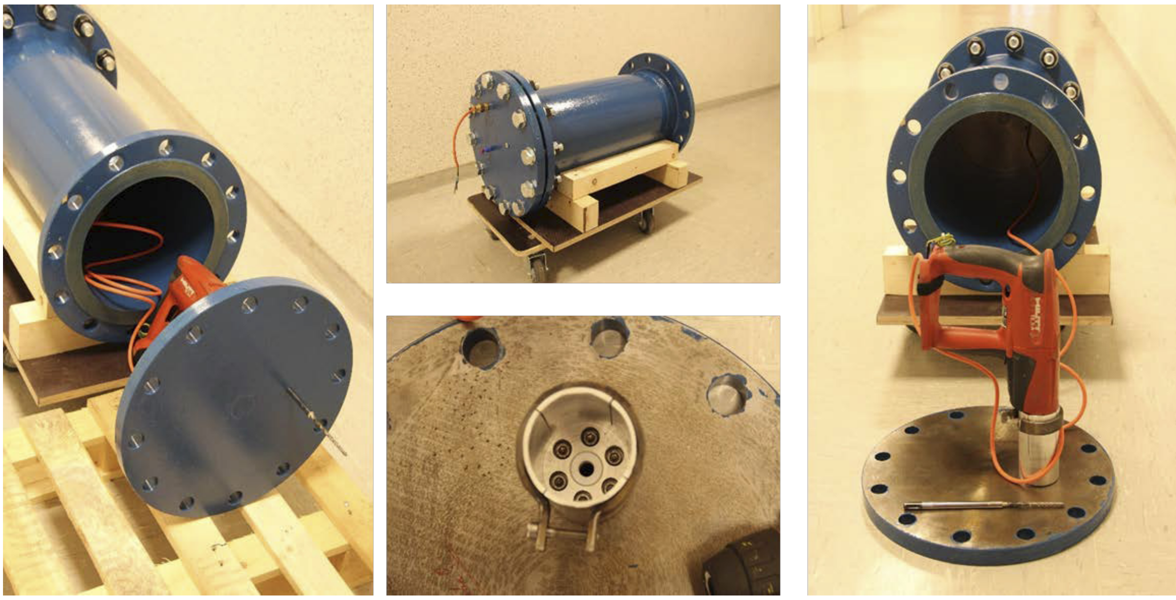


Figure 46 – Hammer Drill & Pressure Chamber

The intension was to compensate the axial force, which is generated by the hydrostatic pressure, by a counter pressure from the inside. The initial experiment has shown a good performance with increasing axial load. However, the axial bearing inside the hammer drill will not work up to 1500 N. This force appears using a drill bit shaft of 12 mm at a depth of 1500 m. 1500 m of water column is the demand from the STAMS proposal. The following diagrams show a decreasing performance with an increase in compensation pressure. The decreasing performance is indicated by the increasing drill time, which is the time between the vertical black bars.

This problem can be solved by using a pressure compensation within the penetrator between outside pressure and atmospheric pressure. DMT has been applying this compensator type for many years as feedthrough in borehole tolls for rotating drive shafts. They will not work for a hammer drill because the drill bit is undergoing linear movements as well as rotational ones. For that reason, DMT did a redesign of their compensator to allow linear movements as required for the hammer drill.

The result is shown in (*Figure 50*) This compensator was tested up to 200 bar. Only an increasing friction was detectable during the experiments, but it was still possible to push the drive shaft at 200 bar pressure inside the pressure chamber by hand into the chamber.

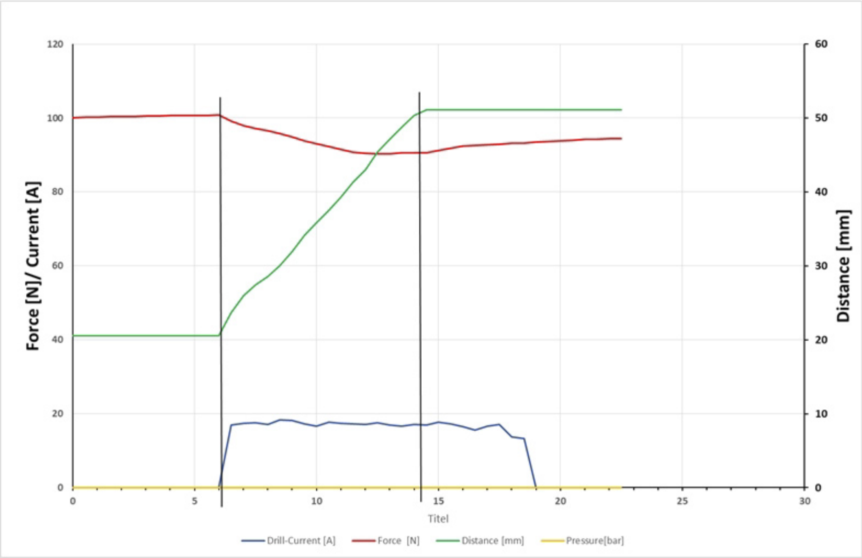


Figure 47 – Without Compensation

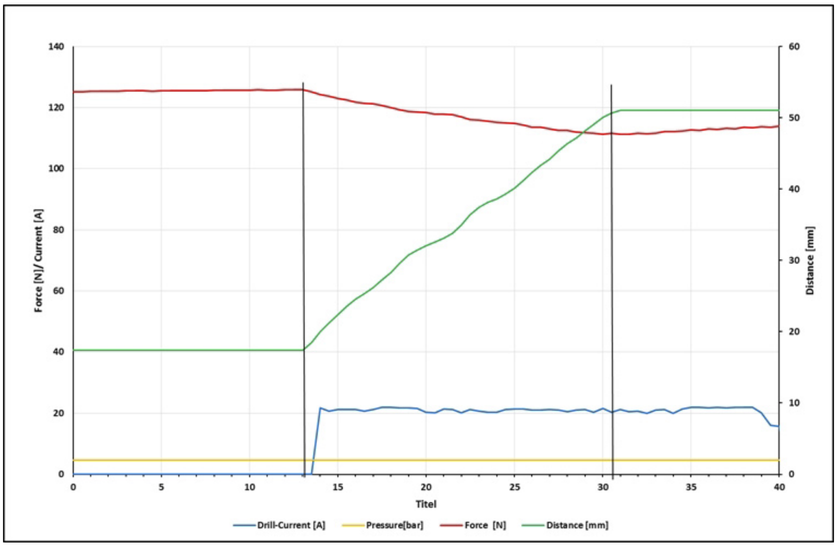


Figure 48 – 4.6 bar Compensation

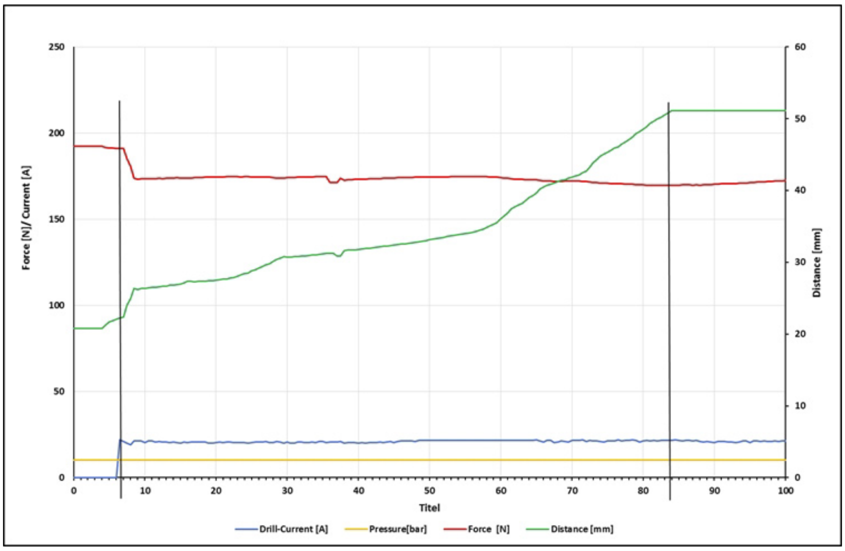


Figure 49 – 10 bar Compensation

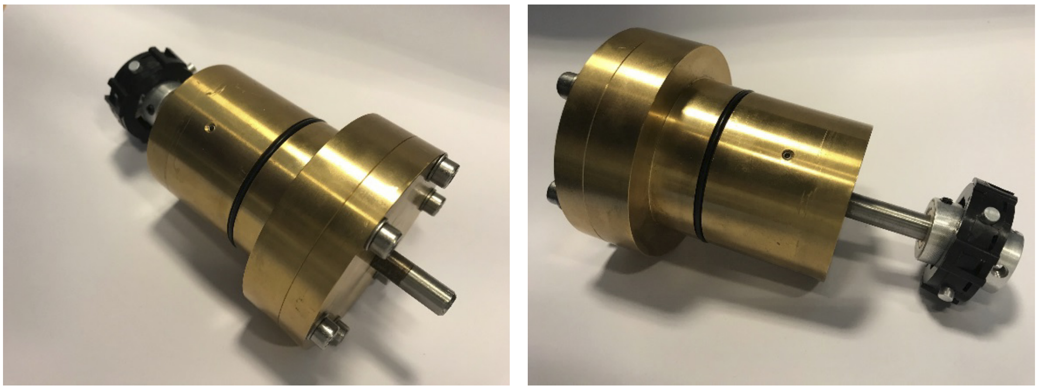


Figure 50 – Compensator (Pressure Compensating Penetrator)

Task 2.4. Definition of the Specific Requirements of a Software Based Analysis Tool, Data Transmission and Acquisition Needs

The software analysis tool was required to allow the preliminary real-time assessment and subsequent analysis of the conditions of the shaft; and control the inspection process of each of the modules. This means that it not only has to acquire the information from all the sensors – including the Multi-Functional Monitoring Module (MMM), Ultrasonic Inspection Module (UIM), fixed measurement modules and the Reference Point Installation Module (RPIM) – but also has to control the process of inspection of the modules and the installation of fixed devices while work is in process.

Each of the modules was required to have a compatible communicating system with well-defined formats for exchanging messages, defined by rules and conventions using open communication protocol standards. It was decided to use open protocols and data formats supported by open-source software, which allowed the developing of software with open-source tools.

In this task, all these mentioned conditions were considered, plus an analysis of all the sensors used in each module, that the software needed to take into account. It was decided to have three different interfaces for each of the separated modules: One for the MMM, one for the UIM, and one for the RPIM. Plus, a first appraisement on the possible design of the software interface and the operation modes for each module was presented.

WP3. Implementation of Periodic Monitoring and Inspection Modules

This WP focused on the design and prototyping of two periodic inspection modules, integrating the sensors, technologies and solutions developed in previous WPs for monitoring flooded shafts. In addition, an approach will be developed to assess the long-term stability of flooded shafts by the analysis of gaseous atmospheres and the chemical composition of the water. The following specific goals have been established:

- G3.1. Design and implement a Multi-functional Monitoring Module for flooded shafts
- G3.2. Design and implement an Ultrasonic Inspection Module for flooded shafts
- G3.3. Design and Implement a water analysis instrument and gain an understanding of gas indicators.

Task 3.1. Prototyping of Multi-functional Monitoring Module

The two approaches for providing the necessary level of waterproofing for the periodic inspection modules were analysed: (1) to protect each of the instruments in the modules individually, and (2) to use a single pressure-resistant protective case for all the components in the modules.

The MMM unit (*Figure 51*) was planned to be composed from third-party sub-assemblies and components developed by Central Mining Institute. At this stage of the development it was assumed, that the MMM would be designed in several sub-modules and that waterproofing is required for several components that cannot be enclosed in the cases used to house the Multi-functional Monitoring Module (MMM). Both the light sources and cameras we have chosen can operate up to 6,000 m depth. Thus, the cases are required for the power, control, registration and transmission units only.

The two approaches for providing the necessary level of waterproofing for the periodic inspection modules were analysed: (1) to protect each of the instruments in the modules individually, and (2) to use a single pressure-resistant protective case for all the components in the modules.

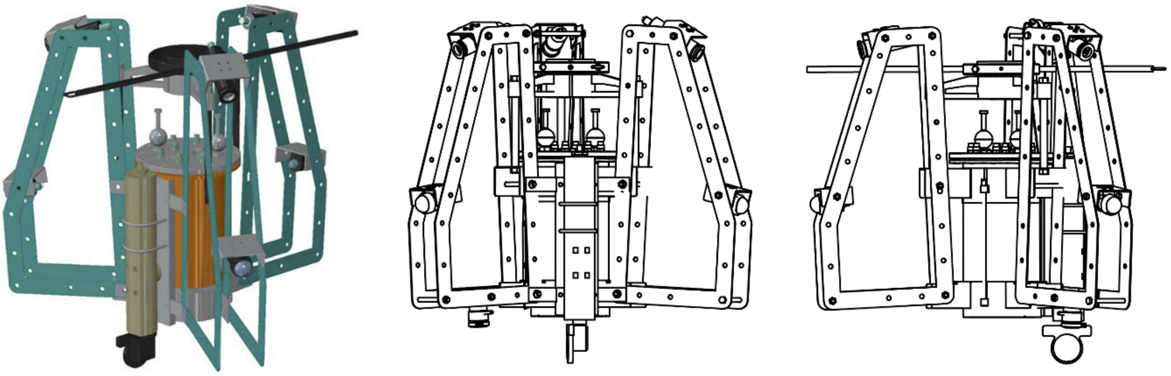


Figure 51 – Visualization and Drawing of the Multi-functional Monitoring Module (MMM)

The casing, a steel cylinder with a screwed cover, protects the devices inside from the ingress of water and moisture. Among the devices installed inside, there were:

- DSL Ethernet Extender,
- Mini PC (Intel NUC Skull Canyon i7-6770HQ/16GB/256SSD/Win10X),
- Storage battery (LiPo 30000mAh 22.2V 6S1P 25C, TATTU),
- Digital Video Recorder.

RLY-8-POE Ethernet Relay Controller. Power for the measuring device is supplied by the MMM battery. The energy is distributed through a set of power supplies and the Ethernet controller allowing individual power circuits of backlights (each separately), a recorder with a set of cameras, computer and sonar. The Ethernet splitter and RLY controller are supplied immediately after the probe is submerged in water.

The recorder carries out the recording of video images from cameras and simultaneously transmits images to the surface using an Ethernet signal. The PC is responsible for controlling and recording sonar data. Data preview on the surface is possible via a remote desktop. Mini PC, video recorder, controller and power packages are mounted on a mechanical core, inserted into the head's casing container (*Figure 52*).

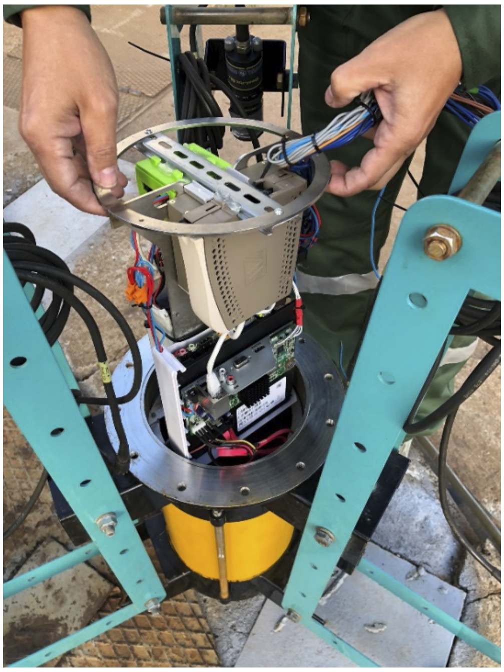


Figure 52 – Panel of Devices Mounted in a Mechanical Core, Located in the Steel Casing

Beside the devices listed above, the rest of instruments are installed outside the steel cylinder casing, that is a base for the arms. Those are connected to the sockets on the casing cover by means of connection wires and listed below:

- 3 Super Wide-i Seacam cameras,
- 3 SeaLite Six LED backlights,
- Kongsberg Mesotech scanning sonar,
- Micron – Tritech Safety Mechanical Scanning Sonar.

The sonar operates on a frequency in range from 600 kHz to 1,5 MHz and enables the highest resolution image. It is designed for inspection of underwater constructions where the highest resolution and sharpness parameters have priority over other parameters. The device can increase the sampling rate of the data, the receiver bandwidth and the transmitter power, and to emit narrow horizontal beam for the fan transducer. The type of transmission is automatically detected and configured. The sonar head is controlled by the MS1000 sonar software.

Thanks to the possibility of folding extension arms, it is possible to use the probe for testing in shafts with different diameters and to adjust the distance of the devices from the brickwork. Depending on the size of the shaft, the arms can be unfolded, or mounted vertically or completely dismantled. Lowering the probe down the shaft takes place safely without the risk of damaging the elements, e.g. through the openings of small shaft flaps.

Communication, data transmission and control between the probe head inside the shaft and the control panel on the surface takes place thanks to the transmission of low-voltage control signals and transmission through copper wires in the cable. Transmission of the signal from the probe via cable is possible due to the use of a non-skid electric rotary coupling coupled to the shaft. The connection is made via a DSL network between two modems, the first of which is located at the winch of the mobile distribution box with other measuring and control elements, and the remaining one is installed inside the probe casing.

The modem processes signal generated in the Ethernet router located in the control panel so that it can be transmitted by means of a cable. Two wires are doubled to improve the signal quality because the DSL modem uses two wires and four are present in the cable. Modem in the probe converts the signal inversely - from two wires to Ethernet. The connection between the devices is shown in *Figure 53*.

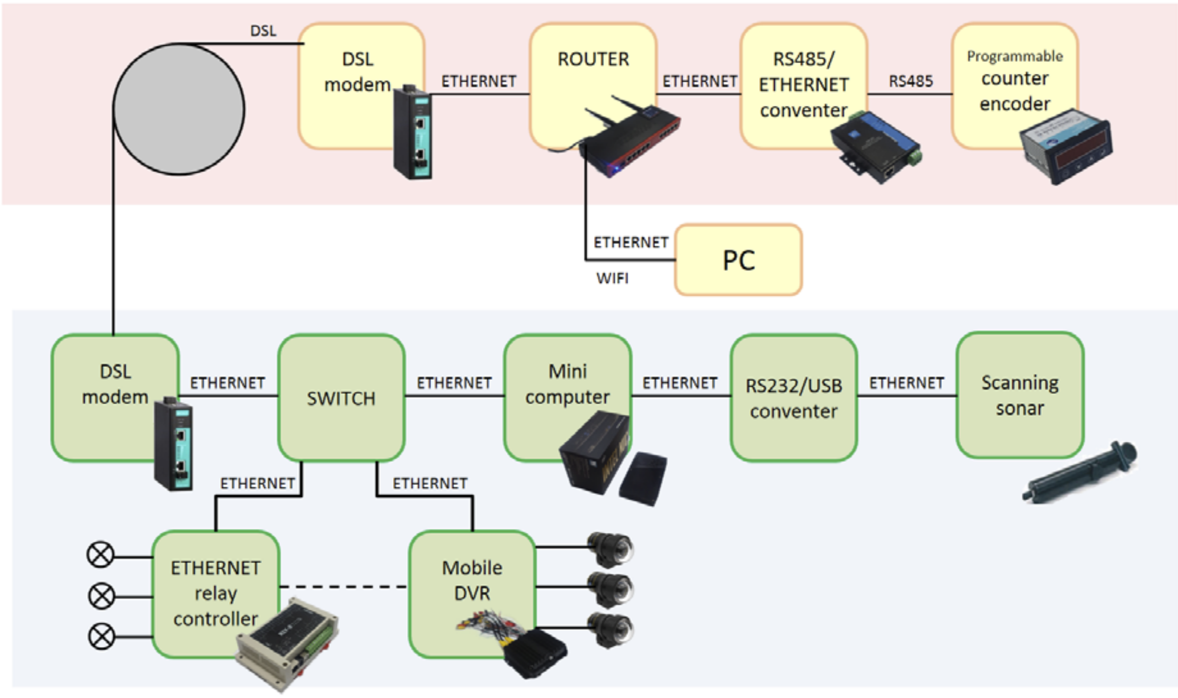


Figure 53 –Connection Scheme Between Devices

Cameras, backlights, echo sounder and sonar are connected to the sockets on the casing cover using connection cables. The DVR carries out the recording of video images from cameras, and simultaneously transmits images to the surface using an Ethernet signal. Mini PC is responsible for controlling and recording sonar data and transmitting data previews to the surface, which is possible by using a remote desktop.

The most crucial instrument in the module, due to poor visual conditions in underwater part of shafts, is the scanning sonar. Therefore, the choice of the type and model of scanning sonar was based on a thorough research. The distinction between the UIM and the MMM has evolved since the start of the project. Because the MMM is larger in diameter than the UIM, the UIM will be useable in shafts with a small access port in the cap. Moreover, it has been decided that the UIM should be developed as a lower cost device for organisations who only require geometry measurement and who cannot afford the much higher cost of the MMM.

Despite the potential difficulties with using imaging sonar hardware in the shaft environment, and despite the decision to use only a profiling sonar in the UIM, the decision of using both profiling and imaging sonar hardware in the MMM was made. This is in recognition of the higher budget for the MMM and a desire to fully characterise the potential of imaging hardware.

During Prototyping of Multi-functional Monitoring Module (MMM) a field condition test was conducted. It took place at the KWK PIAST, Ruch II in #1 shaft in November 2017. It was set in underwater conditions. The undertaken procedure was to submerge probe in the water. First lowering was carried out with the empty case (depth of 190 m), the second lowering - with electronic equipment (40 m).

During the tests, number of issues were encountered, namely, problems with a proper connection between probe and PC, interference in sonar image from its housing, malfunction of cable stacker. Addressing those was urgent and intervention works have been initiated immediately.

Solving the problem of interfered sonar image was a reason to make modification of the MMM. It was decided to uninstall the steel sonar casing (*Figure 54*).

Figure 54 – Disassembling of Steel Sonar Protection Frame

In addition to the original task, a telemetry system has to be developed which can be operated with all submodules and with different types of cable. This decision was made in an early project phase, because the cable situation was not clarified. The most popular solution for data transfer for shaft measurements are logging cables, called “wirelines”. These wirelines are used for all well logging applications all over the world. The wirelines have a double layer steel armor. One layer is wound clockwise around the inner conductors and the other layer is wound counter clockwise. This cable construction reduces the tool rotation during the spool process, and it reduces the tool rotation if the tension increases. The inner cable construction differs. The most common types for logging are 4 conductor or 7 conductor wirelines. Meanwhile, the number of coaxial or fiber optical cables are increasing. These wirelines, except the coaxial and fiber optical ones, have the common disadvantage of poor transmission performance. *Figure 55* shows the frequency response of a 7 conductor 7/16” cable, which is a typical choice for heavy load applications.

In order to be able to use as many of these cable types as possible with the shaft inspection tools with high data output, a special telemetry module must be developed.

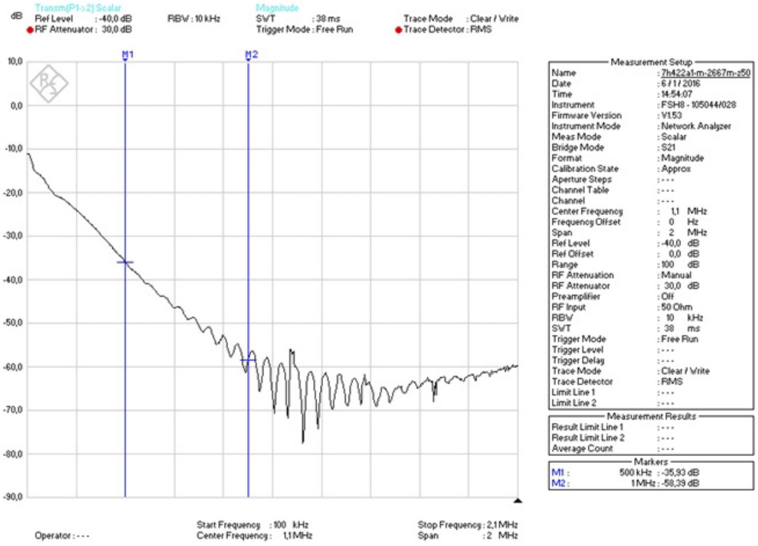


Figure 55 – 7 Conductor 7/16" Wireline Frequency Range

The technological base of this modem is the so-called OFDM technique, well known from telecommunication systems. The available systems based on this technique are not useful for this specific wireline application because the carrier frequency cannot be tuned to the required low frequencies at the lower channels. DMT had developed a similar modem for seismic applications, but the operating frequency range was also not useful. This DMT modem was decided to be the base for the wireline telemetry because it offers the facility of modification, independent of the big chip manufacturers.

