UNEXMIN DELIVERABLE D8.16

RESEARCH ROADMAP

Summary:

The research roadmap for UNEXMIN identifies targets and actions related to the future development of the UNEXMIN technology. A timeline has been constructed, including milestones, objectives and targets to be achieved in order to arrive to full-scale commercial application beyond 2030. This roadmap is therefore commercially-oriented, driven by the strong commercialisation agenda of UNEXMIN.

Due to the PU/Public classification of this document a number of details were considered commercially sensitive and were left out of the final version. Upon request these can be made available for an internal review, together with additional supporting documents and the NewCo Business Plan.

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Table of contents

1 EXECUTIVE SUMMARY 6
2 INTRODUCTION AND BACKGROUND 9
3 RESEARCH ROADMAP METHODOLOGY 11
4 FUTURE SCENARIOS OUTCOMES 22
5 INTERACTIVE MINDMAPPING EXERCISE OUTCOMES 27
6 TECHNOLOGY SURVEY OUTCOMES 28
7 CONCLUSIONS 29
8 REFERENCES 30
ANNEX 1 – FUTURE SCENARIOS EXERCISE 31
ANNEX 2 – MINDMAPPING EXERCISE 33
ANNEX 3 – TECHNOLOGY SURVEY 34

List of figures

Figure 1: UNEXMIN Roadmap methodology comprised of three layers..12

Figure 2: Sustainability Alliance scenario...13

Figure 3: Unlimited Trade scenario...14

Figure 4: National Walls scenario 14

Figure 5: Scenario workshop participants learning about the scenarios and to correlate their vision with the future of the UNEXMIN technology. 15

Figure 6: Scenario workshop participants gave inputs to each of the analysed scenarios taking as a basis the UNEXMIN project's capabilities. These statements were annotated in a sheet of paper, that later was processed into Table 1. 15

Figure 7: Geological data collection group performing a Technological gap analysis & future research and technology possibilities. Geologists and mining engineers made the core of this group. Inputs are processed in Table 2. 17

Figure 8: Navigation and spatial awareness group performing a Technological gap analysis & future research and technology possibilities. Roboticists and software engineers made the core of this group. Inputs are processed in Table 3. 18

Figure 9: Mindmapping exercise in development. Participants gave key words / ideas from the center – the UX-1 robot, representing the technology – to more and more branches of information. The four major categories then englobe all the other, more specific statements. 19

Figure 10: The result of the mindmap exercise was later processed through an online mindmapping tool that resulted in the Mindmap as seen in Figure 14 and the figures of Annex 2. 20

Figure 11: Summary of current state and future possible achievements for the UNEXMIN technology.29

Annex figure 1: Future scenarios' considerations for the UNEXMIN technology..31

Annex figure 2: Technology gap analysis and future research considerations for UNEXMIN – Geological data collection. 32

Annex figure 3: Technology gap analysis and future research considerations for UNEXMIN – Navigation and spatial awareness. 32

Annex figure 4: Development of the UNEXMIN Mindmap during the workshop at La Palma.................33

Annex figure 5: Mindmap resulting from the interactive mindmap exercise. At the center, a UX-1 picture signifies the development of the technology. It is from there that the mindmap evolves, having all other items intrinsically connected to this. 33

List of tables

Table 1: The prospect of the UNEXMIN technology in light of the future raw materials scenarios of the INTRAW project, as seen from the participants' perspective. 24

Table 2: Technological gap analysis, future research and technology possibilities for UNEXMIN – Geological data collection. 25

Table 3: Technological gap analysis, future research and technology possibilities for UNEXMIN – Navigation and spatial awareness. 26

1 Executive summary

At the end of the UNEXMIN project the technology reaches a TRL level of 6. Since the project is driven by a strong exploitation and commercialisation agenda it needs to fulfil certain R&D needs that will be required for the development of a commercial-grade technology solution. The consortium believes that with the help of a systematic R&D workplan this can be achieved until 2030, where the technology reaches TRL-9. In the meantime, immediate research plans could bring the technology to TRL-7/8. In addition, a range of complementary R&D activities could also be initiated around the technology ecosystem created by UNEXMIN, reaching different TRLs by 2030.

The UNEXMIN Research Roadmap was developed with the involvement of internal Partners and external Experts, taking into account a combination of different future-oriented tools:

1) Future scenarios exploration for mineral exploration and exploitation and Technology Gap Analysis (based on future trends for the raw materials sector);
2) An interactive Mindmap exercise, focusing of the future of the UNEXMIN technology based in three key areas: hardware/software, functionalities and applications;
3) Internal Survey conducted with the involvement of UNEXMIN technology partners used to obtain information on different technology components' state-of-the-art (2019), research focused development and technology end-state.

These tools provided the relevant background for the creation of a successful future pathway for the UNEXMIN technology based on:

1) Future applications of the technology
2) Future capabilities and enhanced functionalities
3) Hardware upgrades
4) Software upgrades
5) Disruptive technology and research areas
6) Future scenarios
7) Dedicated funding instruments and /or industry financing

Key findings of the Future Scenarios

The first component of the UNEXMIN research roadmap was produced during a scenario workshop, where 3 different future scenarios were considered. UNEXMIN participants discussed these scenarios and their specificities relevant to the future development of the raw materials sector. The points discussed within this exercise – future scenarios, technology gaps – were investigated by project partners, including the technology developers, and by experts in the fields of mineral exploration, mineral extraction and robotics.

All participants agreed during the exercise that the technology needs to be further developed in order to meet future market challenges of all the envisaged applications. This exercise showed that the UNEXMIN technology is seen as a viable technology with great potentials for further development in each of the future scenarios that were considered. It also shows, as seen by the different comments made by the experts, that the technology can have a positive impact in the raw materials sector, with numerous applications. However, a number of conditions and challenges might also arise, that could limit the uptake and use of the technology on the market, or even making it economically or technologically unfeasible (e.g. a slower than projected advance in sensors' development could limit the use of the technology).

The realisation of some of the areas of research and technology identified during this exercise could result in better, faster and more precise geological data acquisition than what is currently seen in available technological solutions (i.e. remotely operated vehicles and others). As geological data collection and its further interpretation are essential functionalities of the UNEXMIN technology, the further development of these areas can greatly improve the realisation of the Exploitation Plan and the commercial success of NewCo (D8.15), which is the company, established as one of the key deliverables of the UNEXMIN project, that will take over the marketing and future development of the UX class robots.

The potential future components identified from both the software and hardware sides may also become essential parts of the UNEXMIN technology. Their possible future state, including future research and technology opportunities, will mean great improvements in the navigation and spatial awareness systems currently used in the UX robots. Advances in the components that constitute the bulk of these fields can therefore improve the overall performance of the UNEXMIN technology, towards better, faster and safer exploration and mapping of flooded mine environments.

During the course of this work, several long-term future scenarios focusing on raw materials, were considered. These long term-scenarios had been developed by other projects (INTRAW, EXTRACT-IT) and were used as a means of fine-tuning the R&D priorities with the aim of defining areas of work that have the highest chance for success in each of these (long-term) future scenarios.

Key Findings of the Interactive Mindmapping Exercise

The UNEXMIN mindmap gives insight on the connections and synergies between three main domains of the UNEXMIN technology: hardware/software development, new capabilities and market applications. This exercise was developed among the UNEXMIN project partners and therefore, information was obtained from the persons with up to date information on the technology and research know-how.

With this exercise the consortium was able to identify a comprehensive portfolio of items that will need to see evolving research in order to increase the versatility of the UNEXMIN technology and its applications in different environments, including areas that were not foreseen in the original proposal. The potential new applications of the technology besides the original objective (i.e. exploration of underground flooded mines) are diverse and could include, among others, the use of the system for any inspection/exploration tasks in many underwater environments (sea, river, pipelines). These range of topics are now included in the NewCo internal Business Plan.

In order to improve the usefulness of the technology while diversifying its array of equipment and sensors, a number of new capabilities are suggested, with the aim to extend the robotic line of work and, therefore, extend the market possibilities.

An improved version of the current technology, with strategic modifications can result in a more commercially-oriented technology that is more versatile and flexible, and can be used in a wide range of working environments.

Key findings of the Technology survey

An online survey was carried out with the involvement of the technology developers (both hardware and software) of the robotic platform. The online survey examined the state-of-the-art, future research paths and full commercial research status for 5 different areas: (1) Mechanical robotics & mechatronics, (2) Localisation, mapping and UX multi-robot platform, (3) Control, guidance and autonomy, (4) Scientific instrumentation and (5) Data post-processing.

The UNEXMIN technology has reached an overall TRL 6 within the project framework. To step up the technology line and reach a higher TRL a Technology Survey was conducted with the involvement of the technology providers of UNEXMIN. The outcome of the Survey is an immediate research plan for each of the crucial components/areas. Most of these plans work around investing in further development and adaptation of the technology. Others suggest the creation of user-friendly tools. More field testing, especially for software components, is seen as a necessity.

2 Introduction and background

This deliverable was produced within the framework of Work Package 8 - Dissemination, technology transfer and exploitation, Task 8.4 – Research Roadmapping. The present report is the outcome of the activities and exercises developed by the UNEXMIN consortium under this task. The research roadmap's main objective is to set the ground for future technology and research opportunities aiming to bring the current UNEXMIN technology closer to full-scale commercial exploitation.

The research roadmap will thus help the exploitation of results whilst it will also tackle the challenge of further upgrading the system to a full commercial status. The roadmap outlines the desired future vision, research possibilities and the necessary steps to meet the identified requirements by 2030.

The production of this roadmap was preceded by three exercises: (1) a research roadmapping workshop involving scenarios analysis, (2) a Mindmapping Exercise and (3) a survey conducted among UNEXMIN technology developers. The first, focused on future scenarios, aiming to identify research areas that the UNEXMIN technology should pursue in order to better adapt to the characteristics posed by different futures. The second exercise provided information on the direction that the technology should take in three main areas – application, functionalities and hardware/software upgrades. Finally, the survey allowed the technology partners to lay down the state-of-the-art of current technology components and look at their vision for the development of such components for two timeframes.

The UNEXMIN project:

UNEXMIN developed a novel robotic system for the autonomous exploration and mapping of Europe's flooded mines. The Robotic Explorer (UX-1) uses non-contact methods for 3D mine mapping for gathering valuable geological, mineralogical, spatial and visual information. This will open new exploration scenarios so that strategic decisions on the re-opening of Europe's abandoned mines can be supported by actualised data that can not be obtained by any other ways without big costs or risks.

The Robotic Platform represents a new technology line that is made possible by recent developments in autonomy research that allows the development of a completely new class of mine explorer service robots, capable of operating without remote control. Such robots do not exist nowadays. Research challenges are related to miniaturisation and adaptation of deep sea robotic technology to this new application environment and to the interpretation of geoscientific data.

Work started with component validation and simulations to understand the behavior of technology components and instruments to the application environment. This was followed by the construction of the first Prototype (UX-1a; April 2018). Post processing and data analysis tools were developed in parallel, and pre-operational trials launched in real life conditions.

1. Kaatiala, Finland (June 2018)
2. Idrija, Slovenia (September 2018)
3. Urgeiriça, Portugal (March/April 2019)
4. Ecton, UK (May 2019)
5. Molnár János, Hungary (June/July 2019)

The system was tested in 5 sites across Europe, four of them underground flooded mines and one natural flooded karstic cave. UX-1 was iteratively improved after each increasingly demanding trial session.

The most ambitious demonstration took place in the UK with the resurveying of parts of the underground Ecton mine (UK) that nobody had seen for over 160 years. This pilot demonstrated the platform's capacity to retrieve geological, mineralogical and spatial data from flooded environments.

Relevant deliverables for consultation for UNEXMIN background information (found at https://www.unexmin.eu/public-deliverables/):

- D1.1 – Robotic platform prototype requirement specification
- D1.2 – Robotic platform prototype technical and mission specifications
- D2.3 – Laboratory test reports of instrumentation units
- D2.4 – Real environment test report of instrumentation units
- D3.1 – UX-1 robot software architecture report
- D3.2 – Sensors acquisition and registration software prototype
- D4.1 – UX-1 robot mechanics documentation
- D6.4 – Three-dimensional visualisation software suite beta version
- D6.5 – Three-dimensional visualisation software suite final version
- D7.2 – Pilot report from Kaatiala mine
- D7.3 – Pilot report from Urgeiriça mine
- D7.4 – Pilot report from Idrija mine
- D7.5 – Pilot report from Ecton mine

3 Research Roadmap methodology

A Roadmap is a foresight tool for strategic planning. It helps to define targets and actions, and it provides a timeline for arriving to the desired vision. It has been defined as a "flexible planning technique to support strategic and long-range planning, by matching short-term and long-term goals with specific technology solutions (Phaal et al. 2004, Alexander, 2006). It is also used as an "extended look at the future, or to communicate visions, attract resources, stimulate investigations and monitor progress" (Robert Galvin, Chairman and CEO of Motorola). A research roadmap, such as the one presented in this document, has all the characteristics of traditional roadmaps, but with focus on research and technology development.

Whenever a roadmap is prepared, the line of thought and the strategic planning path goes as:

1. Where are we now?
2. Where do we want to be?
3. How do we plan to get there?
4. How will we monitor progress?

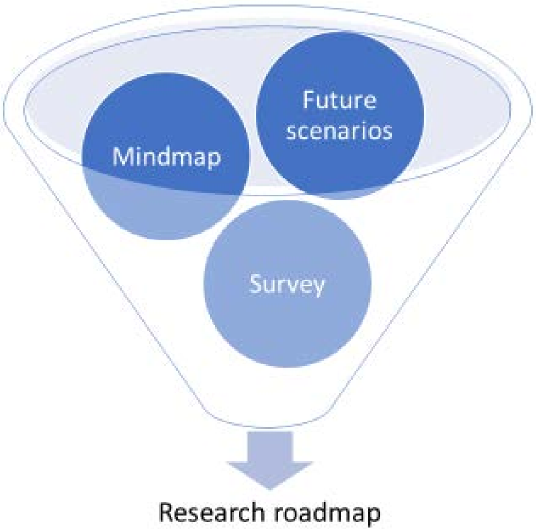
Answering to these questions facilitates the development of a roadmap. This scheme is well applicable for the current roadmapping process for UNEXMIN. The vision is an essential part of the roadmap, describing, what is the desired future that the roadmap is aiming to achieve with the set of research and technology recommendations.

Specific time horizons for the UNEXMIN research roadmap were not established in the beginning of the project. This allowed the consortium time to analyse the current status of technology first, before assessing approximate timelines for specific development levels.

The methodology developed for this research roadmap combines three layers (Figure 1):

1) Future scenarios exploration (based on Wade, 2012) for mineral exploration and exploitation and Technology Gap analysis (based on future trends for the raw materials sector; The Complete Guide to Gap Analysis, 2019)
2) Interactive Mindmapping exercise (based on Buzan, 2002) focusing of the future of the UNEXMIN technology based on three main areas: hardware/software, functionalities and applications
3) Survey among technology partners to obtain information on different technology components' state-of-the-art (2019), research focused development and technology end-state (2030).

These methods were chosen taking into account the Task 8.4 description as seen in the Grant Agreement.