Basically, (*Figure 56*) the carrier frequency (red) is phase modulated by the signal (blue), which results in the output signal (green).

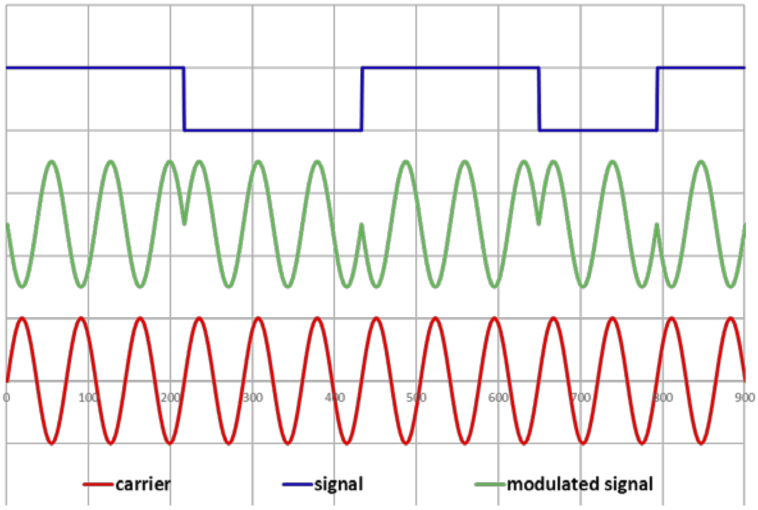


Figure 56 – Phase Modulation

The OFDM technique uses multiple carrier frequencies, in this case 32, representing the 32 data channels. If, as shown in (*Figure 56*), the 0° phase and 180° phase of the carrier frequency is used, each channel will transmit one bit, so 32 bits can be transmitted in parallel. The developed system can handle 4 phase conditions of a single carrier frequency that allows the transmission of two data bits via one carrier frequency. This principle is shown in *Figure 58*.

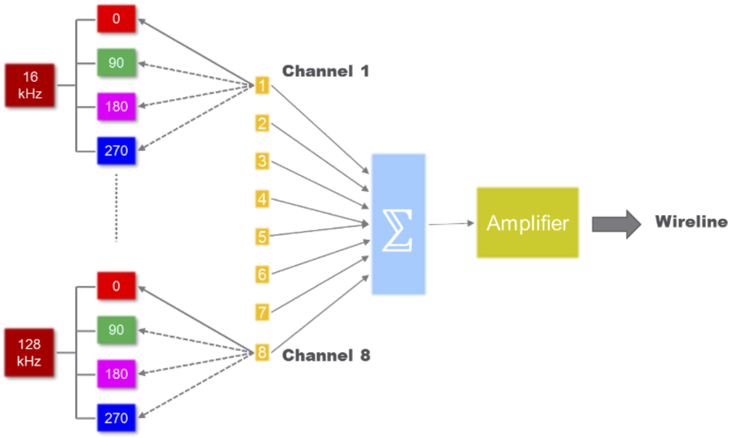


Figure 57 – OFDM Scheme- 8 Channel Demonstration

16 bit data word	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
QPSK coding	0	0			0°											
	0	I			90°											
	I	0			180°											
	I	I			270°											
Channel distribution	1		2		3		4		5		6		7		8	
	16 kHz		32kHz		48 kHz		64 kHz		80kHz		96 kHz		112 kHz		128 kHz	

Figure 58 – Data Transmission Scheme

The resulting hardware (*Figure 59*) is implemented in the CIS. The modem software automatically adapts the number of channels to the wireline performance during the startup phase of the OFDM modem. If a stable connection between CIS and Surface unit is established, three data links are available: One Ethernet UDP link and two serial links with 115200 baud. Within the CIS, one serial link is reserved for the high-volume GRS data and the second serial link is multiplexed for the different tasks and submodules. The UDP link is multiplexed to the PCAS camera, the ROV camera or the docking station camera.

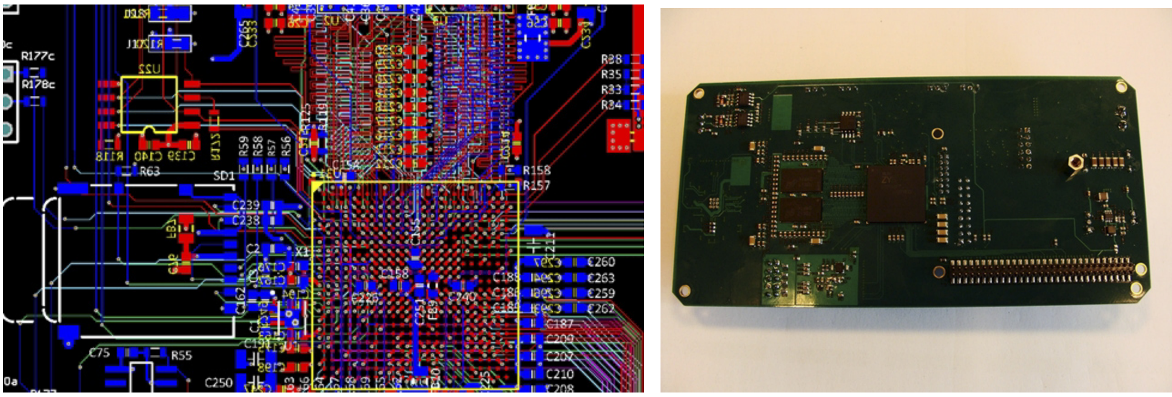


Figure 59 – OFDM Modem

The described modem is, next to the power supply, the main component of the CIS, and it is one of the common modules within the project. The CIS housing is developed in the same style as the GRS housing (D2.1), but instead of the top thread it is equipped with a standard 1 ½” GO-7 tool top.

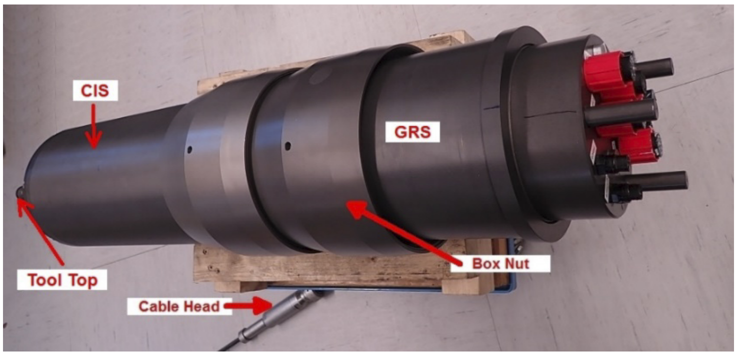


Figure 60 – GRS & CIS Connected

Beside these main components three microcontroller systems are handling commands and data from the surface unit and the other submodules.

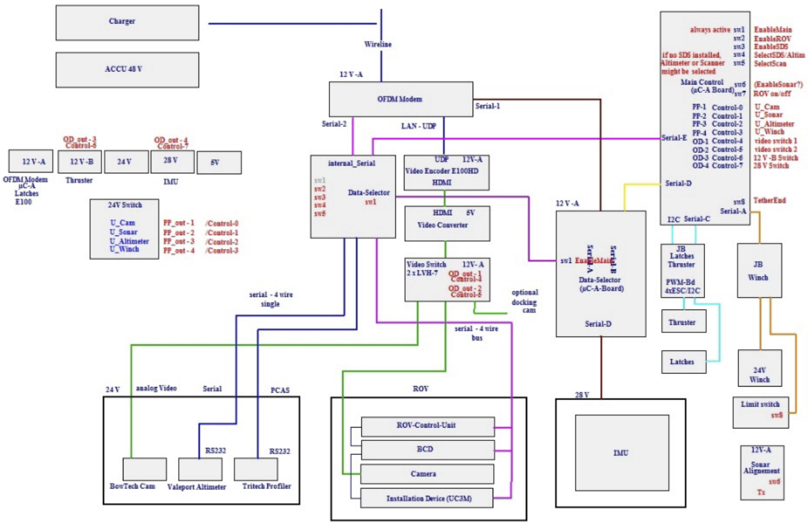


Figure 61 – CIS Structure

The hardware structure shown in *Figure 61* has to interact with the software packages (*Figure 62*).

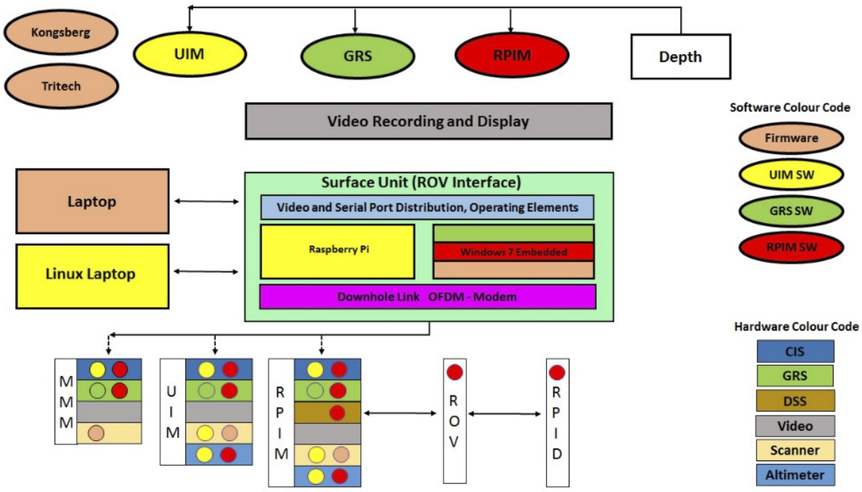


Figure 62 – Software Distribution within STAMS Project

In *Figure 62* all the round, elliptical shapes show the developed software packages, and all rectangles are hardware modules. The circles inside the rectangles indicate the software module which may interact with the module. If there is no circle inside the module, no software access is required.

The connection of the MMM is hypothetical. If a connection to the GRS/CIS is installed, the MMM may be accessed by the UIM or the RPIM software. If it is communicating directly by a special cable connection, the profiler firmware can be used. Firmware is always indicated by the light brown colour.

The GRS Software is mainly a self-contained module for data recording. It is tailored to the currently installed UIM. This software module collects and stores all UIM data for offline data processing. Depth setting is the only available control function. The laptops as shown in *Figure 62* can be connected optionally (instead of the Raspberry Pi) to the related interface serial port, or for firmware operation of the MMM. The main relations are as follows:

- The MMM is operated by the Kongsberg software
- The UIM is operated by the UIM modular software as described below
- The RPIM and ROV are operated by the RPIM software. If the PCAS submodule can be run using the UIM software, or alternatively the Tritech firmware. The structure of the surface unit (ROV) allows the RPIM and UIM or Tritech software to be run in parallel.

Task 3.2. Prototyping of Ultrasonic Inspection Module

<u>Overview</u>

According to decisions made in previous tasks, the UIM will comprise the following common sub-modules connected together in the following order (starting from the top of the UIM): Cable Interface Sub-module – CIS (which contains interface hardware and power supplies), Geo-referencing Sub-module – GRS, Profiling and Collision Avoidance Sub-module – PCAS. Because the two common modules (i.e. the CIS and the GRS) are being designed in a different work package, the design and prototyping work in this task involves the design of the Profiling and Collision Avoidance Sub-module and the design of the interface board which is unique to this sub-module which will be housed in the CIS. Laboratory tests to confirm inter-operability of the PCAS and the common modules are also part of this task.

<u>PCAS Instrument Selection</u>

Off-the-shelf products were readily available to fulfil the needs of the three instruments in the PCAS, namely the profiling sonar, the sonar altimeter and the underwater CCTV camera. Accordingly, an extensive product appraisal was carried out and meetings were held with manufacturers with the result that the following three instruments were selected and purchased, following the due process of competitive tender.

Suitable profiling sonar instruments were identified from Kongsberg, Imagenex, Marine Electronics and Tritech. The Super Seaking Profiler from Tritech was selected as the most cost-effective instrument that met the needs of the project.

Figure 63 – Tritech Super Seaking Profiler

Suitable sonar altimeters were identified from Kongsberg, Tritech, Swale Technologies and Valeport. The VA-500 from Valeport was selected as the most cost-effective instrument that met the needs of the project.

Figure 64 – Valeport VA-500 Sonar Altimeter

Suitable waterproof CCTV cameras with integral lighting were identified from Kongsberg and Teledyne Bowtech. The Pioneer from Teledyne Bowtech was selected as the most cost-effective product that met the needs of the project.

Figure 65 – Teledyne Bowtech Pioneer Underwater CCTV Camera

<u>PCAS Physical Design</u>

The PCAS is the bottom most sub-module in those devices in which it is used (i.e. the UIM and the RPIM). This is a necessity because any other arrangement would require the profiling sonar to operate through vertical supports which would impede the signal. Even if the PCAS is positioned at the bottom of the instrument, though, the fact that the area of the profiling sonar that contains the sonar transducer must not be obscured places constraints on the mechanical design of the PCAS. In particular, the transducer show must be arranged to protrude through a hole in the base plate at the bottom of the PCAS.

Positioning of the PCAS as the bottom most sub-module also means that the sonar altimeter and the CCTV camera that are used for obstacle detecting, can by ideally placed for "looking" vertically down the shaft without artificially increasing the overall diameter of the instrument.

The CCTV camera will be used for visually inspecting the dry portion of the shaft immediately below the instruments while it is being lowered down the shaft before reaching the water level. For this reason, its position and angle are fairly non-critical, the only requirement being that its field of view is not impeded.

The sonar altimeter, on the other hand, provides an indication of the closest reflecting object within its angle of view. This allows an automated alarm to be implemented of any obstacle that posses a collision risk. However, this is only possible if the beam of the altimeter is the same width as the diameter of the instrument and exactly coincides with it at some distance below the PIM. This can only be achieved if the sonar altimeter is angled with respect to the PIM in the vertical plane.

Specifically, the sonar altimeter is angled to causes the altimeter's footprint to exactly coincide with the 300mm diameter of the UIM, plus an all-round clearance of 50mm (i.e. a total of circle of 400mm diameter), at a distance of 3.8m below the base plate of the PCAS. This, therefore, is the distance at which the alarms should be activated. In the case of the RPIM, the sonar altimeter only confirms that there is no potential risk to the PCAS, and the profiling sonar in the PCAS is used to ensure that there is no potential collision risk for the larger diameter Docking Station Sub-module (DSS) of the RPIM. Some renderings from the CAD design of the PCAS are shown as *Figure 66*.

Figure 66 – CAD Renderings of PCAS

A stand has also been designed and manufactured to fit to the bottom of the PCAs and thereby allow the UIM to be places securely on the ground without damaging the transducer head of the profiling sonar. This will be used while adjusting the UIM and winch prior to the start of deployment into a shaft. The stand, which is affixed to the base of the PCAS using G-clamps, is shown as *Figure 67*.

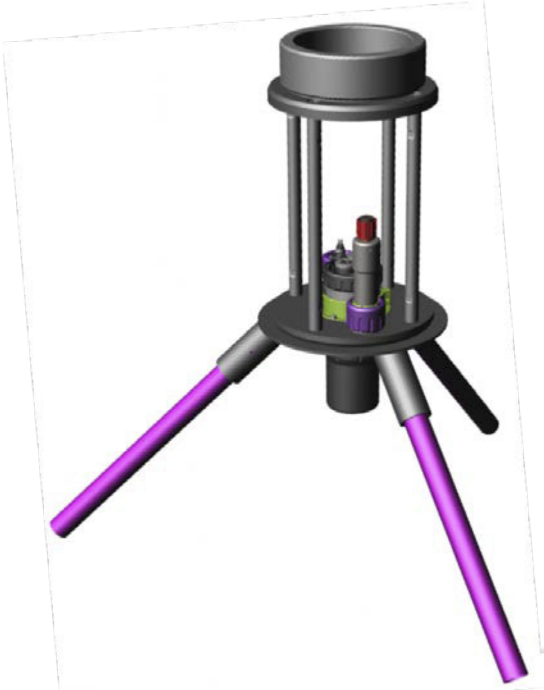


Figure 67 – Stand for PCAS / UIM

Integration of Sub-modules

The CIS, GRS and PCAS, integrated to form the complete UIM, are shown as *Figure 68*. In the final photograph the complete UIM is shown in a test tank at DMT.

Figure 68 – Completed UIM

The successful laboratory tests allowed field tests to be carried out as described under Task 6.1.

Task 3.3. Gas and Water Measurements for the Assessment of Shaft Stability

This task deals with the development of an approach to assess the long-term stability of flooded shafts by the analysis of gaseous atmospheres and the chemical composition of the water.

The objectives of task were more precisely to assess the long-term stability of flooded shafts using the evolution of gaseous atmospheres as an indicator of the degradation of the shaft support system (concrete and masonry) and to develop a device that can measure and monitor, over time, the physical and chemical parameters of water flowing deep into the mine workings.

Concerning the first objective, Ineris (task leader) run a laboratory test program to assess the generation of gasses, when water is in contact with materials used in shaft lining and support systems. Immersion tests performed in the framework of both RFCS PRESIDENCE and RFCS MISSTER projects help designing the experimental tests to be performed by Ineris in RFCS STAMS project. But in STAMS, experiments had to be run in closed systems to monitor their atmosphere and be able to detect any change in gas phase.

Two series of immersion tests have been performed: concrete fragments were immerged in water and experiments were run in closed systems to be able to detect any change in gas phase (*Figure 69*).

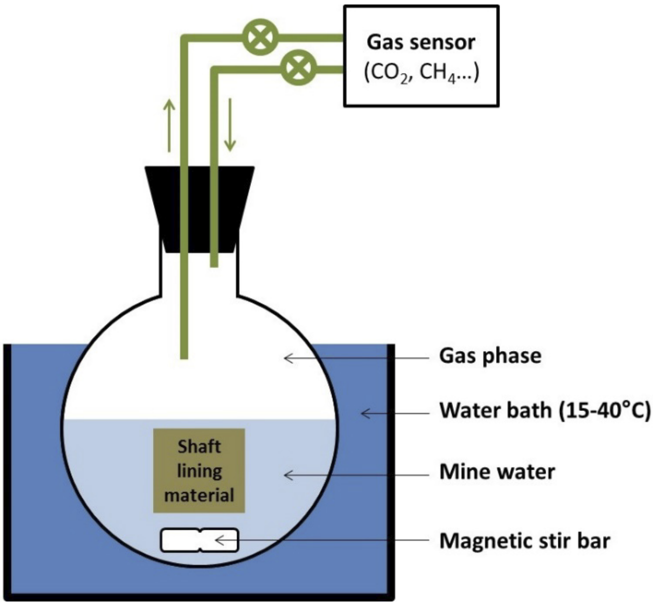


Figure 69 – Schematic Description of Immersion Test

The experimental protocol is described as follows:

1. A concrete fragment (crushed in ~3-cm pieces) is placed in a 1-litre flask half-filled with water.

   Concrete samples were sent by GIG to Ineris and are representative of concrete used to build shafts. Crushing revealed that samples are constituted by cement and aggregates. DRX analyses showed that aggregates are mainly quartz fragments (up to 95% in volume) with pentahydrate (ie hydrated magnesium sulphate MgSO4.5(H2O); up to 4%). Feldspar (albite) and clay minerals (illite and chlorite) are also constituents of aggregates albeit to a lesser extent. Several types of water are used to reproduce conditions in shafts. Acidified distilled water is used to mimic chemical acidic attack. Distilled water with 5 g/l of SO_4^{2-} is used to reproduce chemical sulphate attack. Pure distilled water is used for reference experiments. Experiments with same conditions are run 3 times in parallel (ie in 3 different flasks) to compare results for similar experimental conditions and to ensure obtainment of usable results in case of biological contamination of one of the flasks.

2. The flask is closed. The gas phase trapped in the flask is atmospheric air. Concrete fragments and flask are first sterilized at 120°C and a pressure of 2 bar prior the start of experiment.

3. The flask is sealed using a gas-tight plug with 2 holes allowing gas sampling and reinjection for non-destructive composition analysis on a gas sensor.

4. Water is stirred by using a shaker table (model Edmund Buhler Compact KS15A) only during the night. Shaking is stopped during day time so that gas measurements can be performed.

5. Composition of the gas phase in the flask is regularly analyzed to monitor any disappearance or generation of gas related to concrete degradation.

   Gas analyses were performed using a portable detector (model DRÄGER X-am 7000) and an IR detector (model LICOR LI-820). CO_2, CH_4, CO and H_2S concentrations were monitored.

6. Mine water in the flask is analyzed at the end of the experiment to detect any change related to dissolution of material in water.

The first series of experiments was run from 2 August 2017 to 5 January 2018. It lasted 157 days (5 months). The second series was run from 5 January 2018 to 13 February 2018; it lasted 40 days.

pH and ionic elements measurements have attested that chemical reactions between concrete and aqueous phases occurred during the immersion tests. No notable change of the composition of gaseous atmosphere was monitored during the first series of tests, but gas monitoring has detected changes of the CO_2 atmospheric concentration in the second series of tests. In this series, a detector with a ppm resolution was used. It monitored a decrease of the CO_2 atmospheric concentration in the flasks, which can be linked to concrete carbonatation (*Table 2*). Indeed, dissolution of atmospheric carbon dioxide in water induces carbonates in solution (CO_3^{2-}) which can react with calcium ions (Ca^{2+}) released from concrete. Thus, degradation of concrete due to flooding could be detected by monitoring changes in gas concentration of shaft atmosphere. But as CO_2 is ubiquitous, further investigations will be needed to characterize the precise origin in case a change of the CO_2 concentration is monitored. These investigations will aim to confirm or not if change is related to shaft degradation.

Nature of water	Erlenmeyer number	5 Jan. 2018 T°C lab.: 20°C	1 Feb. 2018 T°C lab.: 20°C	2 March 2018 T°C lab.: 19°C
Distilled water with SO_4^{2-} and acidified with HNO_3	10	475 ppm	0 ppm	No measurement
	11	475 ppm	0 ppm	6 ppm
	12	475 ppm	0 ppm	No measurement
Flask without concrete sample	13	475 ppm	894 ppm	920 ppm

Table 2 – Results of Gas Monitoring for Second Series of Immersion Tests

Concerning the second objective of task 3.3, dealing with the development of a device that can measure and monitor, over time, the physical and chemical parameters of water flowing deep into the mine working:

Water global mineralization is a good indicator of state of water equilibrium with solid in a water saturated environment. Indeed, the measurement of mineralization could be a good way to check evolution of water chemistry as an indicator of shaft degradation. Mainly two cases could be identified. They are schematically presented on *Figure 70* where 2 cases are considered:

a. Under saturated or unsaturated conditions (i.e. in the fluctuation area of water level in the shaft) hydrogeochemical interactions described in paragraph 3.1 can modify the chemical content of the water in the shaft.

b. Discontinuities affecting the lining of the shaft or permeability loss could be the way of water transfer between surrounding aquifer and the shaft.

Ineris proposed to use an easy way to detect these two kinds of shaft integrity loss: the measurement of electrical conductivity along all the shaft water column, as a conductivity logging.