UNEXMIN Research Roadmap

1 – Future applications
2 – Future capabilities and enhanced functionalities
3 – Hardware upgrades
4 – Software upgrades
5 – Disruptive technology and research areas
6 – Future scenarios
7 - Dedicated funding instruments and /or industry financing

Figure 1: UNEXMIN Roadmap methodology comprised of three layers

1) Future scenarios and Gap Analysis

The scenarios exercise was part of a Research Roadmapping Workshop (D8.10) that was held in Bled, Slovenia, on the 30th of January 2018. Project partners and external experts in the fields of raw materials, geology, technology development, policy making and robotics gave their contribution. More information on this workshop can be consulted in the corresponding deliverable document.

During the Research Roadmapping Workshop two different scenario methodologies were followed, resulting in two separate but related exercises. The first one involved the use of future raw materials scenarios developed within the EU-funded project INTRAW (INTRAW World of Raw Materials Scenarios for 2050[1]). The second one focused on a technology-gap analysis, together with an evaluation of future research and technology opportunities to be pursued by the UNEXMIN consortium partners, taking the effects presented from the scenarios. This last exercise focused in two different fields: Geological data collection and exploration, and Navigation and spatial awareness. Both hardware and software aspects of the UNEXMIN technology were considered.

The challenges currently faced by the mining sector, and the need to strengthen European supply of raw materials, are pressing for more innovative, game-changing technologies to be developed. It is well acknowledged that robotics and automation are key factors for enabling such developments and UNEXMIN can become an important actor in this respect. Highly innovative solutions as well as components of the proposed system require a strategic, forward-looking assessment for leveraging its main functionalities and potential. In this context, Technology Roadmap and Scenarios Exploration are proposed methods for assessing future challenges, emerging technologies, market, environmental and political factors.

[1] http://intraw.eu/the-world-of-raw-materials-2050/

Part 1 - **Future raw materials scenarios exploration (INTRAW World of Raw Materials Scenarios for 2050)**

The scenario exploration exercise was undertaken during the first part of the roadmapping workshop. The future scenarios developed by the INTRAW project were used as a backdrop to assess how the UNEXMIN technology would perform under different conditions presented by specific scenarios. During this exercise, participants were asked to make comments and/or suggestions on possible future opportunities and/or challenges that the UNEXMIN technology might face in light of the conditions envisaged by the different scenario situations. Each scenario presents a set of conditions that are related to society, technology, economy and policy aspects involving the mineral raw materials sector until the year 2050.

The three INTRAW scenarios are resumed below (data taken from the INTRAW project webpage). During the workshop, participants had access to the INTRAW project material which detailed the three different scenarios.

1) **Sustainability alliance[2]:** In 2050, the circular economy has become the norm in the big advanced economies. A new generation of political leaders has pushed forward a series of reforms that focus on increasing sustainability, not only in the raw materials industry. Almost every product is produced in an environmentally-friendly way with the aid of green technologies. The civil society puts sustainability above everything else to keep deposits for future generations.

Figure 2: Sustainability Alliance scenario

2) **Unlimited trade[3]:** In 2050, the world of raw materials has experienced steady growth, mainly due to ever-growing consumption. International cooperation and dialogue have created new opportunities to produce and trade raw materials. Access to capital has led to industry integration, technology

[2] http://intraw.eu/about-the-project/scenario-1-sustainability-alliance/
[3] http://intraw.eu/scenario-2-unlimited-trade/

development and productivity improvements alike. Increased global consumption leads to a growth in the raw materials sector.

Figure 3: Unlimited Trade scenario

3) **National Walls[4]:** In 2050, the world of raw materials got stuck as social and demographic pressures triggered a long period of economic standstill, which lead to a rise of protectionist measures. The absence of leadership and insufficient political will did not help to improve the situation. Each country fights for its own agenda. There is little progress in mining practices as reforms have stalled and private investments are low. Economic standstill gives rise to nationalist politicians and protectionist measures.

Figure 4: National Walls scenario

Using the above settings as backdrop and the pathways leading to each future scenario, the workshop participants made statements regarding the expected development and performance UNEXMIN technology on a scenario basis (Figures 5 and 6). A summary

[4] http://intraw.eu/scenario-3-national-walls/

of the comments gathered for each of the scenarios, as well as general horizontal comments that apply to all scenarios, can be found in Table 1.

Figure 5: Scenario workshop participants learning about the scenarios and to correlate their vision with the future of the UNEXMIN technology.

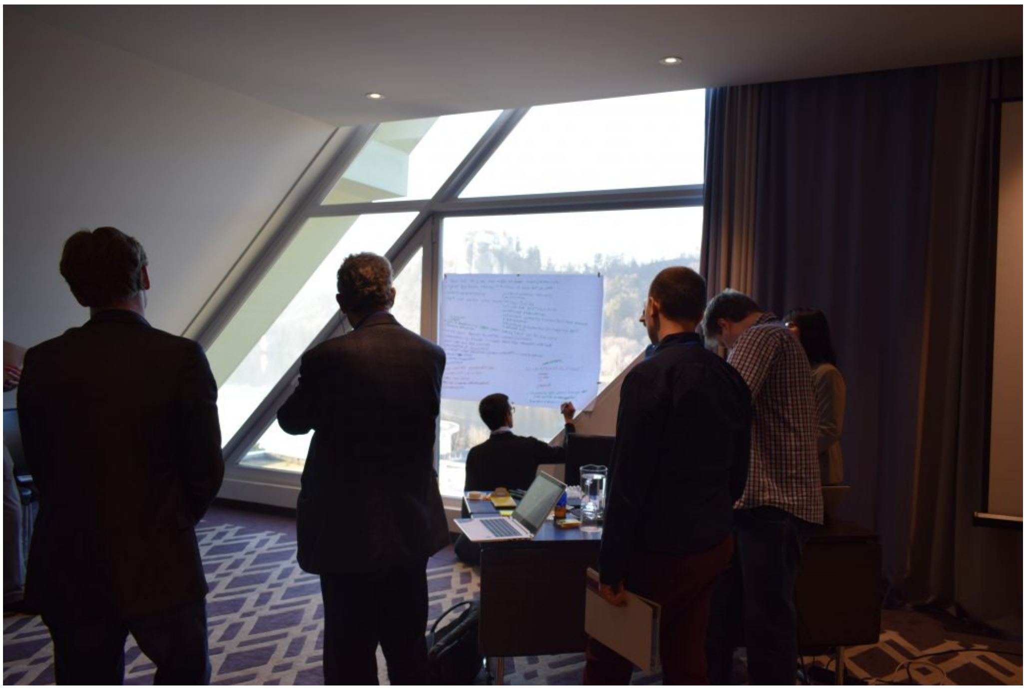


Figure 6: Scenario workshop participants gave inputs to each of the analysed scenarios taking as a basis the UNEXMIN project's capabilities. These statements were annotated in a sheet of paper, that later was processed into Table 1.

Part 2 - **Technological gap analysis & future research and technology possibilities**

The second part of the workshop consisted of a technological gap analysis exercise. Participants were divided into two groups. In these groups, the current and future state of research/technologies in some selected fields were assessed. These fields were:

- Geological data collection (Figure 7)
- Navigation and spatial awareness (Figure 8)

Participants were divided into the two groups according to their background and engaged in a technological gap analysis discussion of each component and functionality with the time horizon of 2030/2050. This process was divided into 3 main elements: a future vision (where do we want to go?), the current status (where are we now?), and the short and long-term developments. This exercise focused on evaluating the present state of the UNEXMIN technology components related to each field, the short-, medium-, and long-term (30 years) research opportunities as well as technology possibilities and finally, the strategies to reach them.

a) Geological data collection:

The exercise related to geological data collection focused on identifying fields of potential improvement of the UNEXMIN technology over short-, medium to long-term time-scales (spawning from 5, 15 and 30 years, respectively), considering current and future developments in those same fields. These fields are envisaged to improve the geological data collection by the UNEXMIN robotic platform. In this context, four main areas were defined: geological modelling (short-term future), integrated geophysical methods (mid-term future), sampling (mid-term future) and, finally, improvement spectroscopy in resolution and processing (long-term future).

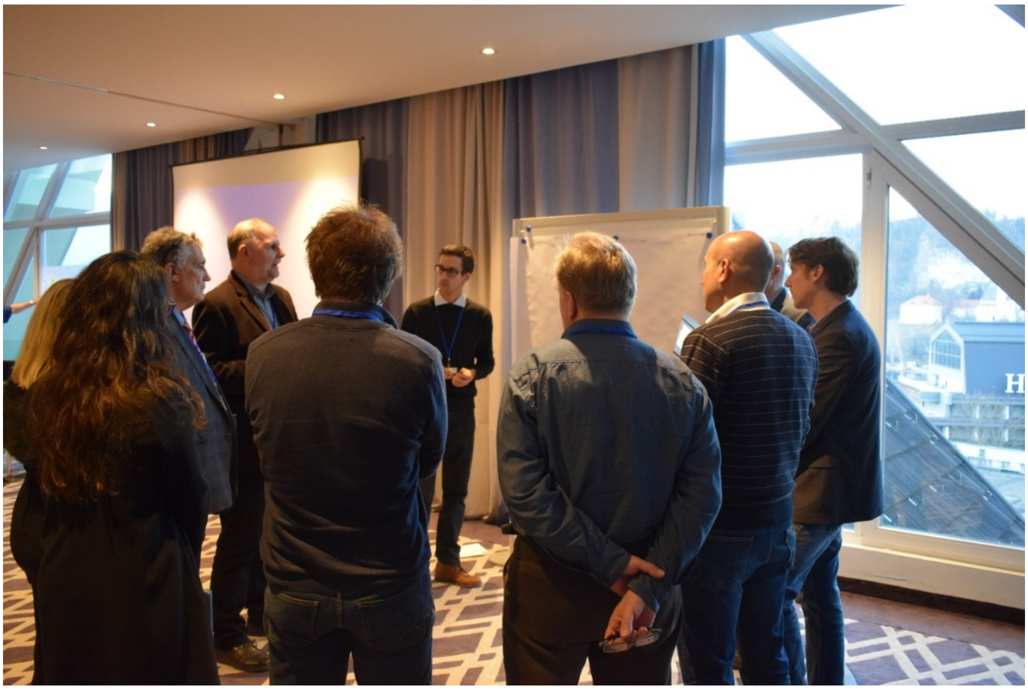


Figure 7: Geological data collection group performing a Technological gap analysis & future research and technology possibilities. Geologists and mining engineers made the core of this group. Inputs are processed in Table 2.

b) Navigation and spatial awareness:

The Navigation and spatial awareness group participants focused on two different, although complementary dimensions: Hardware and software. The evaluated hardware components included Laser, 3D/LIDAR, cameras, GNSS (Global Navigation Satellite Systems), acoustic, communication, locomotion, and IMUs (Inertial Measurement Units). The software components considered were the SLAM (Simultaneous Localization and Mapping)/sensor fusion, real-time mine models, information management and decision-making systems, and artificial intelligence (AI).

Figure 8: Navigation and spatial awareness group performing a Technological gap analysis & future research and technology possibilities. Roboticists and software engineers made the core of this group. Inputs are processed in Table 3.

Altogether, the scenario workshop provided information on:

- Future (including long-term) research needs for geological data collection and, navigation and spatial awareness
- **S**trengths of the robotic system
- **W**eaknesses of technology
- **O**pportunities for the platform
- **T**hreats for the successful implementation

2) Interactive Mindmapping Exercise

A Mindmapping Exercise was held during a consortium meeting at LPRC HQ in Los Llanos, Spain, in January 2019, as a follow-up to the Scenario workshop, part of the overall roadmapping task. During the exercise UNEXMIN experts, from robotics and geosciences, contributed with ideas and discussions that lead to the creation of a Mindmap focusing on four different areas: Applications, Capabilities, Hardware and a new version of the robotic system (UX-X). These areas are built around the UX-1 platform development topic, therefore creating a vision of the consortium to the future of the technology. An image of the UX-1 robot was used at the centre of the mindmap for this purpose.

A mindmap is a widely-used foresight tool that can visually organise information and thoughts on a certain topic. It has a hierarchical structure, showcasing relations among different parts. It starts from the center, that acts as the major concept, and it is built around that concept. Major ideas are connected to the center and then the ideas branch to more concrete, individual terms.

The UNEXMIN mindmap exercise started with a picture of the UX-1 robot in the center which represents the technology. From that point on the UNEXMIN consortium started to lay down ideas and debating for the further development of the technology, creating a Mindmap (Figures 9 and 10).

Figure 9: Mindmapping exercise in development. Participants gave key words / ideas from the center – the UX-1 robot, representing the technology – to more and more branches of information. The four major categories then englobe all the other, more specific statements.

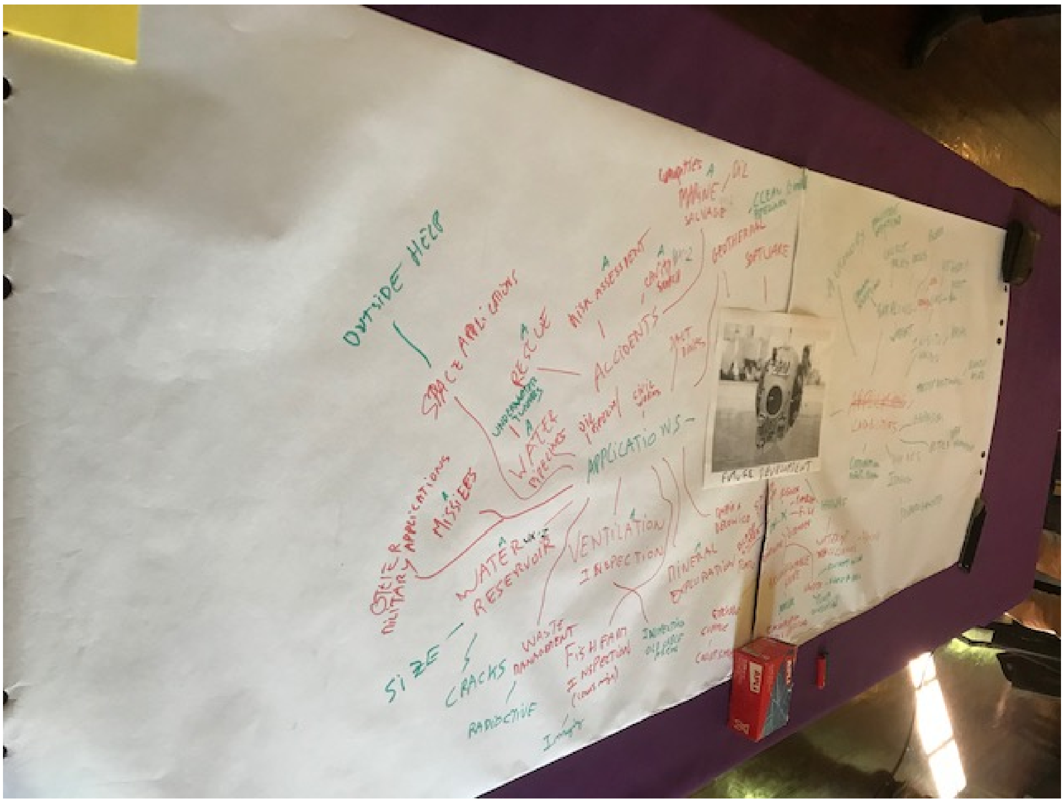


Figure 10: The result of the mindmap exercise was later processed through an online mindmapping tool that resulted in the Mindmap as seen in Figure 14 and the figures of Annex 2.