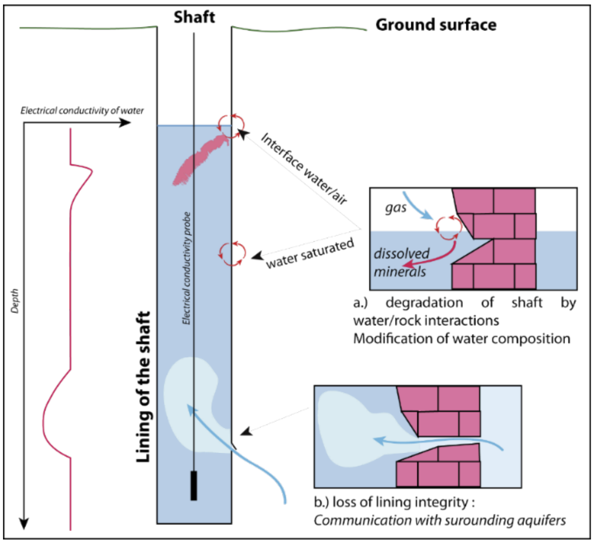


Figure 70 – Schematic Illustration of Supposed Impact of Shaft Degradation on Water

Prospections made by Ineris have revealed that electrical conductivities measurements tools, adapted to shaft monitoring, are presently commercially available. Review of tools showed that this kind of equipment is well-suited to detect water mineralization variations along the water column of a shaft. Those variations could be the consequence of shaft lining degradation linked with hydrochemical reactions or water flow coming from outside of the shaft due to a braking of the lining. Thus, the conclusion of the second objective of task 3.3 was that there is no need to develop a new device to perform conductivity logging.

WP4 Long-term Continuous Shaft Water, Gas and Environment Monitoring and Modelling

The objectives can be collectively summarised as:

- Design of an open access port, tube bundle system with a protective yielding sheath and impact resistant outer skin to withstand shaft filling operations.
- Design of a method to lower and fix a tube bundle system in an abandoned mine shaft.
- Examination of the feasibility of engineering a cost-effective long-term shaft monitoring capability based around a novel contactless inductive power transfer and signalling scheme.
- Consistent with the above, the feasibility will be determined of implementing a long-term shaft (and possibly inset) monitoring and measurement arrangement which includes in-situ determination of water presence, local shaft displacement, water conductivity and possibly gross pollution level.

Task 4.1. Tube Bundle System Design: Methods of Lowering, Anchoring and Positioning, Sampling, Observation and Monitoring

Following the top-level design of the tube bundle system and the broad decisions about the materials in T1.4, the design of the tube bundle system was refined in this task.

Tube Bundle / Electronic Sensor Integration

First of all, because it would have an impact on the final design of the tube bundle, the potential to combine data telemetry within the tube bundle design together with contactless instrument telemetry was investigated, as referred to in the Technical Annexe. There is a clear benefit in that it would permit both elements of the continuous shaft monitoring system – namely the tube bundle and the contactless telemetry system – to be installed at the same time. This would result in productivity and cost benefits to the end user. However, there are two obvious drawbacks. First, it is an objective of this project, wherever possible, to provide a range of solutions from which the end user can choose those elements that are consistent with the particular conditions in the shafts for which they have responsibility and with their budget. Combining the tube bundle and the telemetry system would escalate the cost to those end users that require only the tube bundle or only the telemetry. Secondly, and bearing in mind that abandoned mine shafts represent a hazardous environment, combining the two systems would increase the likelihood of losing the entire continuous monitoring system. It is envisaged, for example, that despite the high degree of protection that is being designed into the tube bundle, there remains a possibility that falling masonry or shaft furniture could damage or destroy the tube bundle system. If the telemetry system were integrated into the tube bundle, such an event would also result in damage to or loss of the telemetry. If the two systems are separate, and particularly if they are installed in different parts of the shaft, damage to one system would probably not affect the other system. As a result of this analysis, it was decided that the tube bundle and the telemetry would be designed as independent systems.

Sample Manufacture and Testing

As a result of consultation with materials scientists and a manufacturer of tube bundles for the mining industry (albeit to a standard design as used in working mines as opposed to the novel design being developed in this project), a decision was made (as discussed in T1.4) to use the following materials in the design of the tube bundle:

- Multi-coloured LDPE (Low Density Polyethylene) sample tubes, 6 mm outside diameter, 1 mm wall thickness,
- 2 mm thick TPU (Thermoplastic Polyurethane) yielding layer,
- 2 mm thick anti-static PVC (Polyvinyl Chloride) outer layer.

Accordingly, a 20-metre length sample was obtained from Colex International for use in testing. The tests were designed to simulate the potentially most damaging incident that is envisaged in an abandoned mine shaft. This would occur, most commonly, due to material falling against the tube bundle. Such an eventuality could occur due to shaft filling operations, as the fill is allowed to fall into the shaft under gravity, although the effect will be minimised due to the fact that the motion of the fill will generally be parallel to that of the tube, certainly after the first few metres of fall. Furthermore, crush damage due to the accumulated weight of the fill material is not expected to pose a significant risk. This statement is made in the light of calculations which show that, unlike water where the pressure rises continually with depth, the friction between particles of a solid substance results in the pressure increasing to a maximum within a few tens of metres.

Alternatively, damage could occur due to portions of the shaft lining or furniture coming loose and falling into the shaft. Such objects could be much larger than the particles of fill material, and they could have much shaper edges. However, like shaft filling, the motion will be almost vertical (certainly after a short period of fall) and hence of little risk to a vertical tube bundle if the object detaches from the shaft wall entirely. However, we can envisage situations that would be potentially damaging due to a horizontal or vertical portion of shaft furniture becoming partially detached and hinging into the tube bundle. Analysis of this eventuality illustrated that there is no such thing as a “typical impact” because there is a large range of weights and sizes, and while we can be confident about the range of final velocities that might be encountered, planning a series of tests to replicate real world conditions would be virtually impossible and not particularly informative. Instead, tests have been carried out, using the maximum final velocity calculated but using a range of weights until damage occurred to the tube bundle.

The experimental procedure involved dropping a range of masses onto a sample of tube bundle vertically from a fixed height. The height used was 2m, a figure chosen in the interests of the ease of building and safely operating the experimental rig. This will have resulted in a terminal velocity of 6.26 m/s – see *Figure 71*. The mass was increased incrementally, and, after each impact, the tube bundle was inspected. The inspection involved an initial inspection of the outer PVC sheath, followed by cutting away this layer to allow an inspection of the yielding TPU layer, followed by cutting away this layer to allow an inspection of the PE sample tubes. A summary of the results is provided as *Table 3*.

Figure 71 – Tube Bundle Falling Weight Experimental Rig

Weight of Falling Mass	**Effect on Overall Tube Bundle**	**Effect on PVC Outer Sheath**	**Effect on TPU Yielding Layer**	**Effect on PE Sample Tubes**
8	Slight initial deformation which recovered quickly	Extremely small superficial marks	None	None
16	Slight initial deformation which recovered quickly	Extremely small superficial marks	None	None
32	Slight permanent (or at least longer lasting) deformation	Minor marks and abrasions	None	Minor flattening and lateral crush marks to all tubes – tubes still air-tight
64	Slight permanent (or at least longer lasting) deformation	Abrasions and some tearing on one side and cut on the other (neither full depth)	None	Moderate flattening and lateral crush marks to all tubes – tubes still air-tight

Table 3 – Results of Tube Bundle Falling Weight Tests

These results are impressive and indicate that the aim of designing a tube bundle that is more resilient than those normally used in working mines has been achieved. However, it is clear that the tube bundle will not survive the significantly more severe impacts that might be encountered in abandoned shafts, in fact it is considered impractical for design a tube bundle that will survive all in-shaft incidents. It should be borne in mind, though, that the probability of falling furniture impacting a tube bundle is very low.

Support Rope and Installation

An extensive appraisal was carried out into means of supporting the tube bundle and a decision was reached that, because of the long design lifetime and the fact that maintenance is difficult or impossible, it would be unwise to recommend that it is self-supporting, even though calculation indicate that this might be possible. Instead a support rope is recommended, and a market survey led to the recommendation of an 16mm double braided rope with a Dyneema core and a polyester outer cover, for example Marlow 16mm D2 Racing Rope. Consideration has also been given to methods of attaching the tube bundle to the rope and the solution devised makes use of pairs of cable clamps, as shown in *Figure 72*.

Figure 72 – Tube Bundle and Support Rope with Recommended Attachments

Following a decision on the support method, attention turned to installation. It was concluded that the break-out boxes (see later) should be installed on site and, in addition, the tube bundle should be attached to the support rope on site. Several winching mechanisms were considered, and low-cost alternatives dismissed in favour of a winch with integral drum. Note is made of the fact that this does not necessarily involve a large capital expenditure because such winches can be hired for between an estimated £4,120 and £6,820 per week, depending on the location, including carriage and a representative of the hire company on-site to attach a new rope to the drum prior to each installation.

Break-out Box Design

There is a requirement, at those vertical positions where air sampling is required, to extract one sample tube from the bundle, and terminate that tube in such a way that there is an open end which is exposed to the shaft atmosphere. This is achieved using an assembly which shall be referred to as a break-out box and below which those bundled sample tubes that have not already been exposed to the atmosphere continue down the shaft. In fact, as described later, in most cases all the sample tubes continue down the shaft to provide additional strength, even though continuing those sample tubes serves no other purpose.

The following requirements apply to the design of the break-out box:

- Allow extraction of one sample tube while not maintaining a reasonable bend radius so not to stress the 4mm/6mm LDPE tube.
- Ensure that the extracted sample tube is fixed in a stable position with respect to the break-out box.
- Ensure that the open end of the extracted sample tube points downwards to reduce the probability of ingress of debris.

- Prevent water, that might be falling in the dry portion of the shaft, from entering the remaining unused section of the same tube that has been extracted and also prevent any possibility of it entering gaps between the sample tubes or between any other constituent parts of the tube bundle. While the tube bundle below the break-out box might survive this, a very conservative design philosophy has been adopted to protect against unknown aspects and thereby ensure a very long lifetime.

- Allow the break-out box to be attached at any point on the tube bundle without the need to thread the break-out box over a long length of tube bundle. This probably requires that the break-out box is a two-part design with the split running vertically.

A detailed design exercise was carried out and a prototype manufactured – see *Figure 73* for CAD images.

Figure 73 – CAD Images of Break-out Box

The method of fitting the break-out box onto a tube bundle has been documented as a step-by-step process to act as guidance for operatives on-site who will fit the breakout boxes as part of the deployment of a tube bundle into a shaft. A sample of these instructions is shown in *Figure 74*.

Turn the yellow adjustment knob clockwise until the blade just touches the tube bundle.

Continue turning the yellow adjustment knob clockwise for four full turns (note that there are eight notches on the yellow adjustment knob so just count 32 notches).

Rotate the ArmourSlice in the direction indicated on the "Rotate →" marking until it has cut around the full 360° of the tube bundles twice.

Figure 74 – Example of Breakout Box Fitting Instructions

<u>End User Implications</u>

The work to be carried out in T4.1, as described in the technical annexe, was a feasibility study of the use of a novel super-resilient tube bundle intended for use in the hostile environment of an abandoned mine shaft. It was emphatically not an aim to fully develop these technologies and to conduct field trials in an abandoned shaft.

Although the prescribed work is, therefore, mainly a scoping study, the work carried out and reported in this document progressed beyond these initial aims. In particular, the tube bundle has progressed to a design which can be manufactured, and a sample has been produced and subjected to surface tests to ensure adequate resilience to falling objects. End users indenting to pursue the use of a tube bundle system for monitoring an abandoned mine shaft can, therefore, order production quantities of the tube bundle developed in this project from the recommended supplier without having to pay any up-front setup charges.

In addition, the design of a break-out box, to facilitate the extraction of a sample tube at a particular position in the shaft, has progressed beyond a scoping study. A design which is suitable for manufacturing has been produced and prototyped and the CAD design files can be made available to end users.

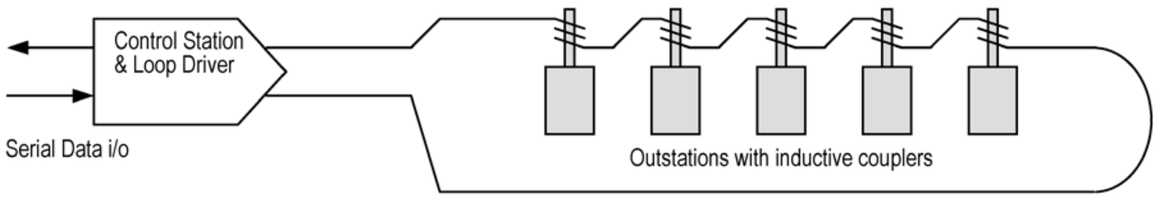
Task 4.2 Modelling and Verification of Underwater Transmission Scheme

The purpose of this Task, and the related 4-3, was to examine the feasibility of engineering a cost-effective long-term shaft monitoring capability using contactless methods of inductive power transfer and data transmission. It was initially expected that water presence, local shaft displacement and water conductivity would be monitored; and perhaps gross pollution level. The salient point of the 'contactless' approach is that it should significantly reduce the cost, and increase the reliability, in a system designed for underwater operation at depth.

It was initially expected that the instrument nodes (or outstations) would be locally powered by an internal battery that was charged by inductive coupling to a line carrying an alternating current. Data would be transmitted from the control unit to the outstations by modulation of the charging current and there would also be a return telemetry channel superimposed on the line. These principles were based on earlier work by The UK's Mines Rescue Service as part of a Fifth Framework project – UPTUN. (European Commission, 2008). An outline description of the initial concept was:

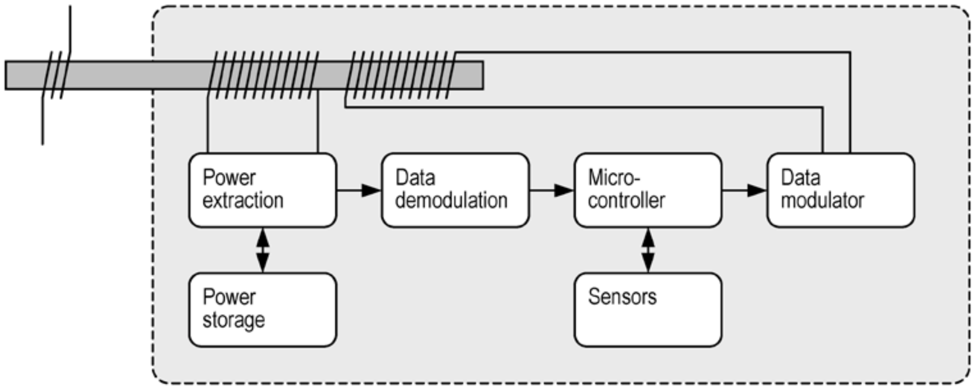
- The system would be modelled for underwater use and high data-rates.
- The instrument nodes would be powered by an internal battery and inductively charged from the communications line.
- The communications line would also carry a modulated signal allowing data to be sent and retrieved.
- Cost and reliability benefits were to be expected, due to the absence of physical connectors.
- The single charging line could comprise a braided stainless-steel core cable with thick polypropylene outer cover, which in principle could be several kilometres in length.
- Many units could be connected to the same charging line.

The concept is shown in *Figure 75* and *Figure 76*. In *Figure 75* the charging line is shown, inductively coupled to each outstation via a ferrite peg, although other topologies are discussed in the text. A block diagram of the outstation is shown in *Figure 76*, wherein line current is modulated by the control station to send data to the outstations; the power and data are separated in the outstation; and the outstations superimpose a modulated current onto the line in order to transfer data back to the control station.



The control station features a high-stability trans-conductance amplifier and bridge driver.
The communications line couples inductively to the outstations and transfers power and data.

Figure 75 – Block Diagram of Underwater Transmission System (UwTS)



The power and data are inductively coupled to the outstation. This is depicted as a ferrite rod. A toroid would provide a tighter coupling but there are practical problems in using such devices.

Figure 76 – Block Diagram of an Outstation

Inductive Coupling

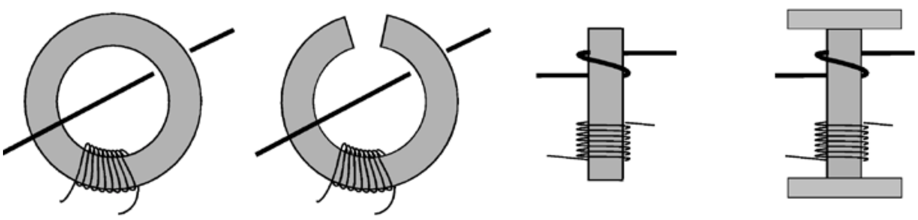
The feasibility study undertaken in this project was initially focussed on the modelling of the underwater data transmission scheme, to determine if problems could be caused by the possible high conductivity of the water. However, it was soon realised that a more significant problem was the issue of the inductive coupling of the devices.

A non-contact inductive coupling using a toroid is an efficient method of providing power transfer, but it has some disadvantages too. Unless the charging line is to be broken and re-connected, it must be threaded through all the toroids during the installation process, which might be inconvenient. Additionally, if we are envisaging a low-cost method of providing a pressure-proof housing (e.g. a cylinder with plugged ends, as discussed in Task 4-4) then a toroid might not easily fit the topology. An alternative scheme, using ferrite pegs was considered, but this provides only loose inductive coupling. Thus, a general study of loosely-coupled coils was undertaken in order to determine a likely design for a physical coupler.

The progression from toroid to peg to bobbin is shown in *Figure 77*. The salient point is that a near-ideal transformer would provide a coupling ratio proportional to the turns ratio, in parallel with a high value of leakage inductance. However, as the coupling becomes looser, due to the inclusion of an air gap or a longer air-based path for the field lines, the coupling ratio degenerates. The leakage inductance becomes lower in value (and therefore more significant), and an additional series inductance appears in the primary circuit.

A bobbin was considered to be the most practicable design. This is essentially a thin ferrite rod with end plates. The function of the end plates can be considered in several ways but, in essence, it is to increase the apparent length of the ferrite rod, which increases its effective permeability and therefore increases the coupling co-efficient. Alternatively, the function of the end plates can be viewed as providing a shorter return path for the flux through the air.

The operation of the bobbin was verified in lab tests, but no attempt was made to build a practicable design, because its implementation is highly dependent on the topology of the pressure-proof enclosure that is to be used which, in turn, depends of the environmental parameters that are to be sensed. Within the scope of this project, the *feasibility* of the design was considered to have been demonstrated.



Topologically, a toroid has practical disadvantages. However, other arrangements, as shown, result in only loose coupling. A 'bobbin' (right-most figure) is likely to be the most practicable.

Figure 77 – Development of a Loosely-coupled Bobbin

Charging and Power Supply

It was originally envisaged that the communications line would provide continuous charging. A design procedure was devised, which allowed the parameters for inductive charging to be defined. Typically, with 100 units on the line, the line driver would provide a controlled current of 200 mA at around 20 V (or 4 W), allowing each outstation to trickle-charge its internal battery at 10 mA (or 40 mW). The charging current would be conveyed as a 300 Hz signal.

The salient point is that the secondary winding of the toroids is clamped at a fixed voltage by the presence of the battery, and it is this that allows the primaries to be connected in series and which therefore requires them to be driven at a constant (or at least, controlled) current. The battery is therefore an integral and necessary part of the outstation. However, this places a limit on the current, because the rechargeable battery must be rated to withstand the applied level of continuous overcharge. It also places a limit on the number of units that can be connected to the line, because the driving voltage must be kept low for reasons of safety.

A further investigation of battery types indicated that continuous trickle-charging was not conducive to maintaining a long product life-time. At the very least, it would be desirable to be able to switch each unit's battery out of the charging circuit, so that it received only an intermittent charge, when required. However, even with this modification, the use of a rechargeable battery is not compatible with a product lifetime of many years. It was decided that the battery could be replaced in favour of a so-called 'super-capacitor' – (cf. *Table 4*), below. Because a super-capacitor's terminal voltage increases as it is charged, it is easy to see that both the intermittent charge concept and the super-capacitor concept require that the energy storage device can be switched out of the charging line circuitry, and the charging line shorted across the secondary side of the circuit, as shown in *Figure 78*.

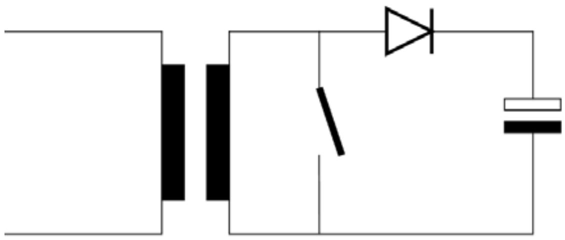


Figure 78 – Representation of Charging Circuit in the Underwater Transmission System

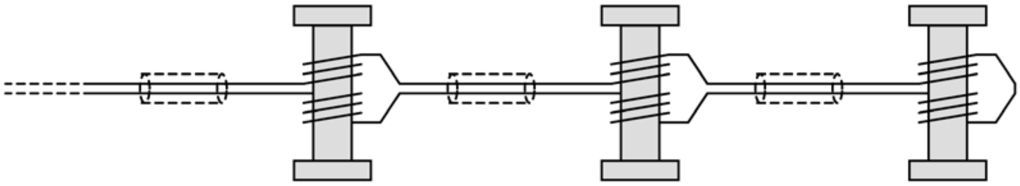
The inductively coupled line is presented by the transformer. The a.c. current is rectified and charges either a battery or a super-capacitor. The switch removes the power storage device from the charging circuit when it is fully charged and presents the necessary short-circuit to the charging line. It may seem strange that the secondary must be shorted, but this is because all the outstations are, essentially, connected in series. This point is further discussed in Task 4-4.

Parameter	**Original Charging Scheme**	**Modified Scheme**
Charging regime	Continuous; controlled-current	Controlled-current; only when needed
Energy Storage	Rechargeable battery	Rechargeable battery or super-capacitor
Power Management	All units charge simultaneously and continually. This limits the number of units that can be accommodated on the charging line.	Units must request power when they wish to charge. Scheme must be managed so that not all units are charging at the same time
Action when full-charge condition reached	Continue to over-charge batteries within their design parameters. However, this is not conducive to long-term operation	Switch the charger out of the circuit and short the charging line to provide system integrity
Discharge characteristic	Power is used directly from the battery	Power is used directly from the battery – or – power is provided via a switching regulator from the super-capacitor
Data modulation of charging current	Yes	Yes

Table 4 – Comparison of Power Management Schemes for the Underwater Transmission System

<u>Communications Line</u>

As noted above, the main modelling exercise involved a study of loosely-coupled coils, as this was considered the more significant problem. The communications line – which is topologically a large single-turn inductor driven by a bridge amplifier operating in a trans-conductance mode – could suffer from problems of instability, but a consideration of this showed that the problem could be solved by configuring the line in a linear out-and-back fashion rather than as a loop (*Figure 79*). This would also reduce any common-mode noise (although the environment of a flooded mineshaft is expected to be fairly quiet, electrically) and allow a higher data rate. The possibility of partially tuning the line, or driving it digitally was also considered, but the indications were that the added complexity would not give rise to significant benefits.



Configuring the communications line as an out-and-back pair, rather than as a loop, has some advantages including common–mode noise reduction. Using a 'bobbin' further helps with the problem of the loosely-coupled coils.

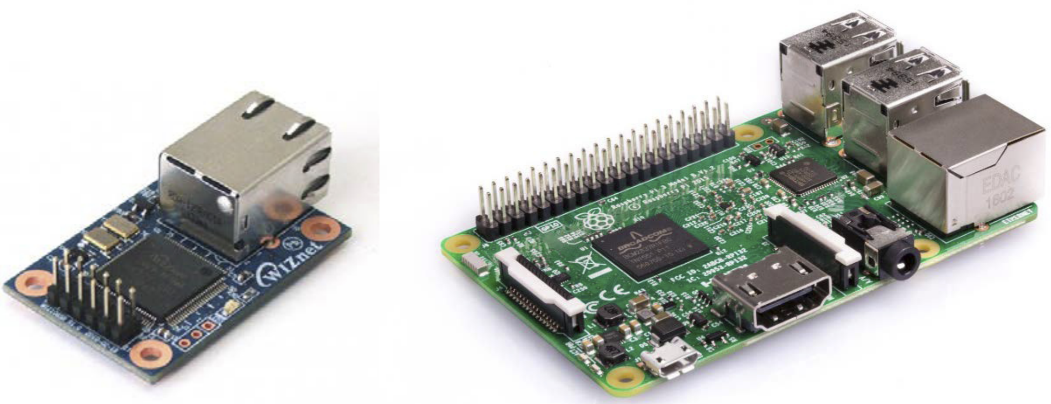
Figure 79 – Common-mode Noise Reduction using a Paired Line

<u>Data modulation</u>

Data communication in the outward direction (i.e. from the system control unit to the outstations) was envisaged to be by a simple on-off keying (OOK) of the current. This requires only a simple demodulation scheme at the receivers. Data communication in the inward direction (from the outstations to the controller) was envisaged to be by a simple frequency-shift keying (FSK) of a 20 kHz carrier, superimposed on the line via an additional inductive coupling. The use of FSK has the advantage that it is easy to generate and that the complexity of the FSK demodulator needs to be reproduced once only, in the control unit. More sophisticated modulation schemes are available, but these require more processing power. A salient point of this system is that it should be simple, low power and cheap. It was considered whether PSK modulation should replace the OOK modulation in order to convey a higher mean power to the outstations, but it was decided that the additional complexity did not warrant that extra sophistication.