Altogether, the mindmap provides information on:

- Hardware and software components that will be necessary to step up a future version of the system;
- New application areas and markets, where the technology can be applied with commercial success;
- New or upgraded functionalities and robotics capabilities that allow the platform to work better, faster and with less resources.

3) Technology Survey

An internal technology survey involving the UNEXMIN consortium was circulated as part of the roadmapping task. All team members involved in the development of the platform, hardware and software alike, were contacted. They provided expertise in their respective areas:

(1) Mechanical robotics & mechatronics
(2) Localisation, mapping and UX multi-robot platform
(3) Control, guidance and autonomy
(4) Scientific instrumentation
(5) Data post-processing

The experts were asked to provide details on these areas for the actual state and for two different future time frames. The exploration of these topics are now included in the NewCo internal Business Plan.

The survey was conducted during the course of August and September 2019. This allowed experts to give replies based on the most recent available knowledge on their fields, also taking into account what they expect for the future of the technology. The technology survey – as it was sent to the partners – can be seen in Annex 3.

4 Future scenarios outcomes

This exercise showed that the UNEXMIN technology is perceived by the experts as an important piece of technology irrespective of the future scenarios. It also shows, as seen by the different comments made by the experts (recorded in Table 1), that the technology is expected to have a positive impact in the raw materials sector, with numerous applications. However, there are conditions and challenges that might arise, limiting the scale of use of the technology in the market, or even making it economically or technologically unfeasible (e.g. slower advance in sensors' development could limit the use of the technology). The outcomes of the future scenarios exercise is processed in Table 1.

Tables 2 and 3 show the results of the technology gap analysis for geological data collection and for navigation and spatial awareness, respectively. These can also be seen in Annex 1.

The areas of research and technology identified during the Geological data collection part will be able to facilitate substantially better, faster and more precise geological data acquisition than what is currently available. As geological data collection and its further interpretation is an essential functionality of the UNEXMIN technology, the development of these areas can greatly improve commercial feasibility. Together with the research and technology fields identified, also their envisaged benefits and pathways were pre-mapped (as seen in Table 2).

The potential components identified from both the software and hardware sides during the navigation and spatial awareness exercise may become essential parts of the future upgrades of the UNEXMIN technology (Table 3). Their possible future state, including future research and technology opportunities, will mean great improvements in the navigation and spatial awareness systems currently on the UNEXMIN technology. Advances in the components that constitute the bulk of these fields can transversely improve the UNEXMIN technology, towards better and faster exploration and mapping of flooded mine environments.

Main outcomes

The most relevant outcomes of the research roadmapping workshop that can be translated into a proper research/technology roadmap for the considered timeframes are:

1) The technology can be widely used to re-explore abandoned mines. A possibility for joint research funds provided by different entities strengthens the technology line.
2) Re-exploration of flooded mines might be a widely applied reality in the future.
3) Innovation-driven research and industry will benefit the development, implementation and constant upgrading of the technology
4) Technology transfer between sectors (eg. space) will improve the technology
5) Geological and spatial data collection can be improved with/by:
    a. Geological modelling
        i. Benefits: Augmented reality, Better structural geology and 3D/4D restauration

        ii. Pathway: Better concepts for geological modelling. Better capacity/computing and better and faster software
    b. Integrated geophysical methods
        i. Benefits: 3D seismic potential and 3D component gravity
        ii. Pathway: Better capacity/computing
    c. Sampling
        i. Benefits: Extended spatial sampling, water sampling in-situ measurements and on-site sampling and analysis
        ii. Pathway: Automation and new sample protocols
    d. Spectroscopy upscaling
        i. Benefits: Reduction in size and price, better position system and reduced data noise
        ii. Pathway: Better capacity/computing, better and faster software, improvement in sensor technology and application of technologies from other fields
6) Hardware upgrading
    a. Laser 3D/Lidar
        i. Pathway: Better resolution and better range
    b. Cameras
        i. Pathway: Better resolution
    c. GNSS
        i. Pathway: Improved accuracy, improved coverage, reduced costs
    d. Acoustic
        i. Pathway: Size reduction
    e. Communication
        i. Pathway: Size reduction, through the rock communications and inter-robot communications
    f. Locomotion
        i. Pathway: Dual means, biomimetic and metamorphic
    g. IMUs
        i. Pathway: No drift
7) Software upgrading
    a. SLAM/Sensor fusion
        i. Pathway: Integrated in hardware and sub-millimeter accuracy
    b. Real time mine models
        i. Pathway: Model delivered to C2 station
    c. Artificial intelligence
        i. Pathway: Self-awareness

Conclusions on future scenarios

Visions for the future of the UNEXMIN technology were discussed and a set of recommendations for hardware and software upgrades were delivered, that together with better data acquisition and other tasks, can make the technology suitable for commercial application in the raw materials sector by 2030 and beyond.

Re-exploring and re-opening old mines will become a reality in the near future and, when that happens, the UNEXMIN technology will be at the forefront of exploration technologies. Technology transfer/fusion with other sectors such as space technology could help UNEXMIN keep its competitive advantage.

Table 1: The prospect of the UNEXMIN technology in light of the future raw materials scenarios of the INTRAW project, as seen from the participants' perspective.

Scenarios	Specific scenario statements	General statements
Sustainability Alliance	1. The UNEXMIN technology is used at large scale - in re-exploring abandoned mines to only get the materials needed. There are joint research funds made available from different countries to further develop the technology; 2. Abandoned mines have a second life and opportunities arise for the UNEXMIN technology such as environmental security assessments, geothermal exploration, high-tech laboratories, optimized exploration, multiple commodity mining; 3. Due to advancements in areas such as recycling and design of new components, the UNEXMIN technology can become obsolete.	1. Further development of the UNEXMIN technology will always be necessary: more/better sensors, more autonomy, etc. 2. There are opportunities to connect the mining industry with other sectors for further development and improvement of the UNEXMIN technology; 3. Innovation in mining is a cultural problem - resistance in innovation can limit UNEXMIN technology applications.
Unlimited Trade	1. A bigger market means more applications for the UNEXMIN technology; 2. Demand in raw materials creates problems in adopting UNEXMIN technology, as the technology might not be ready to be applied at a large scale; 3. Short-term view from industry makes the technology fail	
National Walls	1. The UNEXMIN technology provides economic opportunities for users; 2. Extreme interest in exploring abandoned mines facilitates the use of UNEXMIN technology; 3. Forcing towards innovation made by countries/country blocks benefits the implementation and upgrading of the UNEXMIN technology; 4. Slower advance in sensors' development limit the use of the technology.	

Table 2: Technological gap analysis, future research and technology possibilities for UNEXMIN – Geological data collection.

	Short term ⟷			**Long term**
Field of development	**Geological modelling (micro, mid and**	**Integrated geophysical methods (megascale)**	**Sampling (medium scale)**	**Spectroscopy upscalling (micro scale) - resolution &**
Benefits of implementation	Augmented reality analysis Better structural geology 3D/4D restauration	Well logging 3D seismic potential 3D component gravity	Extended spatial sampling (eg. lake sampling) Water sampling in-situ measurements On-site sampling	Reduction in size and price Better position system Better detection limit Amount of data
Pathway	Better concepts for geological mapping Better capacity/computing Better and faster software	Better capacity/computing Progress in inversion Demonstrative examples	Drones Automation New sample protocols	Better capacity/computing Better and faster software Improvement in sensors technology Application of technologies from other fields

Table 3: Technological gap analysis, future research and technology possibilities for UNEXMIN – Navigation and spatial awareness.