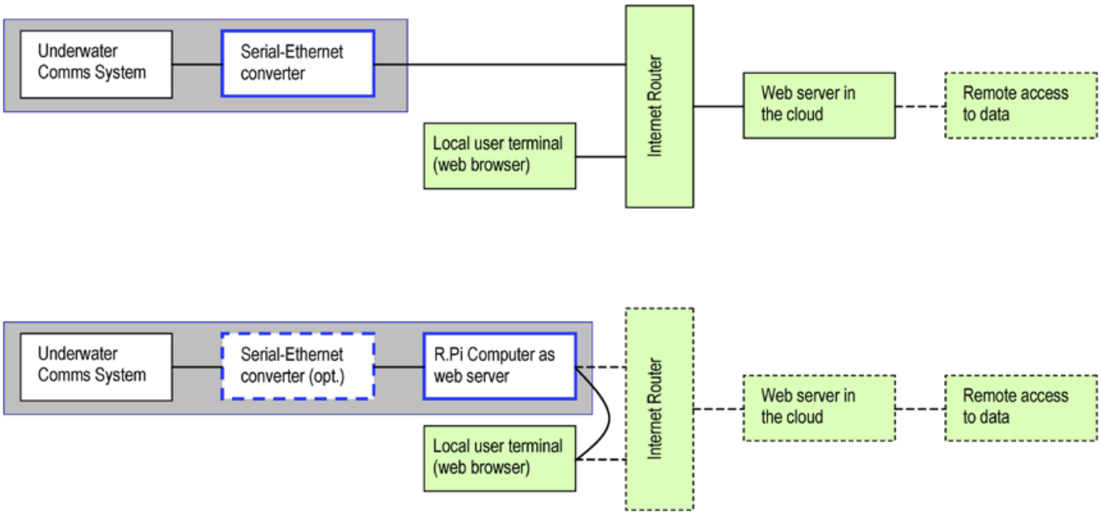
<u>Web Server Interface</u>

It was decided that the data processing and management functions were best handled in a web server environment, where standard programming tools could be used. The most straightforward scheme would make use of an Internet gateway and a web server. Such equipment is available commercially, but an original equipment manufacturer (OEM) solution is desirable for reasons of cost. Two options were considered; a) using a serial-to-Ethernet converter such as the WIZ108SR from WIZnet (**wiznet.io,** *Figure 80*); and b) using a single-board computer, the Raspberry Pi (**raspberrypi.org**), which would provide additional facilities. The low retail cost of these devices suggests that they would be used 'off-the-shelf' but both are available as open-source designs *(Figure 81*).



The WIZ108SR serial-to-Ethernet converter and Raspberry Pi single-board computer.

Figure 80 – OEM Devices for Providing Serial to Ethernet Conversion



Variations on these systems are possible, e.g. by replacing the router with a network switch, and using the Raspberry Pi to provide network control that is usually provided by the router.

Figure 81 – Examples of Ethernet-based Interfaces to the Underwater Transmission System

Using the WIZ108SR serial-Ethernet adapter, the data to/from the underwater transmission system (UwTS) would interface directly to an Ethernet network. A program running in a web-server environment could then interrogate the UwTS and process the data received from it. The operator's graphical user interface would be a web browser, which also communicated with the web server. The Raspberry Pi (RPI) computer has the ability to interface directly with the serial data from the UwTS, or it could interface via the adapter described above. An advantage of using the RPI is that it can host a local web server, and it provides a more self-contained solution. Both these schemes are depicted in the diagrams above.

<u>Concluding Remarks</u>

This task has investigated a number of issues concerned with the modelling and verification of the Underwater Transmission Scheme. As this was essentially a 'feasibility study', no equipment was constructed, but the principles behind some of the various concepts were tested and verified.

It was concluded that the original 'soft-failure' concept cannot, unfortunately, be guaranteed to be accommodated. However, a cost reduction opportunity is still possible, owing to the particular design of the pressure-proof housing, as described in Task 4.4.

Further salient points of the discussion are

- It would be advantageous to eliminate the rechargeable battery from an application such as this, because of the long product lifetime that is required. A super-capacitor would be an appropriate replacement.
- It is necessary to be able to switch the power storage device out of the circuit and to provide 'line clamping' to allow the system to function as intended. This is because the outstations are all connected in series. This fact is obscured by the use of inductive coupling but is nevertheless the case.
- The most practicable design of inductive coupler is probably a ferrite bobbin, because this topology results in a high effective permeability of the ferrite.
- The performance of the inductive coupler can be assessed by applying a mathematical model of loosely-coupled coils but this is highly dependent on the topology of the pressure-proof enclosure that is to be used.
- The communications wire should be implemented as an out-and-back pair rather than as a loosely-constructed large loop. This will aid the stability of the driving amplifier and will also eliminate common-mode noise.
- A simple data modulation scheme (OOK for outgoing data and FSK for incoming data) is probably sufficient for this application.
- The controller functions are probably best implemented in a web-server environment

Task 4.3: Investigation of Long-term Measurement Opportunities

A number of 'measurement opportunities' have been investigated for use with the proposed contactless power and telemetry scheme. Two salient points are that, in order to avoid the need for expensive pressure-proof connectors, it was necessary to consider contactless sensors. Additionally, the system needs to be deployed without maintenance for several years. These points mean that the range of sensors that can be considered is limited in scope. The basic parameters that can easily be measured are water presence, pressure (i.e. water depth), electrical conductivity, temperature and tilt (e.g. shaft displacement). Other measurements, such as acidity (pH) are much more difficult to incorporate into the system. It was initially conjectured that conductivity might be a useful analogue to pH but, as discussed below, this was shown not to be the case. Limitations of sensor biofilms and other fouling mechanic were also considered.

<u>Sensor Review</u>

The following parameters were considered as possible candidates for sensors.

- Water presence and water pressure
- Electrical conductivity
- Temperature
- Tilt and shaft displacement
- Chemical composition, acidity (pH) and redox potential
- Flow rate
- Drip rate
- Turbidity and Fluorescence

Water presence and water pressure: Water presence could make use of a float switch and a magnetic detector. Pressure sensing would utilise a commercial pressure sensor, of which waterproof versions are available. At its simplest, water pressure is related to water depth. In addition, dynamic pressure data could be informative in some situations. A range of high-performance sensors based around a piezoelectric film are manufactured by Keller-Druck (**keller-druck.com**) and take the form of a drop-in coin as shown in the figure below (*Figure 82*). The typical cost of such an insert is about €150, and the output is a calibrated digital signal on an I^2C computer bus.

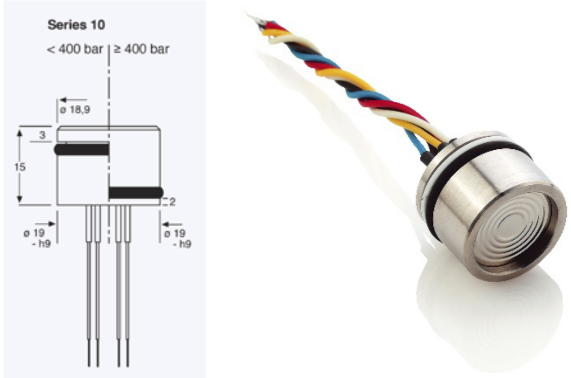


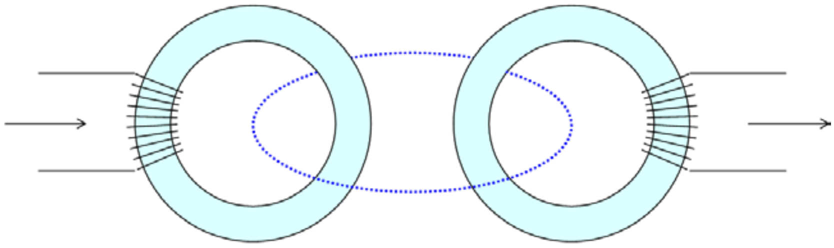
Figure 82 – Example of a Pressure Sensor for use at Water Pressures of up to 1000 bar

Electrical conductivity: Although straightforward in principle, this measurement will suffer from problems due to electrode fouling. Because of this, and the difficulty of making watertight electrical connections to a pressure-proof housing, a contactless method making use of an inductive or capacitive sensor is preferred. That is, we must consider methods that do not require an electrode to be in direct contact with the water. Water conductivity can be indicative of the aggressiveness of the water (*Figure 83*), i.e. its potential to cause chemical damage to the shaft lining, although, arguably, pH is of more importance. It could also be used, in some circumstances, to detect the inflow of water from intersecting galleries and could be indicative of recent flooding events.

<u>Capacitive Method</u>
In this method, a pair of electrodes form a capacitor, with the conductive mine water as the dielectric. The loss factor of the capacitor would be greatly affected by the water because of its high electrical conductivity and permittivity. With this method, the electrodes *could* be in contact with the water but, equally, they could be on the inside of the housing, with the walls (or end caps) of the housing being a part of the capacitive cell – being either a non-conductive material or anodised aluminium.

<u>Inductive Method</u>
This is an established technique. A magnetic device, usually a pair of toroidal coils, is encapsulated to form a sensor. A high frequency alternating current is applied to one of the coils and induces a current in the water. This current then flows through the second toroid where it induces a voltage proportional to the current which is, in turn, proportional to the conductivity of the solution. Thus, the degree of coupling between the toroids is indicative of the electrical conductivity of the water. The principle is shown in the diagram below. It is considered that a modification to the topology

would allow the technique to be used with the underwater enclosure being developed in this project, but that a lengthy design exercise and evaluation would be necessary to determine how this non-contact method compares with a capacitive method. Some useful background reading is given in (Arichika et al. 1992), (Ramírez and Casans 2005) (Rorschach and Herlin 1952), (Rosemount Analytical Inc. 2010).



A signal excites the left-hand toroid, which induces a current in the water. This is coupled to the right-hand toroid, where the detected signal is proportional to the conductivity.

Figure 83 – Principle of Water Conductivity Measurement by Magnetic Induction

<u>*Contact Methods*</u>

The above two methods are illustrative of the fact that more engineering effort is needed to measure water conductivity than mere water presence. But, in light of the 'value engineering' of Task 4.4, it is questionable whether it would be advantageous to use either of the above methods, due to the cost involved. Initially, it may be simpler to utilise a two-terminal current measurement, which would be easily achievable if the plug-ends of the proposed cylindrical housing (see Task 4.4) were made of metal. If they were anodised then this method becomes, essentially, the capacitive method described above.

A two-terminal contact methods may suffer from polarisation effects, which can take place when the voltage used to drive the current through the water exceeds the electrode potential. However, since the electrode potential is unknown, and could be very low, this observation is not of practical use, other than to remind us that the voltage should be as low as possible, and that we should use an a.c. measurement.

Alternatively, a four terminal measurement could be provided by providing two further electrodes which, if they comprised O-ring-sealed bolts would be relatively cheap to construct. However, each addition of hardware reduces the reliability of the equipment in the adverse conditions in which it is likely to be used. Additionally, any fouling deposition that created a current path between a current-injection electrode and a voltage-sense electrode would contribute to a false reading. Thus, is seems that no method of measuring conductivity that involves electrical contact with the water will be reliable in the long term. But whether this problem is outweighed by the fact that a two-terminal conductivity measurement is inherently low-cost is something that would need to be assessed for each individual application.

Temperature: A robust design of temperature sensor would deploy the sensor inside the waterproof housing, as opposed to immersed in the water and connected to the housing by a cable. Such a design would result in a slow response to temperature fluctuations, but this is not considered a restriction.

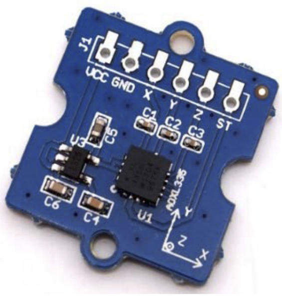


Figure 84 – A Typical Low-cost 3-axis Accelerometer with built-in MCU

Tilt and shaft displacement can easily be monitored using a proprietary tilt and acceleration sensor (see *Figure 84* above). The technology is developing rapidly in this area (largely driven by the mobile phone and games markets) therefore any recommendations made in this report are likely to rapidly become out-of-date. The present state of the art is such that low-cost (less than €10) 3-axis accelerometers can easily be interfaced to small microprocessors.

Chemical composition, acidity (pH) and redox potential can be extremely useful parameters, but none are easy to measure in the context of the present application, i.e. low-cost, rugged conditions and underwater at depth. The salient difference between conductivity and pH is that electrical conductivity is dependent on all the ions that are in solution, whereas pH depends only on the hydrogen ion concentration. Redox potential is like pH in that it uses an ion-specific electrode to measure the electrode potential.

It is interesting to speculate whether analogues between conductivity and the low pH associated with acid mine water can be identified and used, especially if the measurement is constrained to be a two-terminal operation. However, it is clear that no useful relationship exists; which is argued as follows...

Generally, larger ions move slower than smaller ions and so contribute less to the conductivity. The molar ionic conductivity of H^+ and OH^- ions is greater than all other ions, so in a solution containing many species of ion, the H^+ and OH^- ions would usually have the most effect on conductivity. Using Kohlrausch's law of independent ionic mobility it is straightforward to derive an equation that gives conductivity in terms of pH and the concentration of other ions. For an acid solution containing an ion species M, at a concentration denoted by [M], say; the equation shows (not unsurprisingly) that if pH is less than pM then the conductivity is proportional to pH, but if pH is greater than pM then the conductivity depends mostly on [M]. We can derive a similar rule for alkaline solutions. In practice, it is not quite so simple because the molar ionic conductivity depends on concentration, and on other factors. More importantly, this relationship cannot be utilised because we do not know the composition of the water. That is, if the conductivity changes, is this due to a change in $[H^+]$ or is it due to a change in the concentration of other species of ions? This cannot be determined. The conclusion is that are few circumstances in which we can use conductivity as a measure of pH.

Just as the transfer of *hydrogen ions* between chemical species determines the pH of an aqueous solution, the transfer of *electrons* between chemical species determines the redox potential of an aqueous solution. Like pH, the reduction potential represents how strongly electrons are transferred to or from species in solution. Note that it is the *strength* of the electron transfer that is measured (in volts) and not the *quantity* of transfer (in coulombs). In a similar way, pH represents the *strength* of the transfer of hydrogen ions and does not indicate the *quantity* (e.g. the number of ions that can be generated by a buffering solution).

Redox potential can be measured with an ion-selective electrode or, for an overall redox figure, with a general-purpose electrode (e.g. made of gold). However, a reference electrode is still needed – i.e. one that provides a known half-cell reaction and so has a known redox potential. In this way, redox measurement has more in common with pH measurement than it does with a simpler conductivity measurement. The need for a reference electrode makes measurement of redox potential as difficult as the measurement of pH in an adverse environment, where the electrode could be damaged, or contaminated.

The conclusion was therefore reached that there was no useful analogue between conductivity and pH that could be exploited in this application.

Scalar flow rate can be determined, in a basic way by measuring the cooling rate of a heated sensor, place in a water flow. Such a sensor could be a cheap silicon diode. For a given diode current, the voltage is compared with that of a similar reference diode. This scheme has the advantage that is it is a scalar measurement and does not need to be aligned with an expected flow direction. However, it is not certain that such a measurement would provide useful information, and it would need a sensor that is external to the waterproof housing, which increases the cost of the equipment.

In other applications, one of the established non-contact methods of measuring **vector flow rate** uses ultrasonic Doppler measurements of particles or air bubbles in the flow – see, for example, (Arimatsu *et al*. 2004). Another type of sonic flow meter relies on the fact that when sound waves are transported by a medium that is, itself, in motion, the speed of sound can be used to determine the flow rate of the medium. (Gibson 2005). Other techniques are available but non-are suitable in the present application, because of the stringent requirements for sensors to be waterproof and pressure-proof.

Drip monitoring has its uses in scientific investigation of groundwater flow in caves but might not be as relevant in a flooded mineshaft. Nevertheless, if the system under development in this project were to see uses outside mining, a drip-counter could prove to be of commercial interest. A simple piezo-electric dip monitor was described by (Mattey and Collister 2008).

Turbidity can be indicative of several useful conditions, but a sensor that made use of the optical properties of the water might be likely to suffer from bio-fouling. The situation is similar for ***fluorescent dye tracing***. Commercial dye-tracing equipment usually makes use of a spectrometer and might, typically, have sensors to record uranine (sodium fluorescein), rhodamine, optical brightening agent, as well as turbidity and temperature. A description of a comprehensive dye-tracing exercise is given in (Gunn & Kelly 2017a, 2017b). Although these hydrological studies are not related to mining, they give a good indication of present equipment and methods.

The Fouling of Electrodes and Sensors

Biofilms

Any surface placed underwater for an extended period of time is likely to become covered in either a biofilm, or in other deposits arising from the water. Regarding biofilms, the study of marine fouling has a long history and there are many references in the literature. Some selective references are (Dexter and Gao 1988), (Satoshi Nakasono et al. 1993), (Schildhauer et al. 2006), (Percival 1999), (Jinhua et al, 2014). These give an idea of the work in the field. It was considered that a comprehensive study of bio-fouling would require more resources than were available to this project, but a number of points were noted for possible further attention.

A traditional approach – using copper electrodes (copper is a biocide) – is not open to us because the electrodes would certainly react with the mine-water. The same is probably true of other, more esoteric metals that could be used, for example tantalum, molybdenum and tungsten. Another option, reported in the literature, makes use of gold or silver nano-particles deposited on anodised titanium but it seems unlikely that these materials could be guaranteed to survive in mine-water.

It was speculated within this project that it may be possible to avoid the growth of bio-films by using an electrode system to generate ozone (O_3) gas. The anodic half-cell that normally generates oxygen has a standard electrode potential of +1.23 V, whereas the reaction that produces ozone has a standard electrode potential of only +2.08V so, under normal conditions, little ozone is produced. However, this reaction can be observed as an unwanted reaction when the voltage is set higher than necessary. The comprehensive online resource Water Structure and Science (Chaplin, date unknown) provides further information, and reports that tin oxide anodes have proved useful for the production of O_3, particularly if doped with antimony and nickel, as they bind both oxygen molecules and hydroxyl radicals to facilitate the O_3 production. Several researchers report methods of generating ozone by using specially doped metals – see (Yun-Hai Wang and Qing-Yun Chen 2013) and (Fritz et al. 1979). It is known that decomposition of ozone gives rise to several strong oxidants that are capable of killing viruses, amoebae, algae and dangerous bacteria, such as MRSA and Legionella. Ozone will oxidise most metals (except gold, platinum, and iridium) to oxides of the metals in their highest oxidation state, so some care would be needed over electrode choice. Additionally, the chemical cocktail present in mine water could provide some unpredictable chemistry.

Other Fouling Processes

The major problem might not be bio-films at all. In an aggressive mine water environment, it could be that the more severe problem is electroless deposition of metallic ions. Electroless deposition can occur when there are sufficient ionic species present in an aqueous solution that a reduction action can take place to deposit metal ions without the usual requirement of an external source of electrical power. In industry, electroless deposition is commonly used to provide a nickel coating to materials, but other ions can be deposited as well.

Methods of Combating Fouling

It should be noted that contactless sensors do not fully obviate the effects of fouling, if it is possible for the fouling to ‘track’ between electrodes. One possible practical approach to mitigate this could be to use a housing that is ridged, like the porcelain electric insulators seen on overhead power lines, so that the conduction path between the two electrodes was as long as possible and could be expected to make a lower contribution to conductivity when it was covered in a conductive film.

One might expect that an insulating electrode (e.g. made of hard-anodised aluminium) would provide a more consistent two-terminal measurement of alternating current, provided that any fouling material comprised a much thinner layer than the anodising layer. In this situation the fouling material would contribute little to the capacitance of the anodising layer. But such speculation is not backed by facts and, over a long period of time, there could be significant electrode damage, due to corrosion, electroless deposition and, of course biofilms.

Concluding Remarks

This task has reviewed a number of types of sensor and concluded that basic parameters such as water presence, depth, conductivity, temperature and tilt can easily be measured; and that others such as pH are not feasible to measure. A non-contact type of water conductivity measurement should be attempted but methods of mitigating fouling will still need to be undertaken. The primary mechanism for fouling may well not be biological but could be due to electroless deposition.

Task 4.4. Examination of “Value Engineering” Cost Reduction Opportunities

The proposed underwater transmission system (UwTS), described in Tasks 4.2 and 4.3 requires a pressure-proof housing. To reduce the cost of such housings, it was envisaged that submerged sensor nodes operating below a particular depth could be designed with an engineered failure mechanism such that when a sensor fails due to excessive pressure it does so in a way that cannot cause a condition that might jeopardise the operation of the remaining equipment. This Task considers aspects of this value engineering exercise. Some design calculations were undertaken for a low-cost underwater pressure-proof housing; and a prototype housing was designed and tested at depth.

Pressure-proof Housing

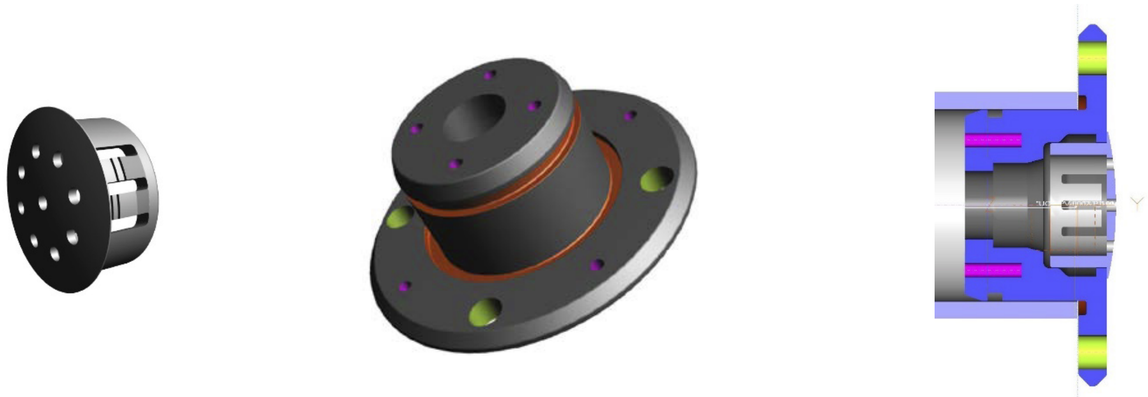
A major problem with pressure-proof housings is the electrical connections that need to be made through the housing. Penetrators, as they are called, can be a significant cost. This is one of the reasons for considering contactless methods of data and power transfer. However, it should be noted that, even if wired sensors were used (e.g. those supplied with waterproof connectors by their manufacturer) it could still be advantageous to employ a contactless method of data and power transfer.

It is well-established that a cylinder with plugged-ends is a robust style of underwater housing. The end caps are inserted with O-ring seals and they press against the ends of the cylinder. The advantage of this type of housing over, say, a conventional waterproof box, is that the symmetry and the directions of the forces mean that the seal is maintained as the pressure increases. There are several examples of commercial products utilising this principle, although those products are intended to be used with penetrators.

Some simple design calculations were undertaken for a low-cost plug-end cylinder. Initially, this was designed to withstand 150 bar (1500 m water depth) with a zero safety factor. The reason for the zero-safety factor was because, to investigate failure mechanisms, a failure of the housing during testing might actually be advantageous. A finite-element analysis was undertaken to investigate the likely failure mode and pressure rating. The results of the FEA were surprisingly close to those that used an analytical model of a thin-walled cylinder.

A prototype of the housing was constructed using an acrylic tube 150 mm in length, with a 40 mm o.d. and wall thickness of 3 mm. The end caps (*Figure 85*) were machined in aluminium and hard-anodized. Two O-ring seals were used – a face seal, against the plate of the end cap and a transverse seal against the wall of the tube. A number of holes were pre-drilled into the metal to allow for anchoring points. One of the end-caps was machined to fit a pressure sensor. Failure was predicted at 98 bar without any safety factor.

The acrylic tube was an off-the-shelf part. It was decided that this was preferable to a bespoke, machined, polycarbonate part because the machining could introduce micro-fractures that could be the source of a failure. The reason for using a transparent enclosure was one of convenience during development, as it allowed LEDs on the circuit board to be viewed. For the initial investigation, no attempt was made to incorporate the inductive coupling of Task 4.2 – the prototype was a test of a low-cost pressure-proof housing; not a test of inductive coupling.



1. Vented plug for pressure sensor. 2. End cap. 3. Cross-section of end cap and plug

Figure 85 – Pressure Housing: 3D CAD Drawings of End Cap

The device was tested by lowering it into a flooded mineshaft, where it survived a test in 400 m of water. On a deeper test, it failed at about 600 m but this is speculated to be due to stresses induced when attempting to free it from debris in the shaft, against which it had been trapped. The failure was clearly explosive in nature – something like the inverse of a balloon bursting – rather than a gradual leak. The sudden inrush of water, at a pressure of 60 bar, did explosive damage to the inside of the housing, including significant damage to some metal brackets inside the enclosure, thus suggesting that a ‘soft-fail’ (as discussed below) might be difficult to accommodate.

The parts for the prototype were not cheap, because they were precision made, and hard anodised, but we consider that the overall *concept* of a plug-end cylinder being *potentially* low cost is still valid. One point that has not been considered at this stage is the long-term integrity of the O-ring seals in the minewater environment.

The prototype enclosure is shown in *Figure 86* below. In this photo, note that the pressure sensor has been fitted, and its flying leads are visible. Also note that the transparent housing allows the O-ring seal to be inspected for integrity. This was a slight concern because the acrylic tube could not be chamfered to aid the fitting of the end caps as this could compromise its integrity by introducing micro-fractures. Not shown in the photo are the four longitudinal threaded rods that hold the assembly together. These are redundant once the assembly is underwater as the water pressure alone is sufficient to hold the end caps on. However, on the surface they are required to counteract the back-pressure that arises when the end caps are pushed home.

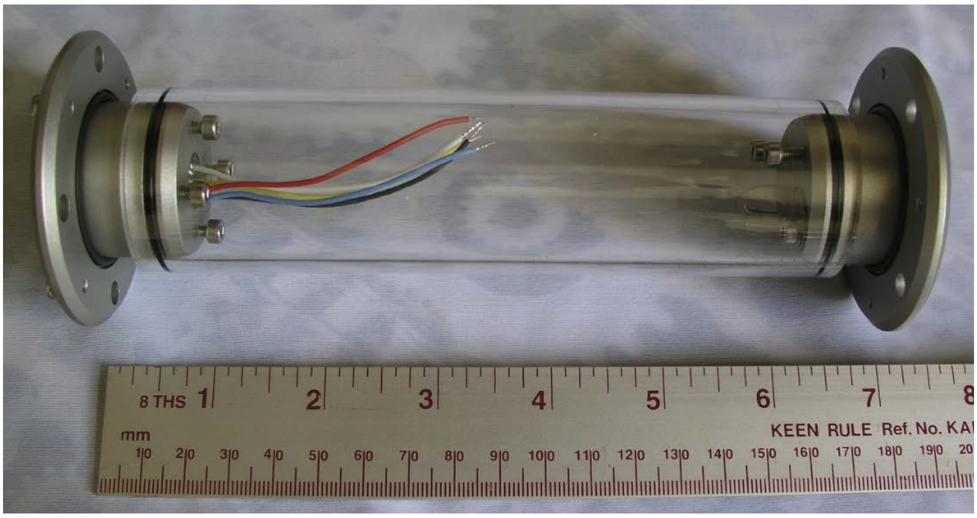


Figure 86 – Pressure Housing: Manufactured Prototype

Soft-Failure of the Electronics

One particular aspect of value engineering is whether sensor nodes can be designed to *soft-fail*. In particular, if the water in the shaft rises, causing increased pressure stress on the sensors, can they be designed to fail in a way that does not jeopardise the operation of the remaining equipment? It is also worth reminding we that the philosophy behind Work Package 4 was that systems installed for continuous monitoring could not be replaced or repaired. Given that we could, therefore, be considering a lifetime measured in decades, the simple longevity of the electronics could also be an issue.

As the design of the sensor package has progressed, it was realised that a soft-failure design might not be possible. The salient point of the contactless power system is that the devices are all coupled onto a single wire, so that they are effectively connected in series, with the inductive couplings essentially acting as a set of transformer primary windings connected in series. In such a situation, the inductance of the transformer appears in parallel with the secondary load (refer to the modelling in Task 4.2) and is therefore insignificant when viewed from the primary side of the circuit. But if the load is removed – say by a circuit fault – then the inductance is in series with the primary circuit and might prevent any significant current flow. Looked at another way, an ideal transformer is 'invisible' and so the impedance in the primary circuit is simply $N^2 Z$ where N is the step-down turns ratio (i.e. N:1) and Z is the secondary impedance. Thus, if Z is open-circuit, then so is the primary impedance.

There are two possible solutions to this difficulty. Firstly, an electromechanical relay or solid-state switch could short the secondary side of the coupler. This is *required* for the revised power scheme, described in Task 4-2, but it is also a possibility for handling the soft-failure – although it is seeming unlikely that this component could, itself, fail in a safe mode.

Secondly, it should be apparent, from the above discussion, that the problem arises because we are considering 'ideal' transformers, where all of the primary energy is coupled to the secondary. Clearly, in a non-ideal transformer, with a small coupling co-efficient, much less energy is coupled and so it follows that the 'loss' of the secondary load has less effect on the primary. Additionally, the primary impedance, after the loss of the secondary, is significantly inductive, so that it could, in theory, be tuned out using a series capacitor. However, the difficulty of using a loosely-coupled transformer is that it requires a much higher voltage in the primary winding.

The situation of loosely-coupled coils was analysed in Task 4.2, and it was expected that the topology of the underwater transmission system (UwTS) would be such that it would necessitate a loosely-coupled system.

Concluding Remarks

The proposed method of inductive power transfer is not feasible with tightly-coupled transformers. Or, at least, if that is the design then outstation nodes must fail with a *shorted* secondary winding. But this is impossible in a general sense because any device that was included to assist the fail-safe operation could, itself, fail. With loosely-coupled transformers the situation is slightly more advantageous, but failed nodes will still alter the characteristic of the line in a way that might be difficult to compensate.

Overall, the conclusion would appear to be that the housing (and the electronics) should be designed to not fail. However, this defeats the object of the 'value engineering' exercise and so it is suggested that, in the event of this feasibility study being taken forward and used to design a specific application, a further detailed analysis of the loose-coupling regime should be undertaken.

The prototype underwater housing was tested in South Crofty Mine, situated in Cornwall, UK. This mine has recently received a dewatering permit from the UK Environment Agency allowing the discharge of up to 25,000 cubic metres of treated water per day into the Red River. The mine has expressed interest in installing a version of the long-term shaft monitoring equipment described in Work Package 4. This would allow the mine to track the water depth in two different shafts as the de-watering operation continued. Collaboration between the University of Exeter and South Crofty Mine is envisaged for this operation.

Task 4.5. Hydro-mechanical and Chemical Modelling of Shaft Long-term Stability

Shaft long-term stability after its closure is mainly governed by the behaviour of its lining which is generally composed of concrete or brick/masonry. Tubing mainly with cast iron is sometimes used when crossing aquifer formations particularly for very old shafts. Shaft stability becomes critical during the flooding phase where lining is attacked by highly polluted water with aggressive minerals such as sulphates and chlorides. This leads to lining weakening and its potential failure, inducing thereafter the risk of shaft collapse.

The flooding phase involves three kinds of loadings applied on the lining. The first one is mechanical and is linked to shaft sinking and lining installation (permanent stress regime). The second loading is hydraulic and is related to the water table regime (water pressure). The last loading is due to corrosion and chemical reactions which occur between mine water and lining materials (loss of thickness and degradation of mechanical properties). Hence, to deal with long-term stability of shafts, it is necessary to examine the risk linked to each one of these three loadings and to couple them at the end for a reliable assessment.

The mechanical behaviour of shaft and lining may be studied by classical approaches (either analytical or numerical) using the convergence-confinement method to evaluate properly the loading within the lining. This requires knowledge of the geological and geotechnical properties of the host rocks, the geometrical data of the shaft (depth and diameter), the lining properties (composition along the depth, thickness and mechanical properties) as well as the procedure of lining installation. For the hydraulic aspect, both the hydrogeological data of the grounds and the lining hydraulic properties are required. Numerical hydromechanical models can then be used to forecast the excess of loading brought on the lining by the water table regime.

The chemical load needs more detailed data especially at the lining level. First of all, the composition of the material as well as mine water which will be in contact should be known. This operation is done commonly by in-situ sampling and by laboratory measurements (density and porosity measurements, mineralogical composition and analyses by Scanning Electron Microscope (SEM) and X-Ray Diffraction (XRD) for lining material and pH, conductivity and chemical composition for mine water). Batch leaching tests can be also carried out and their results analysed in terms of solution composition as well as solid phase. Based on measured properties, the potential chemical reactions and pathologies are evaluated and dedicated numerical models coupling geochemistry with transport are implemented to study the durability of lining. These models consider the thermodynamics and kinetics of the materials in aqueous solutions and the reactive transport to estimate the altered thickness of the lining during the considered period.

Shaft stability is evaluated by calculating a safety factor which is defined as the ratio of the lining material strength by the active stresses. For the hydraulic and mechanical aspects, coupling is classical, and the evaluation of the safety factor is obvious provided using consistent assumptions in numerical modelling and reliable mechanical and hydraulic properties. However, for the chemical aspect, full coupling is not easy. The proposed approach is simple and consists of simulating the chemical reactions and estimating the degraded width from each lining side (internal face inside the shaft and external face rockmass side). This altered width is supposed to be totally ineffective and lost and therefore lining thickness is reduced from each side by this width. The remaining part of lining is assumed to preserve the initial mechanical properties of the material without any weakening effect. Stability can be therefore assessed by examining the safety factor for a given thickness and strength of the lining material and given conditions of the shaft (geometry, mechanical and hydraulic loadings).

Within this task, the proposed modelling approach was applied at two different levels: first, its principle was explained on three French shafts lined with concrete and cast iron where sufficient data were available on the required characteristics of the rockmass, lining and mine water. Two Polish shafts which have collapsed by lining failure were then back-analysed to demonstrate the capability of the approach to reproduce the observed behaviour. Figure 87 and Figure *88* give illustrations of the modelling results on the two French shafts lined with concrete (Simon and Vouters shafts, Lorraine colliery). More details on the work performed in this task can be found in deliverable D4.5 entitled "Specification of the coupled modelling approach to assess the shaft long-term stability".

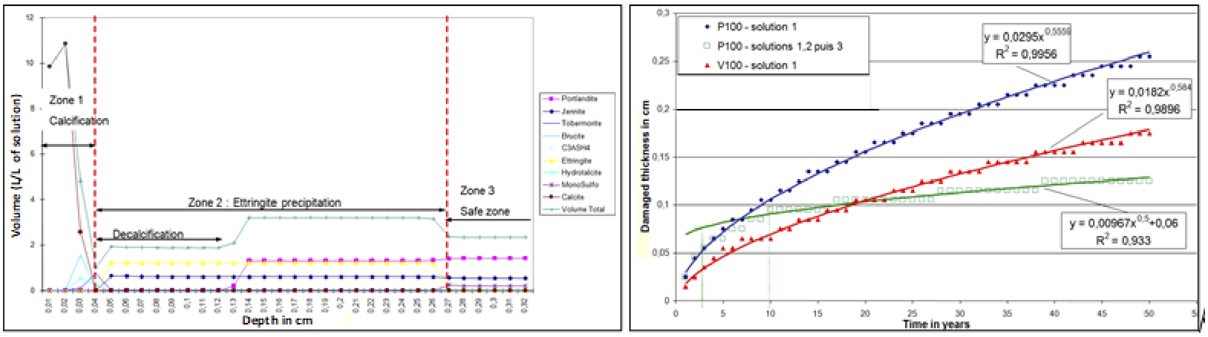


Figure 87 – Chemical Attack of Concrete Lining by Mine Water and Progress of Degraded Front

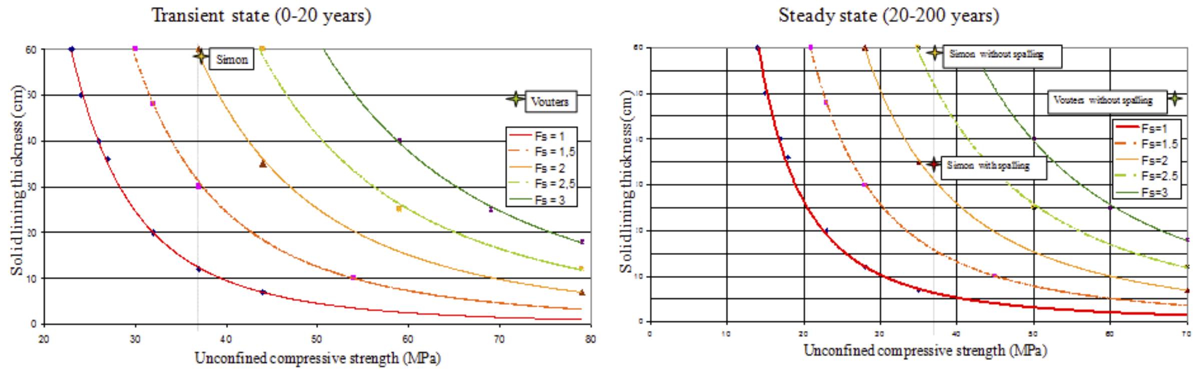


Figure 88 – Stability Conditions of the Two Shafts for the Transient and Steady Phases

WP5: Integration of Technologies and Modelling for Complete Shaft Stability Assessment

This WP comprise the activities to integrate each of the independent modules of the two main lines of research and also integrate them with common technologies (installation device, geospatial and inertial module) for the long-term shaft monitoring stability analysis using software-based tools.

- G5.1 To integrate supporting technologies with the main inspections systems.
- G5.2 To integrate and implement software-based tools for the control devices.
- G5.3 Develop software tools for post-process analysis of data.
- G5.4 Implementation of a mechanical device for installing components in flooded shafts
- G5.5 Calibrate the long-term stability modelling approach with the developed monitoring technologies for the long-term shaft stability assessment.

Task 5.1. Inertial and Georeference Module and Fixed Reference Points

An inertial measurement unit (IMU) was fitted to the GRS (Geo-referencing Sub-module) within this task. This IMU does not physically belong to the project, but it was rented to the project. The IMU output data are pre-processed in the CIS. The pre-processed data are transmitted to the surface unit where these data are merged with depth data. This geodetical data set is used for scanner data correction and rotation.

The scanner provides data with three columns: x, y and z positions. The IMU gives heading, pitch and roll as well as depth (the z position).

The scanner is rotated as it is lowered, meaning that the point cloud produced of the area is offset at each depth by the change in heading of the scanner (*Figure 89*). To obtain an image of the area, the points at each depth must be rotated opposite to the rotation of the scanner, using the information from the IMU.

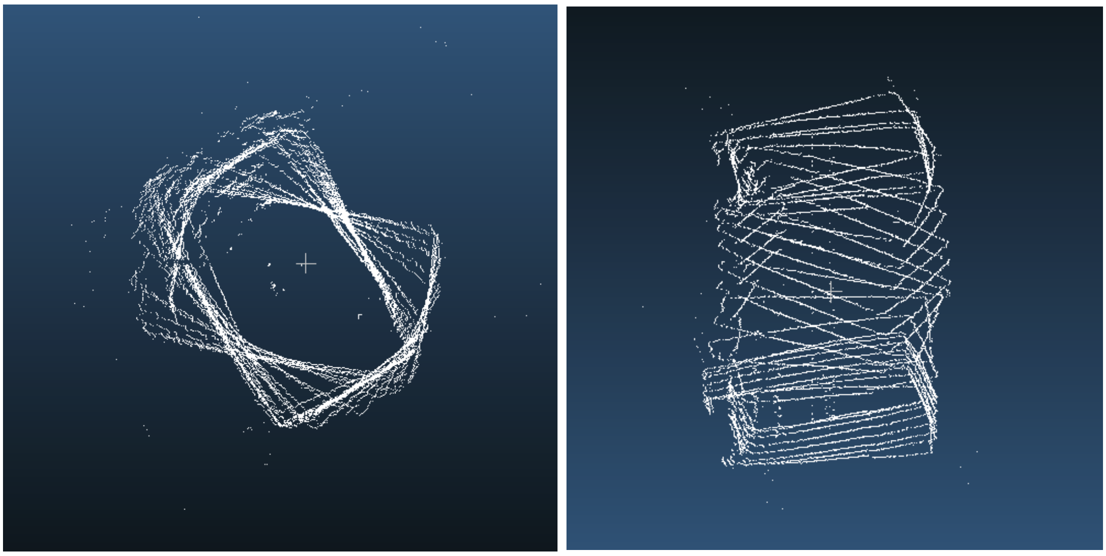


Figure 89 – Data, not Rotated

First, take the average of the headings given for each IMU depth reading. Then subtract these values from the initial heading reading to obtain the necessary rotation for each depth. Every "slice", or scan from a given depth, is then matched to a depth reading from the IMU. Each depth reading from the IMU has a corresponding average heading and desired rotation, which is then applied to the slice.

To rotate each slice, the points at each depth must be passed through a rotation matrix of the form

$\begin{bmatrix} \cos\propto & -\sin\propto \\ \sin\propto & \cos\propto \end{bmatrix}$,

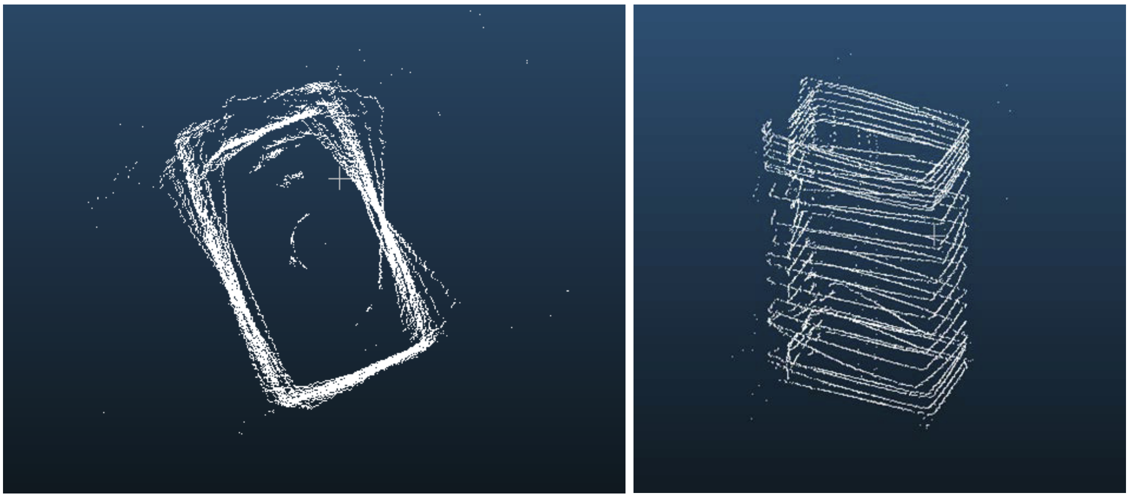


Figure 90 – Data Rotated

Where ɑ is the rotation angle calculated earlier. In this way, each pair of (x, y) values is assigned to a new place based on rotation in the z-axis. This is done for each depth reading. The new data set (*Figure 90*), is then exported as a .PLY file.

As seen in the images, the resolution is poor during these tests compared to the earlier tank test. This can be explained by the interaction of the UIM software, the depth encoder and the sonar scanner. Since the sonar scanner is very slow with a rotation rate below 1 Hz, the tool must also move very slowly. The display software is triggered by the depth encoder pulses (resolution 4 pulses / cm), which also appear only once or twice a second at this low speed. Due to the performance of the Raspberry Pi, the processing takes more than one second, so it can happen that some scans are missing.

The test without the "real" depth encoder did not show this behaviour, because the generator which supplied the depth pulses operates at a 200 Hz pulse Rate. The IMU inside the GRS delivers high output Data at a 50 Hz rate. The data stream is reduced in the GRS for the field test, but the oscillation with a 30 s period can be observed in the left diagram (*Figure 91*), which displays heading versus time. The right diagram shows the heading versus depth.

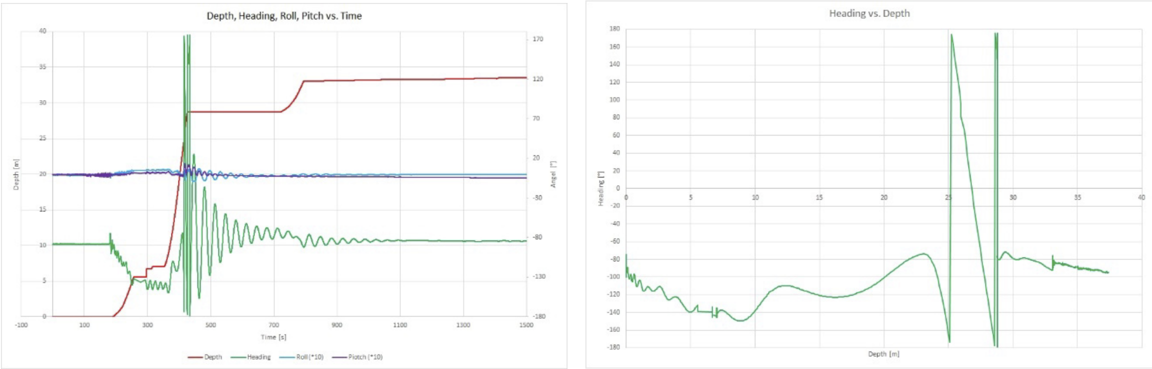


Figure 91 – IMU Output Data

Task 5.2. Software Based Tool for Real-time Control and Post-processing Analysis

In this task, the different modules of the software-based tool for the assessment of the stability of the shaft and the control of the different modules were developed and integrated.

The aim of this task was to implement a post-processing for the recorded data, most importantly the 3D model generation following correction for any unintentional movement of the inspection module. There was interest also in rendering the 3D virtual model as a 3D physical model for rapid prototyping, otherwise known as 3D printing. It was also required to allow metrics to be obtained from the virtual model, and a comparation between scans.

These tools were developed using open-source frameworks and libraries. The meta-operating system used was ROS (which runs over Linux, www.ros.org). ROS is a collection of tools, libraries, and conventions that aim to simplify the task of creating complex and robust robot behaviour across a wide variety of robotic platforms. It provides a distributed and modular design of the software, so that the developer can pick and choose the parts of the software that are useful for him and reutilize it. This was especially useful for the development of the modular software in the project.

The programming language used was Python, which is a high-level object-oriented programming language for general purpose programming. It is characterised by its readability and a syntax that requires fewer lines of code than C, C++ or Java. It is very convenient for software prototyping.

Another important library used was PCL, the Point Cloud Library (PCL) is a standalone, large scale, open project for 2D/3D image and point cloud processing. The PCL framework contains numerous state-of-the art algorithms including filtering, feature estimation, surface reconstruction, registration, model fitting and segmentation.

A software for the PCAS (Profile and Collision Avoidance Submodule), was developed. The PCAS is a common submodule for both the UIM and the RPIM. The sensors comprised by the PCAS are:

- Scanning Profiling Sonar
- Sonar Altimeter
- CCTV camera

It was agreed by the UC3M and the rest of the partners to develop drivers for the sensors instead of using the proprietary software. The main reasons were:

- Integration of the sensors within the ROS framework
- Integration of the sensors in the same User Interface
- More appropriate data display for this specific application

It should be noted that these drivers can be run without the user interface with the Linux Terminal.