	Current state	Short-term	Long-term	End-state (2030+)
Hardware				
1 - Laser 3D/Lidar	Available for U/W	N/A	2x resolution 2x range	5x resolution
2 - Cameras	8k in film industry	8k cameras		
3 - GNSS	GNSS-denied environments (tunnels, etc.)	Short baseline systems improved accuracy Improved coverage	Reduce costs Flexibility U/W adaptation	N/A
4 - Acoustic	M/R Sonar Good resolution / Range	Size reduction (depending on application)	N/A	N/A
5 - Communication	Acoustic LI-FI Wi-fi Cables	Size reduction Bandwidth	Through-the-rock communications	U/W inter-robot communic. (wi-fi, camera-like) U/W C2 (command and control)
6 - Locomotion	Propellers/Jets Catterpilars	Dual means (legs/wheels	N/A	Multiple means Biomimetic Metamorphic
7 - IMUs	Drift is a big problem	N/A	N/A	No drift
Software				
A – SLAM/Sensor fusion	CPU intensive	Google says it is a problem solved, but not true for U/W - uncertainty	Integrated in HW Semantic SLAM Topological mapping	Sub-mm accuracy
B - Real Time Mine Models	N/A	N/A	N/A	Model delivered to C2 station
C - Information Mgmt. System / Decision-making systems	GNSS-denied environments (tunnels, etc.)	Short baseline systems improved accuracy Improved coverage	Reduce costs Flexibility U/W adaptation	N/A
D - Artificial Intelligence	Fault tolerance	Self-awareness	N/A	Opportunistic Science

5 Interactive Mindmapping Exercise outcomes

The four major areas identified during the development of the Mindmap were (1) UX-1's capabilities, (2) the applications for the technology, (3) hardware upgrades and (4) a new version of the current robotic line. Some records of this exercise can be seen on Annex 2.

Main outcomes

The outcomes of the Mindmapping Exercise are diverse but all highly relevant. With this exercise the consortium was able to identify different items that will need evolving research in order to turn the UNEXMIN technology more robust and suitable for different environments and applications. Some of the outcomes of this exercise are aligned with some of the ones that arose during the scenario exploration exercises.

Conclusions on the Mindmapping Exercise

New applications of the technology besides the one targeted and disseminated, i.e. its use to explore underground flooded mines, are diverse and could include the use of the system for any inspection/exploration tasks in many underwater environments (sea, river, pipelines). New and improved capabilities for the robotic technology were mapped and variations to the current version of the system considered. Together they will allow the UNEXMIN technology to reach several markets, fulfilling data needs that cannot be easily solved otherwise.

6 Technology survey outcomes

The results of the technology survey, for each of the five development areas have been incorporated in the confidential internal business plan of NewCo.

Main outcomes

The technology survey showed light on future developments for each of the five areas considered. The answers provided by the UNEXMIN technology developers and experts are considered in the definition and conclusions of the research roadmap.

Conclusions on the Technology survey

The Technology survey shows that the UNEXMIN team of experts understands the need for further development of the equipment and functions of the current robotic platform, as well as the need for research for newer and better tools that can extend and perfect the robot's capabilities at large, as a first research plan necessity. In order to reach a commercially-ready technology the UNEXMIN technology needs to be extensively tested in the application environments (underground flooded mines and others) and be tailor made for diverse users while turning it more user friendly. The UNEXMIN technology developers also acknowledge that a newer version of the current robotic system is desirable in the future.

7 Conclusions

The research roadmap for UNEXMIN was developed taking into practice three different exercises that provided outputs on a number of aspects - Future applications, Future capabilities and enhanced functionalities, Hardware upgrades, Software upgrades, Disruptive technology and research areas, Future scenarios, Dedicated funding instruments and /or industry financing - based on inputs from internal project partners as well as external Experts.

The roadmap process overall shows the evolution of the consortium's ideas over the technology. To this, the fact that the roadmapping exercises were realized at different development stages is of much importance. A summary of the most relevant features/achievements for the different timelines is considered and, in a simple way, lays down the research pathway for future improvement of the UNEXMIN technology in order for this to reach higher TRL levels and to be commercially ready by 2030, can be found on Figure 11.

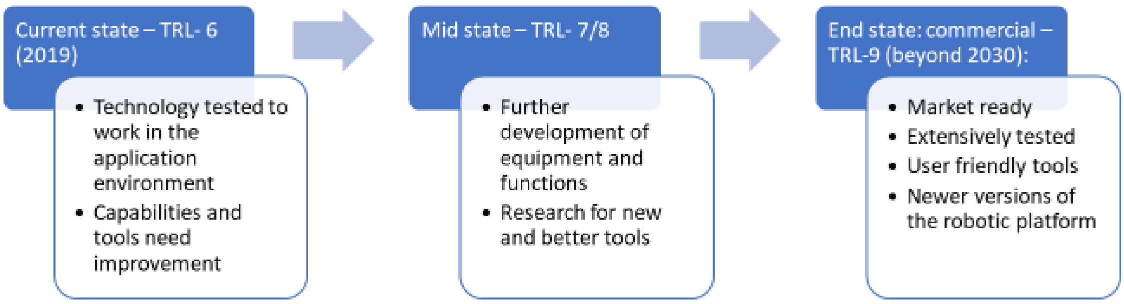


Figure 11: Summary of current state and future possible achievements for the UNEXMIN technology.

The UNEXMIN research roadmap is commercially-oriented, driven by the strong commercialisation agenda of the project, and provides recommendations for the further development and adaptation of the technology in the near future. It serves has a future-looking tool but is my no means legally binding.

Due to the sensitive nature of the data collected, and due to it being mostly commercially-oriented, this public final version of the UNEXMIN Research roadmap lacks in concrete targets, actions and timelines for the further development and adaptation of the UNEXMIN technology. These were incorporated into the UNEXMIN NewCo Business Plan and are confidential in nature.

8 References

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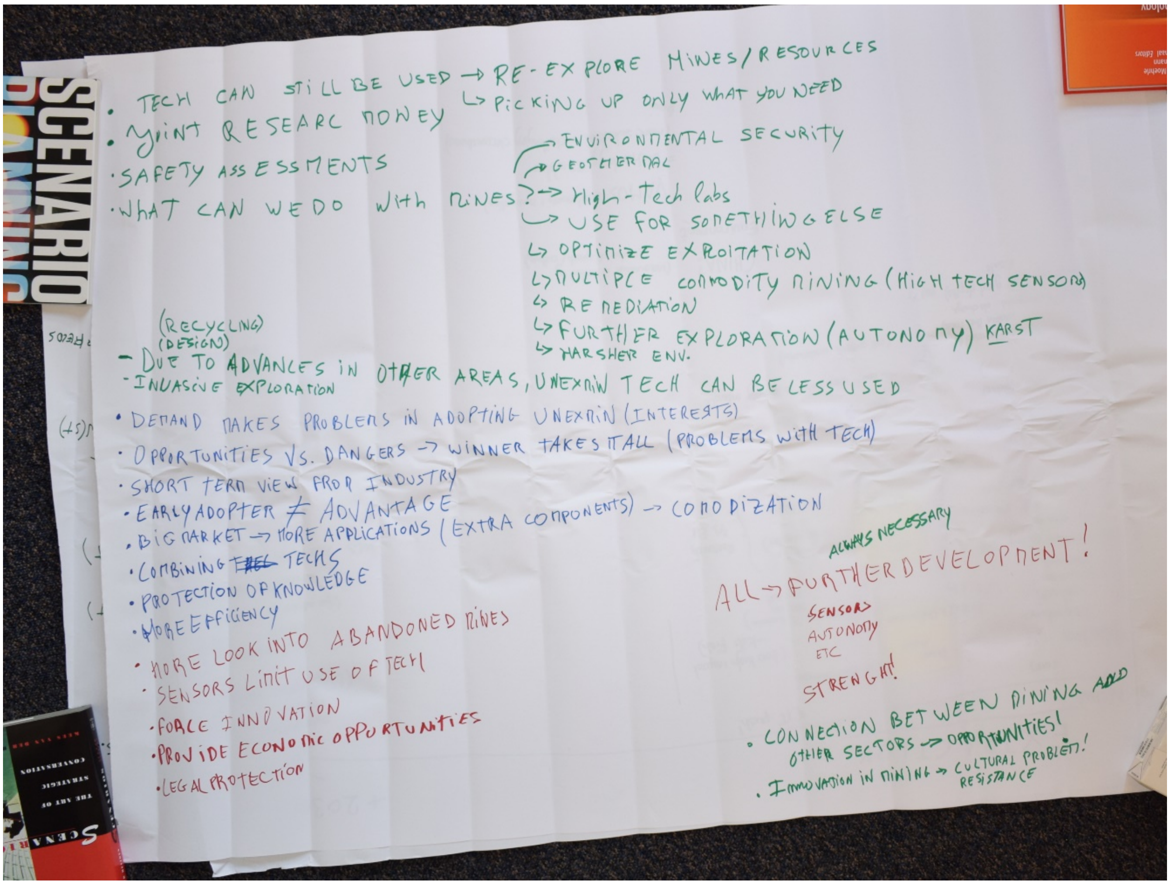
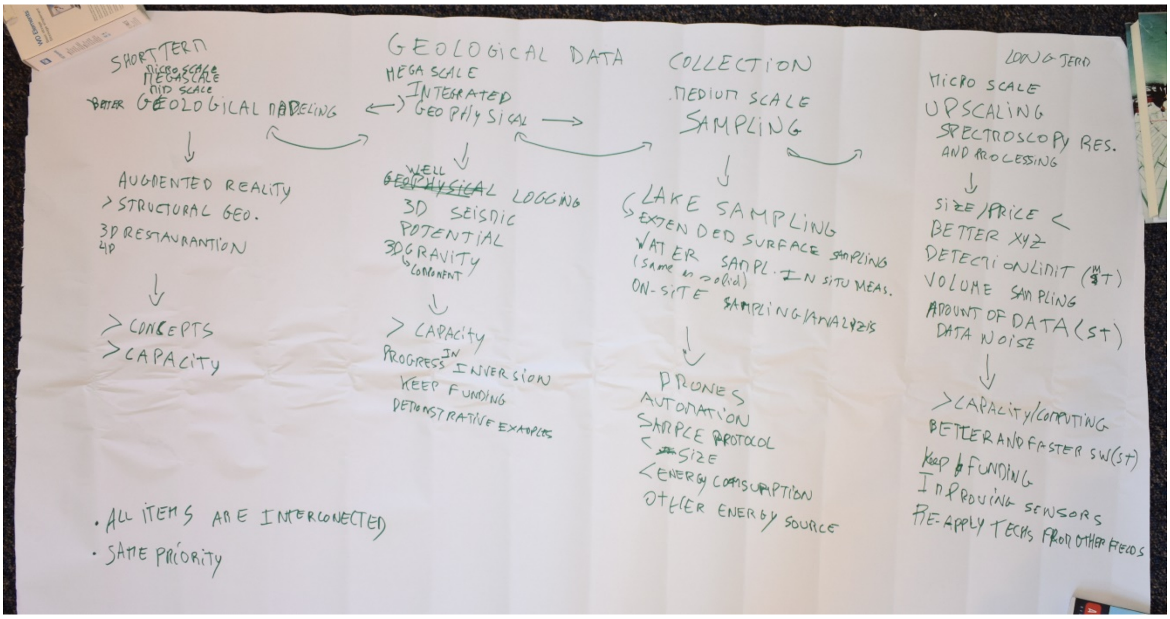
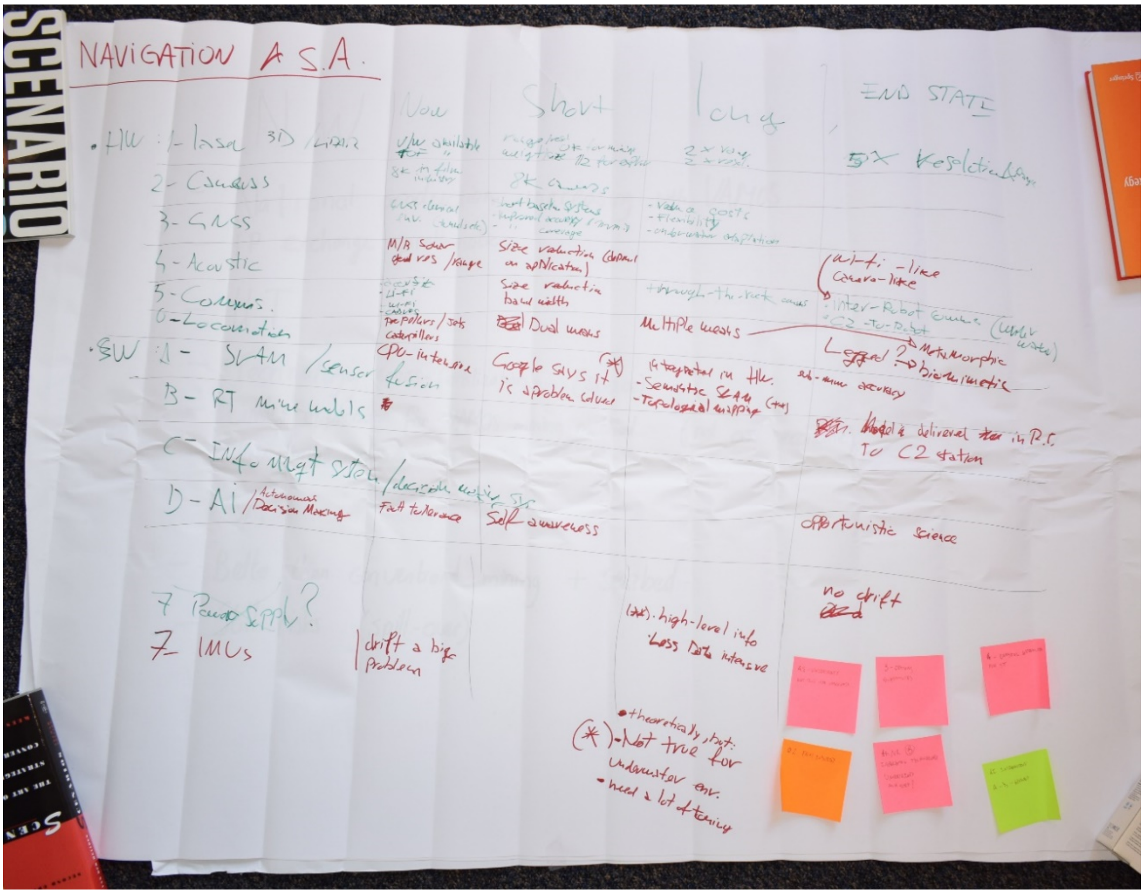
ANNEX 1 – Future scenarios exercise