<u>Profiling Sonar Driver</u>

The Profiling Sonar provides many configuration parameters. The software from the manufacturer (Seanet Pro), only allows to show one scan at a time (see *Figure 92*, left), which is not very practical in this application, since it doesn't allow to see the whole structure of the shaft mesh. Moreover, Seanet Pro only allows to export the data to Microsoft Excel format (*.csv), which doesn't have tools for 3D representation neither. The main motivation to do a personalized driver for the Profiling Sonar, was to do the 3D representation of the point cloud with the scanned data, as shown in *Figure 92*, right.

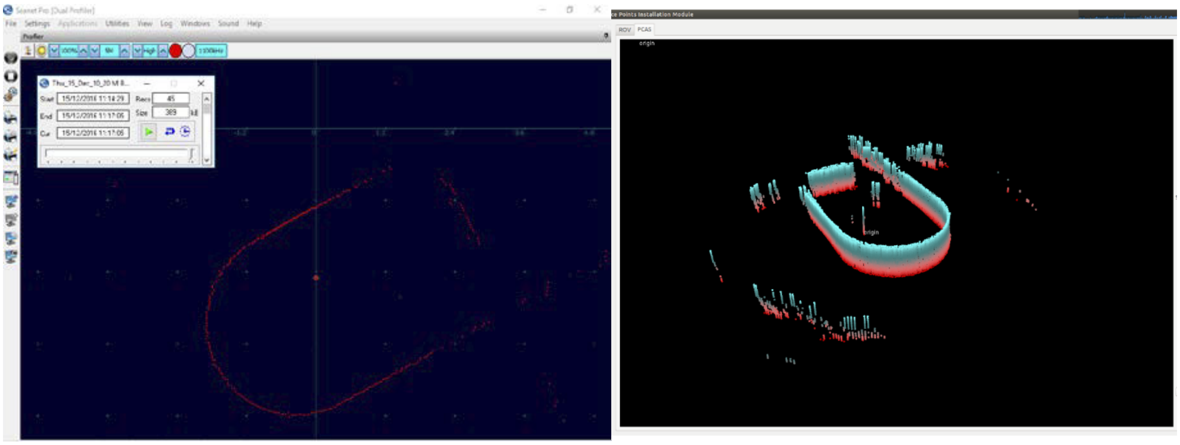


Figure 92 - Left: Profiling Sonar Scan with Proprietary Software. Right: 3D Waterfall Done with the Custom Software

Anti-Collision Altimeter

The Anti-Collision Altimeter is other of the sensors in the PCAS for which a driver has been developed. This is a simple sensor which starts sampling and sending the measurements via serial channel once powered one. The main interest on developing a software for this sensor lied in the integration of its measurements in the user interface. The original interface is simply a serial terminal, as seen below (*Figure 93*). The main advantage of integrating the altimeter in the interface, is the possibility to see its measurements at first sight, while visualizing the other sensors.

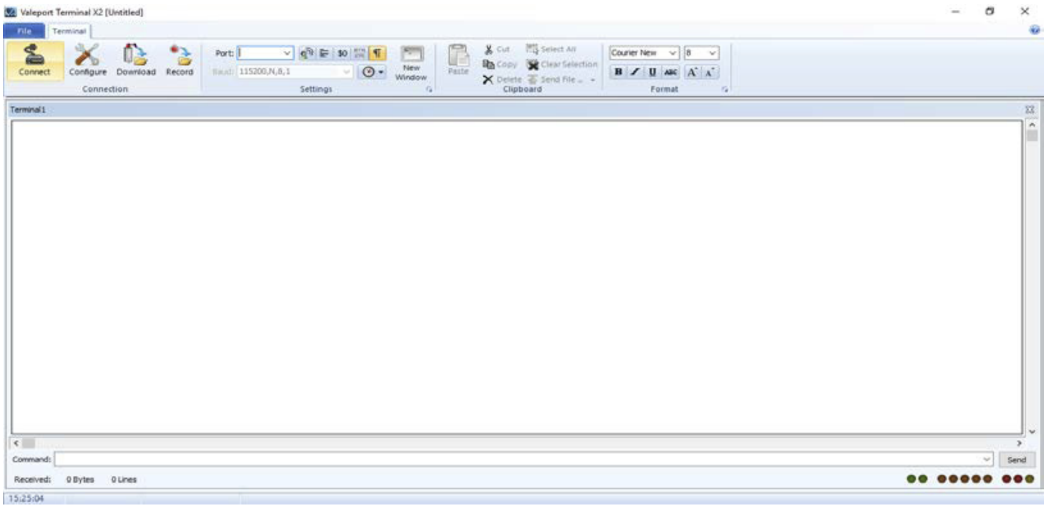


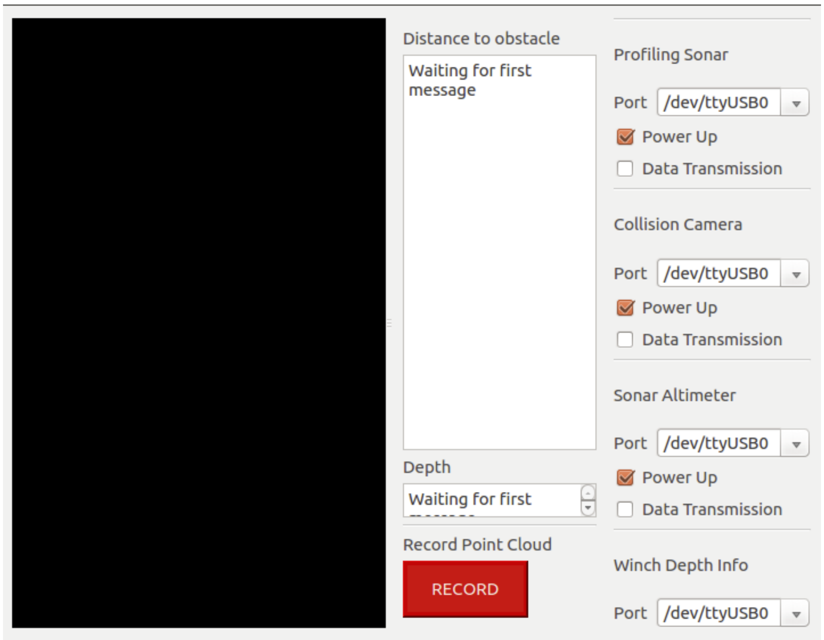
Figure 93 – Original Interface for Anti-Collision Altimeter

CCTV Camera

A driver for the CCTV camera was also developed for the possibility to have all the information in the same window. However, it was finally decided by DMT to directly connect this camera to an external screen.

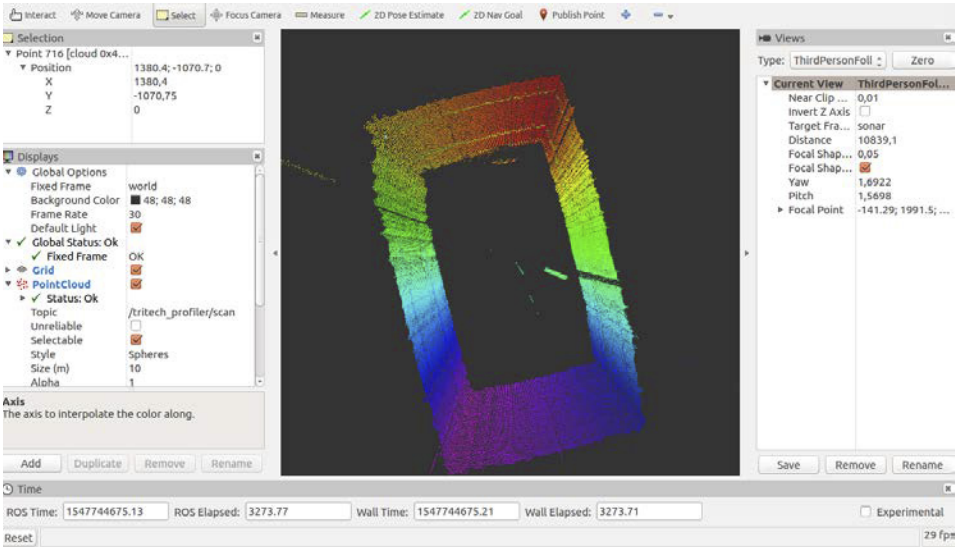
User Interface

The measurements from the previously described drivers were integrated in a single user interface, which runs over a Linux computer (like the low-cost computer Raspberry Pi). Three windows appear when launching the software:



The first one has the following displays:

- The image from the collision avoidance camera (if connected).
- Distance to obstable read from the collision avoidance sonar, depth information read from the winch, and a record button for the Profiling Sonar data.
- Configuration of the powering and data switching.



This window is for the point cloud visualization from the Profiling Sonar. It provides many configuration capabilities of the view, and the possibility to select single points and see its metrics.

The last window is more meant for developers. However, it includes also some further configuration parameters regarding the Profiling Sonar.

The Profiling Sonar is a complex sensor which provides many configuration capabilities. The software automatically loads a default configuration which is meant to work in the specific conditions of the STAMS project (360 degrees scan, high precision...), and also with the recommended settings by the manufacturer. These parameters are named using the manufacturer's notation and it is recommended for the user to consult the profiler's datasheet for more detailed and reliable information about its meanings. The most important configuration parameters who might be useful for the user are:

- **left_limit:** Left limit of sector scan in radians (default 0).
- **range:** Scan range in meters (default 2).
- **right_limit**: Right limit of sector scans in radians (default 2п).

- **step:** Mechanical resolution (Resolution enumeration) (default 0.5 degrees; high resolution).

Task 5.3. Calibration and Application of the Coupled Modelling Approach with the Monitoring Technologies

Further to the cases analysed in WP4 to illustrate the proposed coupled modelling approach and to show its ability to reproduce and to explain the behaviour of collapsed shafts, four additional shafts belonging to the industrial partners were selected for application and demonstration of the development made within the project. Long-term stability assessment of these shafts requires the acquisition of a lot of data covering the shaft itself and its construction, the rockmass in which it is sunk, and the lining material installed for its reinforcement. This includes geological, hydrogeological, geotechnical and chemical data. Unfortunately, rarely these data were completely available for the four shafts and therefore it was necessary to estimate them or to make assumptions to perform the modelling work. Our proper experience with European coal mines was used to evaluate the missing properties or to make the wise hypotheses. Sensitivity analyses were also carried out to overcome the lack of data and to give indications on stability conditions.

Shaft stability modelling is deemed to be calibrated with field measurements made with the new developed monitoring systems. However, at the end of the project, the acquired measurements were simply qualitative and did not allow performing a real calibration.

The coupled modelling approach applied for long-term stability assessment of the different studied shafts is based on many assumptions and uses various parameters mainly at the chemical and mechanical levels. To validate the assumptions made and to better adjust the parameters used, a laboratory testing programme was set up on concrete samples submitted to water solutions. Concrete was selected as it represents the most common shaft lining material in coal mines. The principle of the tests consists of submitting concrete samples to different water solutions and studying the chemical reactions and their effect on the mechanical properties. Two water compositions were considered: the first one is a typical mine water reproducing the conditions of Fondòn shaft, and the second corresponds to a very aggressive solution with a high concentration of sulphate and a relatively weak pH. Due to limitation of the testing period, part of the tests was conducted at high temperature to accelerate the chemical reactions.

To illustrate the modelling work performed on the four selected shafts, only the shaft where an inspection was possible with MMM is presented below (shaft 1 of Piast colliery, PGG - Poland). A brief summery is also presented on the laboratory testing programme. More details on the studied shafts as well as on the testing programme can be found in deliverable D5.2 entitled ”Calibration of the coupled modelling approach with the measurement technologies”.

<u>Stability assessment of Shaft 1, Piast colliery, Poland</u>

The shaft is located in Kolonia Wola south east of Katowice. It is connected to three other shafts of the colliery and is currently used as pumping station. It was sunk in two periods: the first one ended in 07/08/1978, and the second, in 29/10/1980. The shaft has a total depth of 669.5m and an internal diameter of 7.5m. During the mining operations, it was used for personal and material transport as well as for ventilation. The lining is made by concrete either poured or in blocks.

The geological cross-section includes Quaternary formations (from 0 to 48.9m), Tertiary formations (from 48.9 to 214m) and Carboniferous formations. Quaternary formations are represented by layers of sand and gravel as well as plastic clay prone to swelling. Tertiary formations are also made by alternating layers of sand, plastic clay and indurated clay. Carboniferous formations are composed of strata of shales, sandstones, among which coal seams with a thickness of up to 2m occur. Water horizons are identified in each geological system mainly in the sand, gravel and sandstone layers.

Mine water samples are taken in shafts 1 and 4 at different dates and depths and chemical analyses are made. The concentrations of the governing elements of mine water in the foreseen chemical reactions with lining are: 110 to 775 mg/L for sulphates, 1000 to 17700 mg/L for chlorides, 177 to 415 mg/L for bicarbonates and 7.0 to 8.2 for pH.

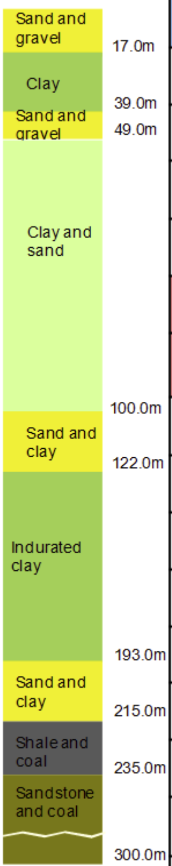
The examination of the stratigraphic column showed that the critical area which may undergo failure lies with Quaternary and Tertiary formations particularly in the sand, gravel and clay layers. As the geotechnical properties of the different strata were not available, they were assessed based in our experience with Polish coal mines and the collapsed shafts back-analysed in Task 4.5.

Due to bad host rocks and water horizons in the quaternary and Tertiary formations, a dedicated concrete lining was installed. This lining is made with two rings of concrete. The characteristics of the different lining sections along the depth of the shaft are given by *Table 5*. It is important to note that thicker lining and higher concrete strength were installed when crossing sand, clay and gravel layers. For modelling, the two concrete rings were homogenised in a single one with an average thickness of 1m and an average Unconfined Compression Strength (UCS) of 30MPa.

In the absence of data on concrete composition, cement is assumed to belong to class I and aggregates are assumed to be not reactive. When considering the highest concentrations of the most reactive chemical elements in mine water, the estimated width loss obtained in two centuries with the most severe hypothesis would be around 57mm from each side of concrete lining.

Using the analytical convergence-confinement method, a sensitivity analysis was conducted on the stability conditions of the concrete lining for different depth sections. *Figure 94* shows the results of the most critical section located at 215m depth (sand and clay ground) and emphasises that a concrete lining thickness reduced from 1 to 0.6m allows guaranteeing the stability with a safety factor higher than 1.5 provided its strength is above 12MPa.

An axisymmetric finite element model was then established from the surface to a depth of 300m and simulations were run in two steps to reflect lining installation time. The areas submitted to the highest deviatoric stresses (shear) correspond to the very weak layers of sand and clay particularly at depth 215m (*Figure 95*). Overall, the numerical results are consistent with the analytical approach and show that the safety margin taken in the lining design allows overcoming the weathering phenomenon induced by chemical reactions as well as the effect of hydraulic loading which was not considered in the modelling.



No.	Depth [m]	Inner lining		Outer lining	
		Type	Thickness [m]	Type	Thickness [m]
1	4.5 – 25	Concrete R_w200	0.50	Brick 350	0.51
2	25 – 50	Concrete R_w200	0.50	Brick 350	0.51
3	50 - 125	Concrete R_w300	0.50	Concrete R_w300	0.40
4	125 – 142	Concrete R_w250	0.50	Concrete R_w300	0.40
5	142 – 200	Concrete Rw300	0.50	Concrete Rw300	0.80
6	200 – 214.5	Concrete R_w300	0.70	Concrete elements R_w400	0.40
7	214.5 – 230	Concrete R_w250	0.50	Concrete R_w300	0.40
8	230 – 278	Concrete R_w200	0.50	Concrete R_w300	0.60
9	278 – 284	Concrete R_w200	0.50	Concrete R_w300	0.50
10	284 – 372	Concrete R_w200	0.50	Concrete R_w300	0.50
11	372 – 515	Concrete R_w250	0.50	Concrete R_w 300	0.45
12	515 – 600	Concrete R_w250	0.50	-	-
13	600 – 635	Concrete R_w300	0.65	-	-
14	635 – 669.5	Concrete R_w250	0.65	-	-
Rw# means a concrete having unconfined compression strength of # bar					

Table 5 – Characteristics of the Lining Sections of Shaft 1, Piast Colliery

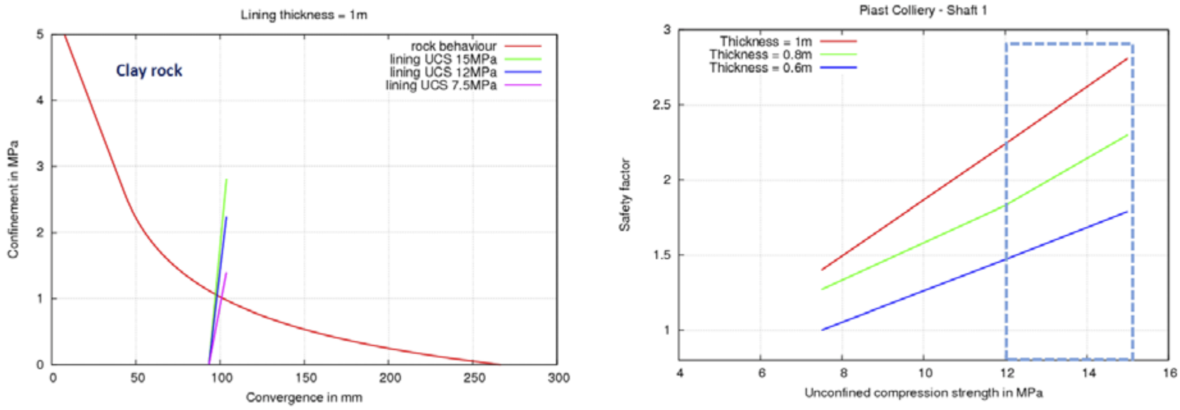


Figure 94 – Sensitivity Analysis on the Stability Conditions of the Clay Ground Section

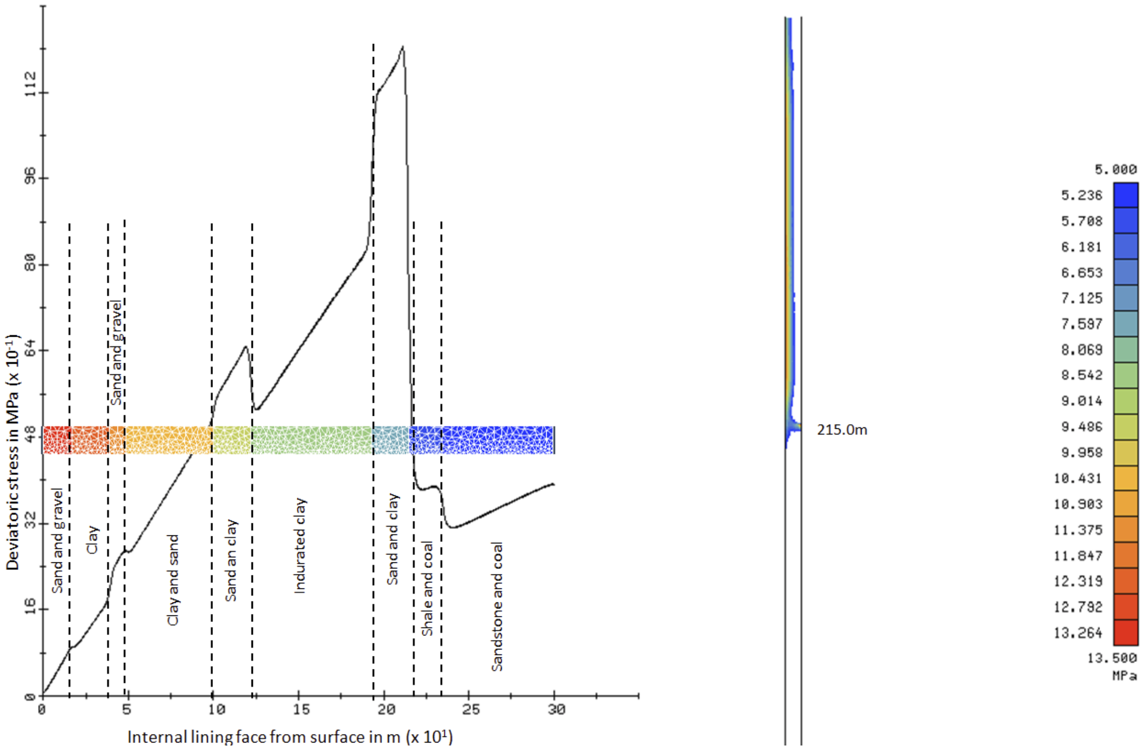


Figure 95 – Distribution of the deviatoric stress at the internal lining face (left) from surface to 300m and required UCS of concrete to ensure lining stability (right)

Modelling calibration was not possible with the measurements of the new developed monitoring systems because the measurement concerns the exterior inspection without strain and displacement measurements. At the last period of the project, only inspection with MMM was conducted in the shaft. This monitoring system allows detecting lining potential failure either by camera observations or sonar scanning when an irregular variation of the shaft wall is identified. During the investigation, no particular lining damage was observed confirming hence the results of the stability analysis.

<u>Laboratory testing programme</u>

Assuming that concrete is made by non-reactive aggregates, the only chemical reactions would occur between cement and mine water. Portland cement (CEM class I) was considered and dedicated cylindrical sample were immersed in water solutions at two controlled climatic conditions: room temperature and 70°C. The two water solutions were prepared in laboratory from the mixture of two mineral waters and the addition of solutes and an acidic-base solution. Before starting the tests, the initial characteristics of both mine water and cement were measured.

Each prepared sample was installed in a dedicated container to avoid interactions and evaporation during the testing period. Water volume was assessed to be equal to at least ten times cement sample volume to allow continuous exchange with stagnant water (*Figure 96*). The total testing duration is 6 months and comprises three phases. At each period of 2 months, the following analyses are made:

- general measurements: loss of mass, formation of precipitates, density and sound velocity;

- chemical analysis of water: pH and concentrations of Cl^-, SO_4^{2-}, NO^{3-}, Ca^{2+}, K^+, Mg^{2+}, Na^+, HCO^{3-};
- physical properties and mineralogical analyses of altered cement: porosity measurements using different methods, SEM and composition by XRD;
- mechanical properties: uniaxial compression test to identify UCS, Young module and Poisson ratio.

Solution	Mine water		Acidic water
Temperature	Room temperature (T=20°C)		T=70°C
Period	2 months	4 months	6 months
Number of tests	Initial state + 12 tests, each one is performed on two directions with regard to cement pouring: Total: 26 samples		

Figure 96 – Testing Programme (top), Tests Conducted at 70°C in a Climatic Cell (bottom left), and Analyses Conducted on each Sample after Testing (bottom right)

After laboratory testing and analyses, chemical modelling was conducted to reproduce the observed phenomena and to fit the governing parameters. Mean values derived from laboratory analyses were used for the composition of the two water solutions. The initial cement composition was calculated on the basis of an oxide cement belonging to class I followed by a simulation of the hydration phase. The results which can be derived from both laboratory measurements and numerical simulations are classical and can be summarised as follows:

- portlandite is first dissolved;
- Calcium Silicate Hydrate CSH_1.6 is then dissolved and CSH_1.2 or CSH_0.8 or amorphous silica could be precipitated;
- Ca^{2+} is released from these dissolutions and consequently calcite is precipitated;
- hydrotalcite is first dissolved but could be precipitated close to the contact zone;
- ettringite is first dissolved, but could precipitated also deeper in the cement;
- Mg^{2+} is also released and consequently brucite is precipitated;
- the altered thickness for classical mine water at room temperature is around 1.7mm with a portlandite degradation depth of around 0.7mm and a calcite depth of around 0.3mm;
- temperature and acidic solution increase degradation; for the extreme case of acidic water and temperature of 70°C, the total altered thickness is around 3.1mm (*Figure 97*);
- In all cases, local porosity decreases and this contributes to limitation of alteration.

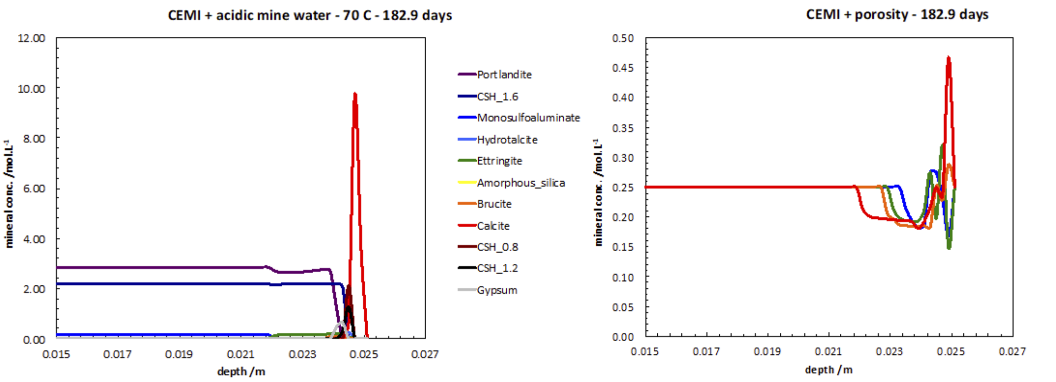


Figure 97 – Cement Composition along the Sample Axis after 6 Months of Testing in Acidic Mine Water and 70°C (left) and Porosity Variation in the Four Conditions (right)

The main conclusions of the laboratory tests can be summarised as follows:

- The altered thickness of cement is very limited even when using very acidic mine water and high temperature,
- Modelling is able to reproduce the laboratory results in terms of chemical reactions and extension of the alteration process.
- Variation of mechanical properties after water attack is very difficult to be identified due to the limited thickness of the altered area with regard to the sample dimensions and the phenomenon of results dispersion which is very common in laboratory testing even for very homogenous materials.
- Consistency between laboratory and modelling results allows validating the assumptions made when assessing the long-term stability of shaft lining. In fact, the hypothesis made for this assessment (constant porosity, spalling and collapse of the degraded zone) are pessimistic and lead to a loss of a high lining thickness and therefore are very safe.

WP6: Field-trials, Assessment and Technology Transfer

Although some of the technologies will have required previous tests, in this last WP the integrated systems were tested in order to allow a final assessment to the monitoring system for flooded shafts. In addition, the project outcome was disseminated.

- G6.1 To demonstrate the scope of the technologies developed on the project.
- G6.2 Assess the viability of the proposed measurement system.
- G6.3 Generate reports with the conclusions of the results.
- G6.4 Provide the basis for future developments and technology transference.
- G6.5 Demonstrate the reliability of the coupled modelling approach for assessing the long-term shaft stability.
- G6.6 Disseminate the results of the project.

Task 6.1: Demonstration of Systems and Equipment at Selected Shafts

In this task, we presented the demonstration of the developed systems, carried out by the partners of STAMS with the assistance of the industrial companies during the last period of the project.

<u>Multi-functional Monitoring Module (MMM)</u>

Field trials of the Multi-functional Monitoring Module were carried out in five locations in Poland (*Figure 98*). Four of those shafts are owned by project partners: three are managed by SRK and one by PGG. Moreover, one test was conducted in shaft that belongs to Tauron Wydobycie (Polish coal company) and it was performed as a part of dissemination efforts.

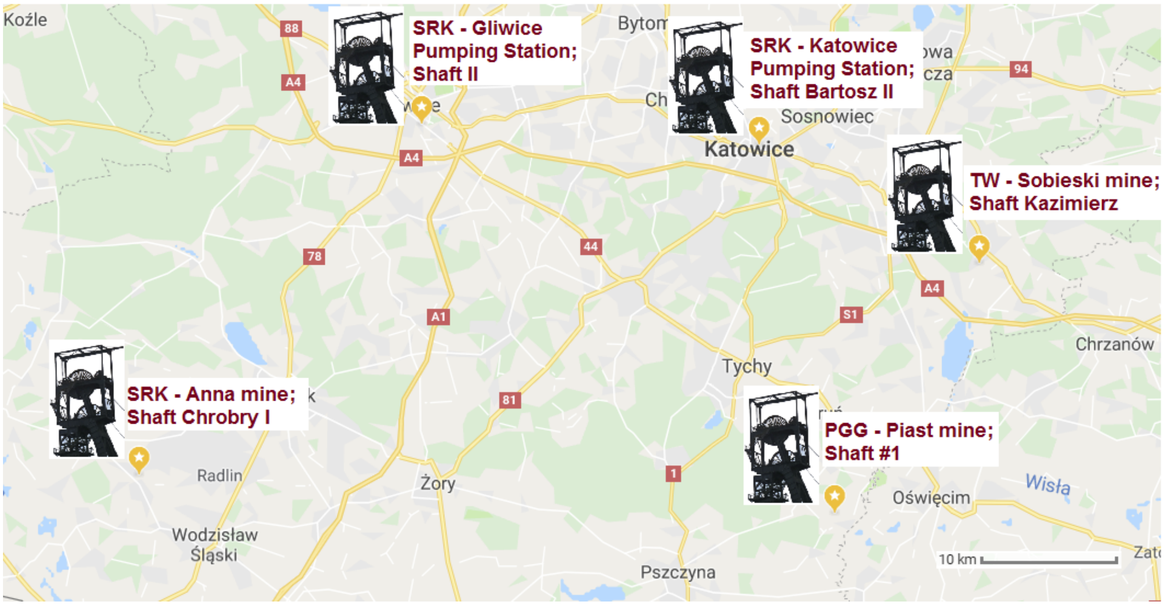


Figure 98 – Location of MMM Field Trials – Poland – SRK and PGG

Individual shafts differed in lining, diameter, access, size of shaft opening, installations and organization of the site, etc. From this reason, each test required an individual approach. Conducting test in known location improved work and reduced time of preparation, but differentiating the tested shafts was more favourable in terms of adjusting the module to various conditions. Under different needs, both approaches have been taken.

All of MMM tests were carried out between November 2017 and December 2018. Cooperation with two polish mining related companies (SRK S.A. and PGG S.A.) allowed testing the prototype in real conditions throughout the course of the project. Summarized information on the peformed tests were included in the table below (*Table 6*).

Table 6 – Dates and locations of conducted tests

No.	Date of test	Place of test	
1	29.11.2017	KWK Piast (PGG)	#1 Shaft
2	7.03.2018	KWK Anna (SRK)	Chrobry I Shaft
3	2 ÷ 10.04.2018	KWK Piast (PGG)	#1 Shaft
4	4 ÷ 6.07.2018	Sobieski Colliery (TAURON Wydobycie)	Kazimierz Shaft
5	4.10.2018	KWK Piast (PGG)	#1 Shaft
6	16.10.2018	Katowice Pumping Station (SRK)	Bartosz II Shaft
7	18.10.2018	Gliwice Pumping Station (SRK)	Shaft II
8	11 ÷ 14.12.2018	KWK Piast (PGG)	#1 Shaft

Function of individual trials changed in time. First trials were conducted to test the construction of the module and its waterproofing. During next trials it was possible to determine the correctness of the connection between operator and the machinery and to detect encountered problems, failures and minor issues. In the following trial tests all the instruments were being adapted to the specific conditions of the shafts. Eventually, the purpose of last trial tests was to improve the routine of conducting the examination and develop a safe, efficient and reliable procedure of shaft examination.

First trial test, conducted in 2017 resulted in both encouraging results and several issues. Conducting the field trial has confirmed the proper design of the trestle, waterproofing of the capsule, and the ability to control the up/down movement. Encountered problems were identified as:

- no visual connection with the cameras,
- poor quality of recorded films,
- errors in the visual recording of cameras,

- no record of sonar scan,
- the sonar housing causes interference,
- incapability to put the arms in vertical position,
- no depth record,
- no speed display,
- malfunction of cable stacker.

Urgent issues were addressed immediately, some of them concerning the construction of the MMM. Following tests generated less problems. During the second trial, that took place in Chrobry I Shaft the malfunction of the cable stacker was resolved (*Figure 99*). The cable was extended to its maximum length and rewinded back on the drum, thanks to which its positioning was correct.

Figure 99 – March 2018 Trial, Resolving Cable Stacker Issue

Third field trial was set to be combined with the MMM presentation held for all of STAMS partners. The MMM presentation, which all the STAMS partners were invited for, was held on 10th April 2018, but the field trial in this location started over week earlier, on 2nd April 2018. The MMM was submerged in the water, once again verifying the waterproofing. The connection between the equipment on the MMM and the computer was successful. All of the issues encountered during the first trial has been confirmed to be solved. The main inconvenience became incorrectly illuminated camera image and lack of profiling sonar output and the quality of imaging output. A selection of photographs from the field trial are presented as *Figure 100*.

Figure 100 – March 2018 MMM Field Trial Combined with Presentation

Following field trial was arranged to take place in July 2018. The aim was to improve the routine of configuring the required equipment, the monitoring process itself, and the quality of the sonar output. Central Mining Institut (CMIPL) was the only partner involved in the preparation of the test. Kazimierz Shaft belongs to company Tauron Wydobycie SA and this specific trial test was performed as a part of a dissemination activity directed towards potential recipients. Unfortunately during the last day of tests, water has entered the MMM case. Effects of failure are presented in *Figure 101*. Presumably this issue was a result of an imprecise tightening the cap of steel cylinder casing. This drawback caused an delay in performing future examinations. It was established, that few of the MMM devices would need to be replaced. The priority was to prepare the module for the upcoming tests as soon as possible, unfortunately it took almost three months to conduct another test.

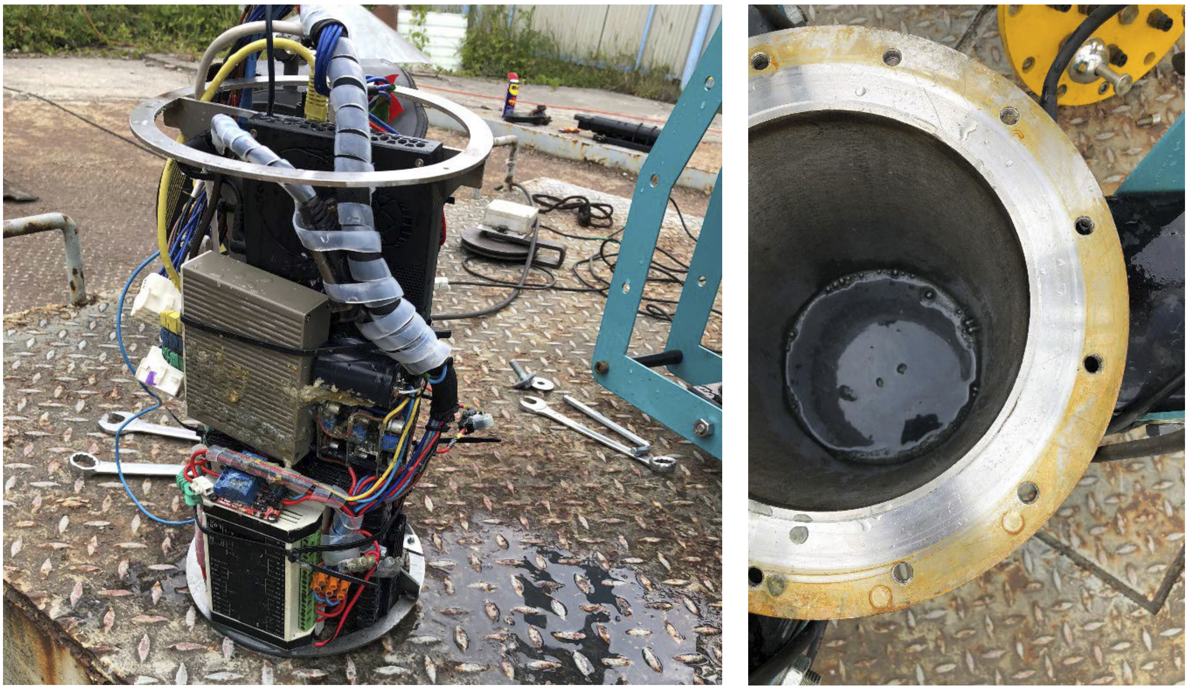


Figure 101 – July 2018 MMM Failure Outcome

To provide secure conditions of the test it was decided to conduct it in Shaft No. 1 of the Piast mine. Familiar conditions were favorable in submerging the capsule for the first time since the incident of damaging the probe. The goal of this test was to assure the water resistance of the capsule and a proper functioning of new components. In the limited time, the team managed to submerge the MMM about 200 meters below the water level. The test was successful.

Back in October 2018, beside the test on Piast Colliery, there were performed two other trials. One of which took place in Katowice Pumping Station, second – in Gliwice Pumping Station. The goal of those was to assure the water resistance of the capsule and a proper functioning of new components, test the correctness of the connection between the work station and the module, test the functionality of the sonar, improve the quality of sonar input and improve the routine of conducting the examination. A selection of photographs from the Bartosz II Shaft field trial is presented in *Figure 102*.

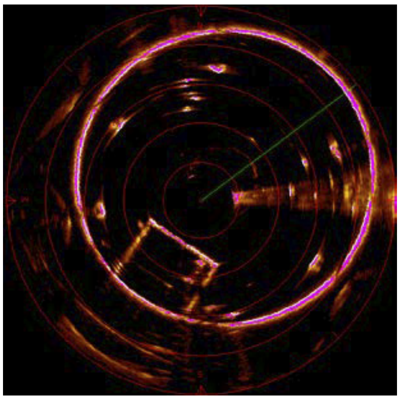
 

Figure 102 – Bartosz II Shaft Field Trial, Camera and Sonar Profile of Flooded Shaft

The last field trial took place in December 2018 in Piast Colliery. The main purpose of this field test was to perform entire and complete examination of the sunk part of shaft lining with the use of MMM, so form and scope of this examination would be consistent with a form and scope of the future commercial examination of the sunken shafts. Therefore it was decided to scan the lining of the shaft every twenty meters to be able to evaluate with appropriate approximation its condition and presence or absence of major defects and lacks in the lining.

All the procedures related to the last field trial lasted for four days, from 11th to 14th of December 2018. On the first day two trailers with the winches and all the equipment were brought over to the inspection site. The last day was scheduled to clean the inspection site, remove the installations and bring the equipment back to Katowice. A selection of photographs from the inspection site are presented in *Figure 103*.

Figure 103 – December 2018 MMM Field Trial – Paist Colliery

The sonar scans were performed on 12th and 13th of December at depths: 215, 235, 255, 275, 295, 315, 335, 355, 375, 395 and 415 meters below ground level.

As a result of the examination video image from all of three cameras and sonar output were obtained.The sonar output haven't shown neither major irregularities nor any relevant and alarming loss in the lining structure. The images obtained from sonar performance are presented in *Figure 104*.

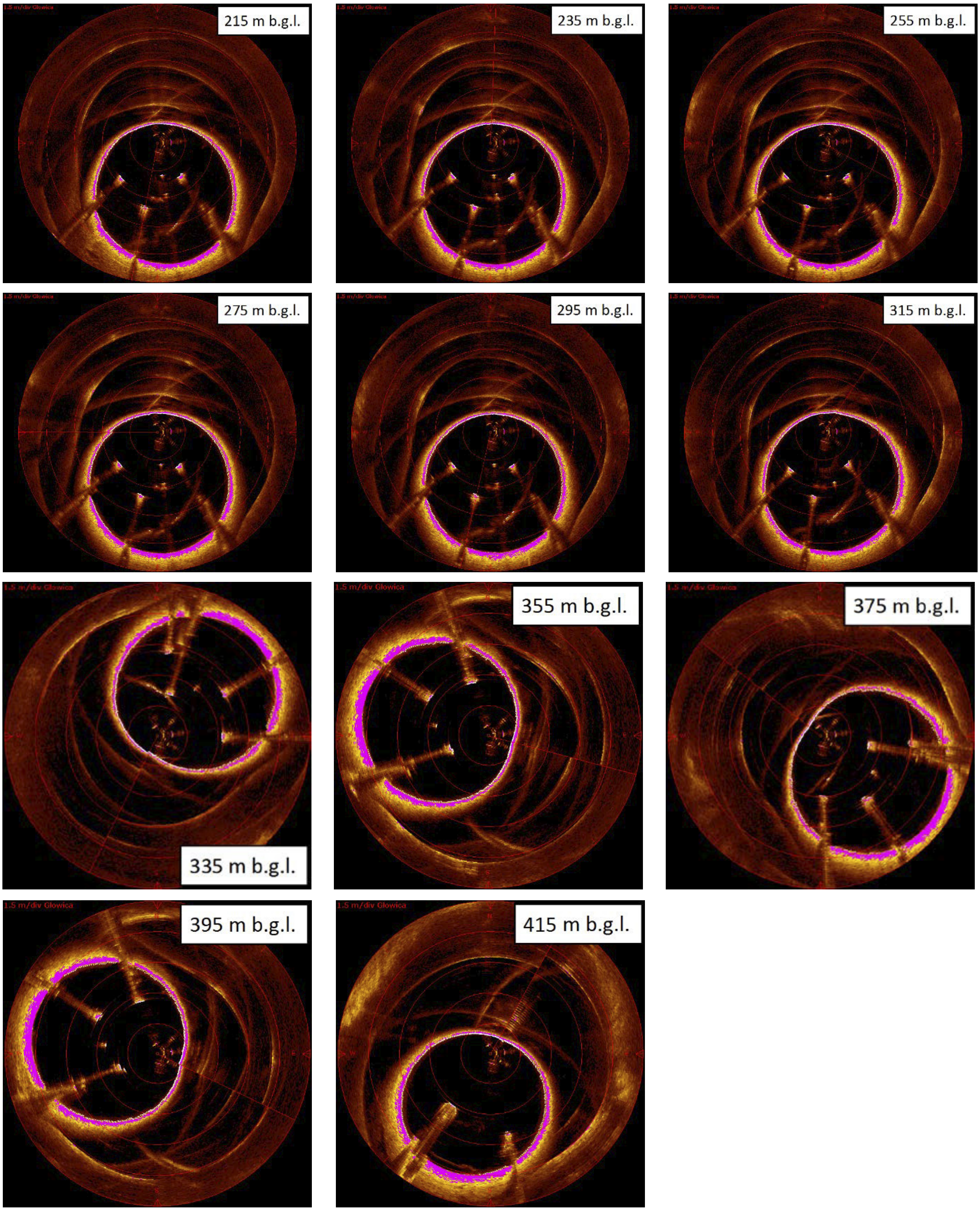


Figure 104 – Imaging and Profiling Sonar Output from December 2018 MMM Field Trial

<u>Ultra sonic Module UIM</u>

Following extensive laboratory testing, a field trial of the UIM was carried out on 21st and 22nd March -2018 at the No. 2 Shaft of the abandoned Smithy Wood Colliery (Norfolk Mine), Thorpe Hesley, near Rotherham, South Yorkshire, United Kingdom. The access port is 383mm in diameter. This demonstrates the reduced size advantage of the UIM compared to the MMM. Deployment of the latter would have involved expensive engineering work at the surface to create a larger diameter opening. The following encouraging results were obtained:

- The physical stability of the complete assembly, including its waterproofing, was demonstrated.

- The UIM was successfully deployed in the shaft using the winch and services provided by a third-party company. This is an important result for organisations that do not have access to winching facilities in-house.

- The CIS was shown to be operational with the exception of the serial data switch, as described later.

- Useful data was obtained from the GRS.

- Although not fully complete at the time of this first trial, the software for controlling and monitoring the UIM (and other PIMs) was demonstrated.

However, problems were encountered, most notably, although data was obtained from the profiling sonar, that data did not appear to represent a cross-section of the shaft. Subsequent analysis revealed that it is possible to programme the unit to operate on a frequency that is not supported by its hardware and such a command had, inadvertently, been sent by the software. Discussion with Tritech, the manufacturer of the profiling sonar, provided useful insight into the parameters that control it operation. This resulted in to changes to the software, ensuring correct initialisation, and providing a facility for the operator to revert to default settings in situations, like the one experienced, when meaningful data is not obtained.

Left: Preparation of UIM and Attaching Wireline Prior to Deployment

Above: Robertson Geologging Winch Vehicle

Above: Preparing to Lower UIM into Shaft

Right: Fine Adjustment of Position Before Final Deployment

Figure 105 –UIM Field Trial Photos: Thorpe Hesley

Following remedial work, attention turned to arranging a second field trial. However, because the UIM field trials started later than anticipated, due primarily to the fire at DMT which resulted in a delay to the work with the UIM and an extension to the project, the time period for which the No. 2 Shaft, Smithy Wood Colliery (Norfolk Mine) at Thorpe Hesley was available was exceeded. Specifically, a few months after the field trial, planned work started on converting the shaft into a water pumping station. This prevented its use for a second test. Also, the other shaft in the UK that had been prepared by the Coal Authority – at Hartington in Derbyshire – was subsequently found to have a blockage and work also started on that shaft, shortly after the Thorpe Hesley test, to convert it into a pumping station. No other shafts in the UK had been identified as potentially suitable, and the limited amount of available time did not permit further sites to be found and prepared. An extensive search for a suitable shaft was carried out in Germany when it became clear that a second test could not be carried out in the UK. Only one shaft was identified where permission would have been available for its use – Kirchhain Shaft – but this shaft was not accessible due to the lack of an access opening and safety reeling below the surface. Only special certified companies are permitted to make these installations at an open shaft. The remaining time did not allow this work to be carried out. Shafts were available in Poland and Spain but the available time for these shafts was dedicated to tests of the MMM and the RPIM respectively, as described elsewhere in this document.

Since a shaft was not available to carry out an additional field test on the UIM, the testing rationale was reappraised. It was noted that all the issues that required access to an actual shaft had already been addressed at the first on-site test. Therefore, it was decided that the functionality of the profiling sonar in the PCAS, the main element that had not been proven during the field test at Thorpe Hesley, would be addressed in additional extensive laboratory tests.

The tank used for this test measured 220mm × 125 × 80mm. By way of contrast, the survey of shafts carried out in T1.1 suggested that we need to be able to monitor shafts to a maximum diameter of 8m but, because the access port might be only 1m from the shaft wall, a maximum range of 7m is necessary. However, this does not imply that carrying out a test in a tank with a maximum horizontal dimension of 220mm is not a valid approach. The maximum range of the Tritech Super SeaKing profiling sonar is quoted as 40m, even in its short-range, high resolution 1.1MHz mode, as used in the UIM. As a result, for mine shaft inspection, this instrument will never be used at a range even close to its maximum and, therefore, the size of the tank is not considered an issue.

Because of the limited depth of the test tank, and because the other modules (CIS and GRS) had already been shown to be operational, only the PCAS was deployed in the tank. The other two modules remained in circuit, outside the test tank, because their functionality is required by the software, and so that the tests were as close as possible to the actual use in a shaft. This test was a complete success, as evidenced by the profiling sonar results shown in *Figure 106*. Note that the non-uniform cross-section is due to additional elements that were deliberately fixed to the tank wall to simulate shaft furniture.

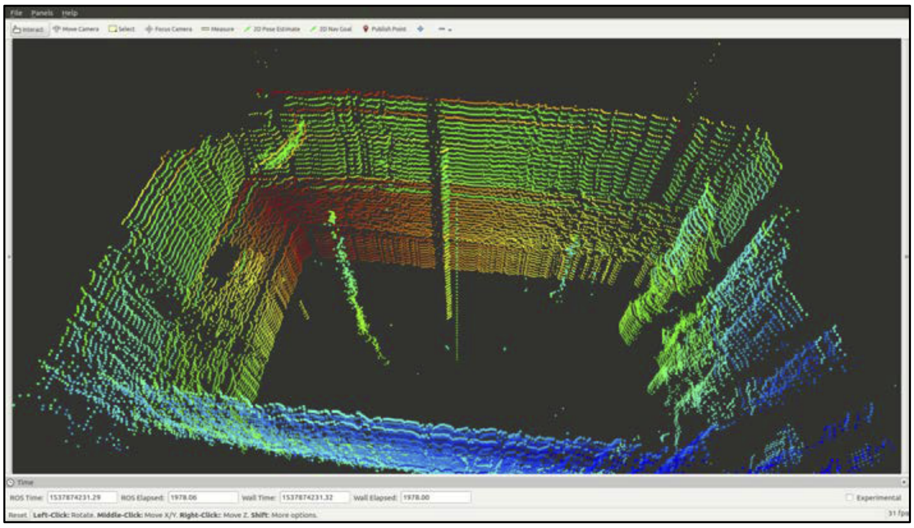


Figure 106 – Reference Point Detection in Water Tank with Pipes and Steel Plates

The final set of additional laboratory tests were carried out in the same tank but with the complete UIM assembled. This permitted correction so be made to the data for unintentional motion during winching which, in this case, was caused deliberately. This test also gave succesful results.