Annex figure 1: Future scenarios' considerations for the UNEXMIN technology



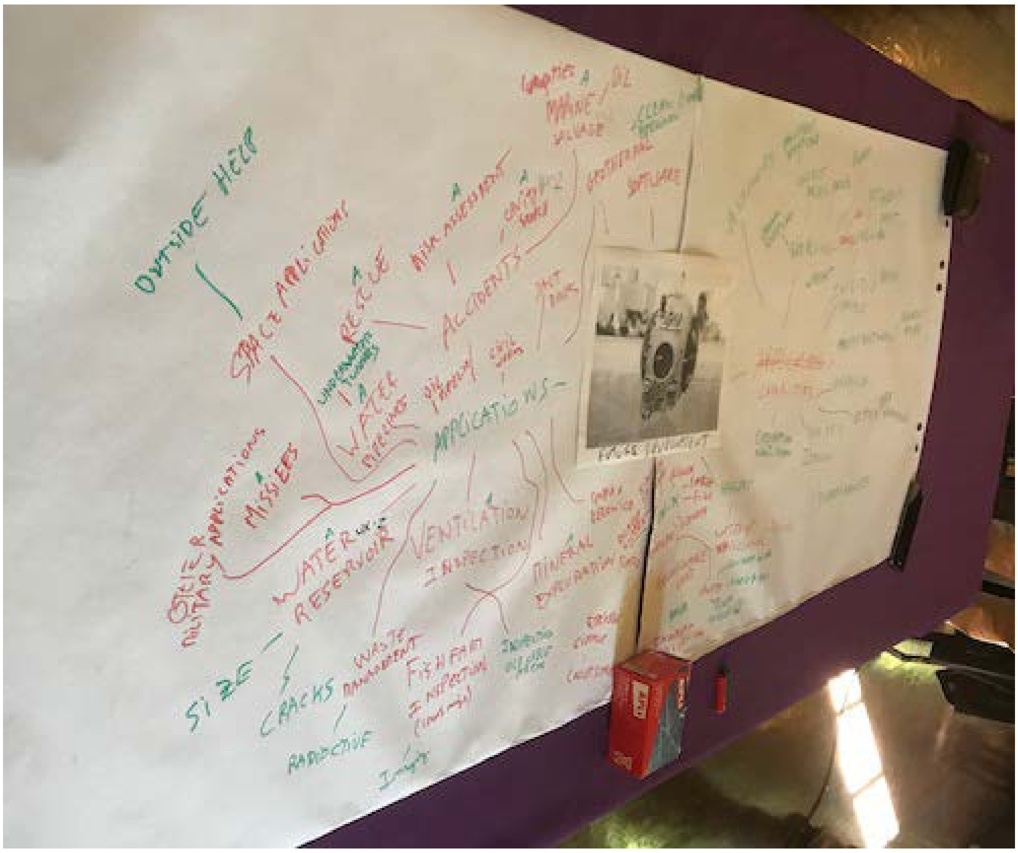
Annex figure 2: Technology gap analysis and future research considerations for UNEXMIN – Geological data collection



Annex figure 3: Technology gap analysis and future research considerations for UNEXMIN – Navigation and spatial awareness

ANNEX 2 – Mindmapping exercise

Annex figure 4: Development of the UNEXMIN Mindmap during the workshop at La Palma



Annex figure 5: Mindmap resulting from the interactive mindmap exercise. At the center, a UX-1 picture signifies the development of the technology. It is from there that the mindmap evolves, having all other items intrinsically connected to this.

ANNEX 3 – Technology survey

Input for the roadmap on the UNEXMIN technology and capabilities

Part of document: D8.16 Research Roadmap
Internal working document

Introduction, scope

The research/technology roadmapping task for UNEXMIN focuses on the future development of the UNEXMIN's technology, including Hardware, Software and Multi-robot interaction compenents. At the same time, it is expected that a number of disruptive technology/research areas are identified. The final roadmap will have three main studies or parts. It aims to provide guidance for future developments of the current UNEXMIN technology.

Part 1 – Scenarios analysis: This part builds onto the scenario workshop exercises held in Bled in January 2018 as part of the joint UNEXMIN and ¡VAMOS! conference. The scenario workshop was used to create discussions on the further development of the various elements of the technology. This exercise identified areas of research and technology that will affect the development of the technology in the future.

Part 2 – The Mindmap: With a mindmap exercise, held in La Palma, January 2019, relevant concepts of the UNEXMIN technology line including hardware, software, capabilities and applications, were considered. The mindmap gathers information on the future possibilities of the UNEXMIN technology in the four areas above described.

Part 3 – the Partner survey (this document): The objective of this exercise is to gather information from the project partners (technology representatives) on the topics of 1) Robotics, 2) Multi platform, 3) Autonomy, 4) Post-processing & 5) Instrumentation, regarding three different stages: the current state-of-the-art of the UNEXMIN components, the immediate research plan and, finally, the market-ready research plan. Part 3 is further explored next.

Instructions to complete the document (part 3)

The aim of this part of the roadmap is to provide a framework to guide and coordinate future research and development of the UNEXMIN various components. It describes 1) what is the state-of-the-art, 2) what are the immediate research needs after the project and 3) what needs to be done to reach market level application (TRL 9).

These 3 points are completed by the technology representatives, who worked on the components during the project lifetime. Each point is expected to reach one or two paragraphs, or ~5-10 bullet points.

Altogether, this document describes what is next, after the project, and it identifies concrete research needs and actions to be taken in order to arrive to the desired future: market readiness level and full commercial application beyond 2030.

Topics to complete:

1. State-of-the-art, timeline: 2019
    - Current state of the specific aspect, achievements, results during the project.
2. Immediate research plan, timeline 2019 - 2030 (TRL 7-8)
    - What are the immediate research needs after the project: Next actions, next targets to continue the research on the technological component after the project.
3. Market-ready research plan, timeline: beyond 2030 (TRL 9)
    - What needs to be done to reach pilot level application (TRL 9): Requirements of the aspect before integrating it into a fully commercial UNEXMIN application.

The UNEXMIN technological components:

- Mechanical robotics & mechatronics -> Jussi Aaltonen
- Localisation, mapping and UX multi-robot platform -> Alfredo Martins, José Almeida, Eduardo Silva
- Scientific instrumentation -> Norbert Zajzon, Richard Papp
- Control, guidance and autonomy -> Claudio Rossi, Ramon Suarez
- Data post-processing -> Steve Henley, Hilco van Moerkerk, James Tweedie, Mike McLoughlin

Component description

// Please scroll down to the section you are responsible for, and complete the tables.

Mechanical robotics & mechatronics

Responsible researcher, institution: Jussi Aaltonen, Tampere University **State-of-the-art (2019)**
Current state of the component, achievements, results during the project
Current state:

Immediate research plan
Next actions, next targets to continue the research on the technological component after the project.

Market-ready research plan, TRL 9
Requirements of the component before a fully commercial and market ready UNEXMIN application

Localisation, mapping and UX multi-robot platform

Responsible researcher,institution: José Almeida, Alfredo Martins, Eduardo Silva, INESC TEC **State-of-the-art (2019)**
Current state of the component, achievements, results during the project

Immediate research plan
Next actions, next targets to continue the research on the technological component after the project.

Market-ready research plan, TRL 9
Requirements of the component before a fully commercial and market ready UNEXMIN application
Provide input here

Scientific instrumentation

Responsible researcher,institution: Norbert Zajzon, Richard Papp, University of Miskolc **State-of-the-art (2019)**
Current state of the component, achievements, results during the project

Immediate research plan
Next actions, next targets to continue the research on the technological component after the project.

Market-ready research plan, TRL 9
Requirements of the component before a fully commercial and market ready UNEXMIN application
Provide input here

Control, guidance and autonomy

Responsible researcher, institution: Claudio Rossi, Ramon Suarez, Universidad Politécnica de Madrid **State-of-the-art (2019)**
Current state of the component, achievements, results during the project

Immediate research plan
Next actions, next targets to continue the research on the technological component after the project.

Market-ready research plan, TRL 9
Requirements of the component before a fully commercial and market ready UNEXMIN application

Data post-processing

Responsible researcher,institution: Steve Henley, RCI **State-of-the-art (2019)**
Current state of the component, achievements, results during the project

Immediate research plan
Next actions, next targets to continue the research on the technological component after the project.
•

Market-ready research plan, TRL 9
Requirements of the component before a fully commercial and market ready UNEXMIN application