<u>Reference point installation</u>

Field tests of the Reference Point fastening system were carried out in HUNOSA premises, with participation of UC3M and HUNOSA, on 9th and 10th of October 2018. UC3M designed the software package to control the ROV, and the firing mechanism, while HUNOSA was in charge of selecting and preparing the test site, including the winch to haul the ROV.

The objective of the tests was to validate the results obtained in the laboratory test in field conditions. Once the viability of performing direct fastening in underwater conditions was proved, the next step was to perform it in the concrete wall of a flooded mine shaft. Although the ideal case would be performing the tests with the complete RPIM (*Figure 107*), due to the impossibility for DMT to take the RPIM with the winch truck to Asturias, the tests were carried out with the ROV and the fastening device from UC3M as shown in *Figure 107*.

The first day the test was carried out at Sotón Shaft Workshop in Asturias, Spain, to check the operation of the winch and the communications between the topside computer and the ROV, when using the slip ring integrated in the winch drum (the one be used the next day on the mine shaft)

Figure 107 - Communication Tests at Sotón Workshop in Asturias

The second day, the firing test in the mine shaft was performed, at Mosquitera shaft in Asturias, Spain.

Figure 108 – ROV with the Fastening Device Being Lowered into Mosquitera shaft in Asturias

The tests were performed near the water surface (around 5 meters), since without the protective case of the RPIM it could be dangerous to lower the ROV at higher depths. The ROV was lowered with its own cable, using a winch provided by HUNOSA. Test results were very positive (*Figure 109*). The navigation of the robot worked correctly, one of the Reference Points was fixed to the Shaft wall and the ROV battery autonomy was enough for carrying out the operation. However, the following problems where encountered:

- Concrete was weakened, and it spalled when shooting the bolt, making more difficult than in ETSIAN test for the Reference Points to stay attached.
- Entangling of the cable with a pipe, which could be solved by navigating back the path followed. This confirmed the necessity of having a Docking Station where the robot can be lowered more safely.

Figure 109 - The Aluminum Core of the Reference Point Bolted to the Shaft Wall (left) and Pipes in the Mine Shaft (right)

As result of these tests, the following conclusions can be extracted:

1. Although the viability of the Reference Points attachment has been proven, it was detected the need of using longer nails in mine shaft concrete, because the weakened/damaged concrete spalls and thus a higher penetration on the wall is required.
2. The complicated and unknown environment that the mine shaft presents also remarked the necessity of using a Docking Station, to avoid the entangling of the wire with possible obstacles.
3. Finally, the teleoperation worked properly, but the difficulty of the operation evidences the interest of developing in the future an autonomous deployment and navigation method.

Task 6.2. Analysis, Assessment and Equipment Appraisal

Monitoring solutions for abandoned flooded shafts, that have been researched within STAMS, comprise technologies for both continuous and periodic measurements. In the area of periodic monitoring, which allows detailed inspections to be carried out on an occasional basis, so that changes are detected before those alterations are able to cause damage. Working practical systems have been developed for periodic inspection. Guidance is provided on using the periodic inspection modules – the Multi-functional Monitoring Module (MMM) and the Ultrasonic Inspection Module (UIM) – plus the Reference Point Installation Module (RPIM) which is used with the UIM.

The Multi-functional Monitoring Module (MMM) is capable of making several types of measurements including visual inspections, sonar profile and imaging monitoring. The Multi-functional Monitoring Module, in its full equipment configuration, consists on a steel casing, three arms and the various specialized instruments. The casing provides mounting for the arms and the sonar instrument. Inside the casing there are power, control, registration and transmission systems installed. As proven during the trails, the Multi-functional Monitoring Module enables conducting the examination in underwater parts of shafts that are partially or completely flooded.

The UIM records shaft profiles using a profiling sonar instrument to obtain an accurate three-dimensional mode of the shaft geometry. It can be seen that the UIM is comprised of three sub-modules which are shown separately for clarity but, in use, are connected together. The Cable Interface Sub-module (CIS), which is also used in the RPIM, provides power supplies and communication capabilities as well as a mechanical connection to the wireline. The Geo-referencing Sub-module (GRS), which is also used in the RPIM, contains inertial positioning systems to allow the motion of the module within the shaft's cross-section to be monitored, thereby allowing unintentional movement such as rotation and pendulum motion to be taken account of in generating the 3D shaft model. The Profiling and Collision Avoidance Sub Module (PCAS) houses the profiling sonar and two instruments for detecting obstacles below the UIM which could cause a collision risk. A CCTV camera is used for this purpose above the water level and a sonar altimeter is used for collision avoidance below the water level. The Ultrasonic Inspection Module last test was carried out in December 2018. Results of this tank test indicated some issues, that can be corrected in the software and will easily and quickly be implemented when commercial opportunities arise for the UIM.

The Reference Point Installation Module (RPIM) is a modularly structured device, which purpose is to install reference points on the lining of a shaft. The RPIM has some sensors in common with the UIM, that is, the PCAS, which includes the Profiling Sonar, the Sonar altimeter, and the CCTV camera. Mentioned reference points can subsequently be detected the UIM to provide an additional element of positional information, thereby allowing more accurate comparisons to be made between subsequent inspections. The characteristic elements of the RPIM include the Remotely Operated Vehicle (ROV) and the fastening device carried by the ROV, plus the Docking Station Sub-module from where the ROV is deployed.

Conducting shaft examination is a very specific procedure. It is carried out in variety locations of various conditions. Those vary due to country in which shaft is located, mine conditions or development of the shaft site and all the surrounding constructions. Different shafts are flooded on sections of various lengths. Often, the conditions on site require work above grate depths.

Regardless the instrument being submerge in the water (MMM, UIM, RPIM) special precautions must be taken. This is extremely important to ensure the safety of the crew. The team conducting the inspection must consist of a minimum amount of people required in the instrument guideline. Each person must be aware of the work health safety policy, work with caution and wear full work clothing and equipment including helmet and height safety harness. For safety reasons, during whole examination process, a mobile gas detector should be present on the site.

All possible activities should be carried away or at a safe distance from a shaft opening. Those would be in example: setting the trailers, securing it from moving, assembling the trestle, operating the winches. During operations carried out above the shaft or in the near distance of the shaft opening members of the team are obliged to wear full work clothing and equipment including helmet and height safety harness and to attach safety harness lanyards onto a stationary and permanent element of the structure for safety. Approaching the shaft opening must be conducted wearing mobile gas detector, due to the possibility of release of gasses from the shaft.

T6.3. Results Dissemination

The objective of the dissemination task is to bring together the partners of the project and the end-users. That is obtained thorough different national and European actions.

The coordinator participated to a workshop in September 8, 2016 (http://www.robo-spect.eu/), the workshop took place in Athens (Greece) co-organized by ICCS and AIRBUS Defense and Space concerning the using of robotic system in civil engineering: tunnel inspections. We gave a large apercu of STAMS. Participants had the chance to learn more about the STAMS project. The event was attended by 50 participants;

A dissemination workshop was organised in Katowice in Poland, by Central Mining Institute. There were more than 50 participants from 7 mining companies (PGG, JSW, PG Silesia, Tauron Wydobycie, Węglokoks Kraj; LW Bogdanka), state and local authorities and other related to Shaft drivage and maintenance companies (CSRG, SRK, 'Bolko'- pumping station; PPG Row-Jas; PBSz, etc.).

The workshop was held 11th of April 2018. It took several hours and included a series of lectures presented by representatives of INERIS, ARMINES, UNEXE, UC3M and GIG. Moreover, GIG has demonstrated the potential of the MMM for investigating and monitoring the flooded shafts. The participants expressed their interest for using such tool to inspect and monitor the shafts. are presented in *Figure 110*.

Figure 110 – Photographs from the Dissemination Workshop

The information concerning the workshop was held on Central Mining Institute website (https://www.gig.eu/en/news/project-stams-short-long-term-stability-assessment-and-monitoring-flooded-shafts) and commented on the mining related polish press website (http://nettg.pl/news/149473/gig-naukowcy-i-gornicy-o-badaniach-zatopionych-szybow).

As part of a dissemination one of the MMM field trials was performed on shaft belonging to potential recipient – polish coal mine company Tauron Wydobycie SA. It took place in July 2018.

2.3. Conclusions

The main achievements made during the progress of the STAMS project are:

A database of flooded shafts in Europe, was built and analysed. It describes the range of depth, diameter, flooded zone, nature of lining, etc. It is useful for the management of closed shafts.

The Multi-functional Monitoring (MMM) and Ultrasonic Inspection modules (UIM) were designed and tested indoor and outdoors for macroscopic inspection of lining of flooded shafts. The UIM and MMM were designed considering the specificity of the flooded shafts (diameter, depth, water, etc.). The MMM, UIM were manufactured and tested. First laboratory tests, and then in-situ tests were carried out at SRK and PGG flooded shafts. To avoid collisions a specific sonar altimeter was selected and integrated into the UIM and MMM modules.

The electronic components were also prepared and integrated in the different inspection modules (UIM, MMM and RPIM). The integration of the cable interface, geo-referencing, and docking station sub-modules was achieved and tested in the laboratory and in situ.

The imaging sonar was selected and tested. It is able to give good information about the state of the lining and the water quality.

The design and the construction of the housing part for the protection in underwater conditions (150 bars, corrosive environment) were accomplished for the two modules.

A geo-reference point was designed and manufactured. A specific module was developed for the preliminary design of a device for fixing reference points. The acoustic reference point of a 3D object was selected in the project. The direct fastening method was selected, and the system was adopted for shaft conditions. Two fixing points were designed, the first one using the ROV system, and tested in different specific situations in deep flooded shafts. The reference point was designed and built and tested in the laboratory and in-situ.

Communication software was adopted and improved for the purposes of the project. Computer simulations were carried out to show the ability of the software, to work in realistic investigations and in-situ shaft monitoring. The communication system analyses the data formats for data exchange and open protocols. The software (open source) allows the visualization of the inspected zones of the shaft and compare the profiles and the videos.

The chemical composition of water and gas in flooded shafts was studied. Lab tests showed that degradation of concrete due to flooding could be detected by monitoring changes in the gas concentration of the shaft atmosphere. The equipment to detect water mineralization variations along the water column of a shaft is already commercialized and can be used in flooded shaft conditions.

A tube bundle system was developed to sample gas from the non-flooded zone. Its novel properties provide protection against the harsh environment of an abandoned shaft. A 20m sample length was manufactured and subjected to various tests on its toughness which confirmed its suitability. A breakout box was designed and methods of support and installation were studied.

Electronic sensors were studied for long-term monitoring of the flooded section of shafts. A novel underwater contactless method of power and data transfer was modelled, opportunities for low-cost sensing including protection from biodegradation were studied, value-engineering opportunities were investigated, and a low-cost waterproof housing was prototyped.

A numerical hydromechanical and chemical coupled modelling approach was developed for the assessment of long-term shaft stability and applied to French shafts lined with cast iron and concrete. The results showed the consequences of the reducing of the thickness of the lining on the shaft stability and the creation of a sinkhole on the surface.

Chemical reactions between mine water and lining materials, and the resulting alteration, may weaken the stability conditions and induce failure. The initial stability conditions before flooding are critical, and if the mine water is acidic the risk of failure is greater.

The equipment developed in the other WPs (UIM, MMM, RPIM) were demonstrated in the real conditions of flooded shafts.

Different tests of the MMM and UIM carried out in shafts (SRK, PGG, Hunosa and UK coal Authority), reaching a depth close to 1km. The tests resulted in both encouraging results and several issues.

3. EXPLOITATION AND IMPACT OF THE RESEARCH RESULTS

3.1. Technical and Economic Potential for the use of the Results

Shafts are arguably the most important workings in underground mines. Their technical state determines the safety and efficiency of mining operations to a large extent. Depending on the context, the lining of shafts may require periodic inspection and continuous monitoring to assess their condition and stability. However, in most ventilation shafts serving active mines, and in pumping stations using submersible pumps, there is no personnel access equipment installed. This makes it practically impossible to perform direct inspections on the lining of even the non-flooded portions of the shafts, because there is no safe means of access. In European coalmines, there are many unequipped shafts, which are mainly up cast ventilation (exhaust) shafts and, less often, intake shafts. In Poland, there are currently 30 active shafts which are partially flooded, whose lining must be evaluated every five years according to legislation. However, given the technical limitations (lack of proper equipment), even when limited inspections are possible, they are carried out only on the upper, non-flooded shaft sections. It should be emphasized that in such cases the full assessment of shaft lining stability is impossible using currently available techniques. Similarly, in the UK, there are an estimated 1,000 – 5,000 flooded open coal mine shafts and a legal obligation to ensure their safety.

The most important countermeasures to avoid shaft catastrophe is the periodic or continuous inspection of their technical state. Poland, Germany, France, Spain, UK and other countries are concerned by the long-term stability of existing flooded coal mine shafts. However, the devices used in other industries for underwater inspections are not suitable for the conditions of deep-flooded mine shafts. As a result, most shaft inspections are concerned only with the non-flooded sections.

Thanks to industrial partners involvement in the project, namely PGG SA and SRK SA from Poland and HUNOSA from Spain, from the beginning of STAMS project, the operations of design and implementation of new instruments were performed in consultation with the interested parties. The minimal and optimal range of measurements needed for shaft evaluation, the mechanical needs for each device, and their functional requirements, were defined. In order to achieve our goal, the industrial partners filled in a questionnaire prepared by Central Mining Institute (CMIPL/GIG). As a result of the questionnaire, a total of 23 shafts were analysed. HUNOSA studied different closed shafts and analysed which ones are most suitable for the project in terms of the equipment and methodology that is expected to be used. KWSA (now PGG) studied selected, partially submerged shafts, where there is the problem of the evaluation of the technical condition of the flooded section. SRK studied shafts which, in contrast to the above ones, are located in the area of abandoned coal mines and are now working as submersible pumps.

Two periodic inspection modules have been developed: the Multi-functional Monitoring Module (MMM) and the Ultrasonic Inspection Module (UIM). As the name suggests, the MMM can make several types of measurements including visual inspections, sonar profile and imaging monitoring, with the option of adding extra facilities in the future. The UIM provides more limited options, its purpose being to record shaft profiles using sonar technology, but it is a lower cost unit for end users with a smaller budget and has a smaller diameter for use in shafts that have a smaller diameter access port.

The UIM provides a single capability, that of obtaining sonar profiles in the flooded section of a shaft. This is achieved using a Tritech Super Seaking Profiler. It does not offer an imaging sonar capability although the associated software can generate a waterfall display in real time to assist the operator in identifying features. The UIM contains a geo-referencing capability. This allows unintentional horizontal movement, such as rotation and pendulum motion, to be recorded so it can be taken account of by the software which records, displays and analyses the profiles. It uses a custom-designed inertial measurement unit comprising three orthogonal gyroscopes and three orthogonal accelerometers, to measure true-heading, roll, pitch and angular increment, and velocity increments, with respect to the X, Y and Z axes.

The UIM, when extended with the ROV and DSS option, correspond to the RPIM. It provides the option to place sonar reference points on the shaft wall, in order to generate unique markers within the shaft. This is especially important if other significant textures are disappearing or changing from one survey interval to the following interval. The second important aspect is the close-up optical inspection of single spots on the shaft wall. This was not the original purpose of the ROV, but the on-board camera delivers this information. The payload frame can be used in future to carry additional inspection sensors like depth cameras, stereoscopic cameras like the Intel RealSense, or narrow–range, high-frequency sonar imaging systems. The universal ROV interface to the fastening device offers these options. This will turn the RPIM into a periodic inspection module.

The Multifunctional Monitoring Module (MMM) is designed as a fully functional module for use by those end users who require the additional features it offers, can justify the cost of the more expensive unit, and intend to use it in shafts that have a sufficiently large access port. The MMM features arms, on which the CCTV cameras are mounted, that can be configured vertically or horizontally, depending on the size of the shaft's access port. As the name suggests, the MMM is designed to provide a broad range of shaft monitoring capabilities. Other facilities could be added later, but initially it offers a profiling/imaging sonar and a range of CCTV cameras with LED lighting which can be configured to point in any direction. In future, the MMM could perform assessments of the technical condition of the flooded parts of shafts (including temporarily flooded parts), pumping stations, retention tanks, possibly bridge pillars and abutments, large diameter holes, and other hydrotechnical facilities under the water table with the technical capabilities to deploy the probe.

There are two major economic effects of the application of MMM examination. First, in case of failure detection, analysis might result in prevention of a potential catastrophe. These kinds of incidents are characterized by unpleasant consequences, economical effect being just one of many. Second, including the MMM among commercial flooded shaft examination options might result in regular income. The topic of determining and assessing the stability of the flooded parts of shafts becomes more and more important in the mining industry. The dissemination activities in Poland have resulted in the interest of commercial recipients. Not only did they verbally express their interest in using such a tool to inspect and monitor the shafts during Dissemination Workshop in April 2018, but mine company Tauron Wydobycie SA has also shared its premises to conduct a test in the Kazimierz Shaft.

As required by the task descriptions, most of the work on continuous inspection has been involved with researching methods and techniques, as opposed to developing practical solutions. This aspect of the project, therefore, could provide valuable insight to permit further development. The exception to this was the development of a tube bundle that has been designed to provide a very long-term monitoring capability of the atmosphere in the hostile abandoned shaft environment in which ongoing maintenance is not possible. A practical system was not required to be demonstrated in an abandoned shaft, because it is only the actual tube, and its associated break-out boxes, that have a unique requirement. By way of contrast, the surface equipment, that would be required to implement a working system, is identical to that which is already commercially available and is used in working mines. The tube bundle was designed and prototyped and subjected to tests, involving dropping weights onto the tube from various heights, which demonstrated adequate resilience to the types of adverse incident anticipated in abandoned shafts. The design can be made available to end users to allow manufacture without the need to pay setup charges. Similarly, advice has been provided on methods of supporting and installing the tube bundle, and of installing it in a shaft. A breakout box – which allows the atmosphere to be sampled at specific positions in a shaft – has also been designed and prototyped and detailed fitting instructions have been provided. This design can also be made available to end users.

The developments realized in the STAMS projects have a large impact on European abandoned coalmines. The MMM and UIM have been developed to monitor and assess their long-term stability conditions to prevent costly collapses. In addition, the tube bundle was designed for use as a continuous measurement system of the gases in deep flooded shafts.

The results of the project will be useful for end-users, and will contribute to alerting them in the case of unfavourable conditions. This will allow the authorities to take the suitable measures relevant to the problems reported. The workshop organized by GIG (Poland) highlighted clearly the interest of end-users in such tools for the inspection of the deep flooded shafts.

The impact of STAMS is very important because the need for continuous assessment and monitoring of the stability of abandoned shafts will increase in the following years.

The STAMS project deals with the very important topic of risk assessment of the deep abandoned flooded shafts in European coalmines. The project has a very practical dimension.

The RFCS STAMS project results allow the evaluation of a flooded shaft to help direct and optimise shaft remediation measures such as grout pouring and injection.

The project allows the assessment of the stability of flooded mineshafts based on monitoring and numerical modelling tools. The numerical modelling can predict the behaviour of flooded shafts and the range of values of measurements. The comparison between numerical modelling and monitoring guarantees the quality and robustness of the results and their application.

The STAMS project clearly highlighted that the evolution of gaseous atmospheres cannot be used as an indicator of the degradation (durability) of the shaft support system (concrete, masonry and tubbing). The laboratory tests clearly highlighted that the degradation of the concrete lining is a long-term process.

3.2. Applications

The STAMS project tested the different tools in laboratory facilities (DMT, UC3M and UNEXE) and in-situ shafts in Poland (SRK, PGG), in Spain (Hunosa) and in the UK (Coal Authority).

The different applications and tests have shown the need to improve devices developed for industrial applications.

4. LIST OF FIGURES

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6. LIST OF ACRONYMS AND ABBREVIATIONS USED

CAD	Computer-aided Design
CCTV	Closed-circuit Television
CIS	Cable Interface Sub-module (MMM specific abbreviation)
CEM	Portland cement
DSS	Docking Station Sub-module (MMM specific abbreviation)
DVT	
CSH	Calcium Silicate Hydrate
FEA	Finite Element Analysis
FSK	Frequency-shift keying; a type of data modulation
GRS	Geo-referencing Sub-module (MMM specific abbreviation)
I2C	Inter-Integrated Circuit, pronounced I-squared-C, is a synchronous, packet switched, serial computer bus
i.d.	inside diameter
IMU	inertial measurement unit
LDPE	Low-density Polyethylene
LED	Light Emitting Diode
MMM	Multi-functional Monitoring Module (MMM specific abbreviation)
MTBF	Mean Time Between Failures
o.d.	outside diameter
OEM	Original Equipment Manufacturer
OOK	On-off keying; a type of data modulation
PA12	Polyamide 12 (a type of Nylon, also known as Nylon 12)
PCAS	Profiling and Collision Avoidance Sub-module (MMM specific abbreviation)
PCB	Printed Circuit Board
p[ion]	In chemistry, the prefix p symbolises a negative base-10 logarithm. Thus pH means $-\log_{10}[H^+]$ and pOH means $-\log_{10}[OH^-]$, where the square brackets denote ionic concentration in mol/dm^3.
PCL	Point Cloud Library
PLC	Power Line Communication
PMMA	Polymethyl methacrylate; ‘Perspex’
PSK	Phase-shift keying; a type of data modulation
PP	Polypropylene
PTFE	Polytetrafluoroethylene
PIM	Periodic Inspection Module
PVC	Polyvinyl Chloride
RPIM	Reference Point Installation Module (MMM specific abbreviation)
RP	Reference Point
ROV	Remotely Operated underwater Vehicle
RPI	The Raspberry PI Computer. A small single-board computer
SEM	Scanning Electron Microscope
TBS	Tube Bundle System
TPE	Thermoplastic Elastomer

TPU	Thermoplastic Polyurethane
UCS	Unconfined Compression Strength
UIM	Ultrasonic Inspection Module (MMM specific abbreviation)
UV	Ultra Violet
UTS	Ultimate Tensile Strength
UwTS	Underwater Transmission System, the subject of WP4 of the RFCS STAMS project
XRD	X-Ray Diffraction

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The main objective of the STAMS project was to implement solutions to monitor the lining stability of flooded shafts, including the non-flooded portions, for long periods of time.

Two categories of equipment were researched. The first allows detailed measurements to be made periodically and the second category allows less detailed measurements to be made continuously.

Two periodic monitoring modules – the Multifunctional Monitoring Module (MMM) and the Ultrasonic Inspection Module (UIM) – were developed, based on a large database of flooded shafts in Europe. They can investigate the state of the lining shafts under high pressure and turbulent water. A Reference Point Installation Module was developed using an ROV (Remotely Operated underwater Vehicle) to fit specially designed reference points. Software was developed to control these instruments and analyse the data and the measurements. The functionality of the developed tools was successfully verified first under laboratory conditions and then in-situ in real flooded shafts.

For continuous monitoring, detailed studies were conducted into electronic sensors that do not require an electrical connection to the line. A tube bundle system was designed and prototyped for very long-term operation in hostile environments.

In addition, laboratory tests were carried out to investigate the production of gas as an indicator of the degradation of the lining of the flooded shafts.

Finally, advanced coupled numerical models were realized to study the effect of degradation on the local and global instability of flooded shafts.

Dissemination of the results was done through scientific and technical papers and via a specific workshop organised for mining companies in Poland.

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