
# Defining FET * research topics supporting the ICT challenges of mineral extraction under extreme geo-environmental conditions

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* FET : the Future and Emerging Technologies Programme is the European Commission‘s ICT pathfinder for new ideas and themes for long-term research.
http://cordis.europa.eu/fp7/ict/programme/fet_en.html

## Ambition

EXTRACT-IT aimed to identify emerging and potentially disruptive trends in how ICT could be used in future deep mines. The challenge for EXTRACT-IT was to turn such potential future applications into Calls for Proposals under the Future and Emerging Technologies (FET) Programme of Horizon 2020[1], supporting the development of these anticipated future trends in the present. The FET programme promotes high risk research, *"offset by potential breakthrough with high technological or societal impact"*. In particular FET Proactive fosters *"novel non-conventional approaches and foundational research in selected themes in response to emerging societal and industrial needs."* The project mission of EXTRACT-IT was to identify multidisciplinary research topics in the cross-section of future deep mining and ICT. These research topics must be exploratory in nature, representing a challenge far beyond what is considered "applied research" today. They are expected to fuel ICT research of fundamental character and will provide novel pathfinder topics for researchers within the ICT and mining research communities.

1 Horizon 2020: The EU Framework Programme for Research and Innovation → http://ec.europa.eu/research/horizon2020/

## The Background

Europe's dependency on imports of strategic raw materials is growing every year despite research efforts in the development of recycling technologies and substitution. The demand for strategic minerals is expected to evolve at a fast speed by 2030, as a result of the resource requirements of emerging technologies, such as Europe's ICT industry. Several studies have established that from a geological perspective there are a great number of mineral commodities available within the geographical boundaries of Europe, and theoretically high levels of self-sustainability could be reached on a range of raw materials, if the technological challenges could be overcome by research and development.

Today's mineral ICT research focuses on the development of tools that increase the autonomy of extraction and ore processing (such as driverless haul trucks, automated loading systems, remote control systems, etc), facilitate rapid data evaluation in remote control rooms (e.g. new augmented reality applications) and allow a better understanding of ore bodies (e.g. predictive modelling and 3D visualization). These research efforts will push the technological and economic feasibility of mineral extraction to ever greater depths, but they lack the "paradigm change" that is often referred to as a basic requirement if the truly extreme geo-environmental conditions are to be mastered by technology. An equally important challenge is the development of solutions that could work in difficult formations (not necessarily at ultra-depths), or on small deposits, where traditional mining approaches will remain uneconomical in the foreseeable future.

EXTRACT-IT was launched, because in today's favourable mineral-policy environment there could be room for investigations beyond applied research, supporting breakthroughs and paradigm changes as to how minerals are extracted and processed with the help of emerging ICT. Such paths will not offer immediate solutions to our needs in the present, but they should have the potential to deliver solutions in the more distant future, when Europe might need them the most.

For scientific breakthroughs in minerals exploration and extraction, basic research is needed, in which the risks are offset by potential high pay-offs with high technological impact, not just on future mining and ICT, but across a broad-range of scientific disciplines as well. The identification of actual research topics is, however, not an easy task. They need to have the potential to support mining industry requirements in the future, whilst they must represent basic-science challenges for ICT in the present. EXTRACT-IT used a scientific foresight study in identifying some of these scientific domains. The identification of potentially emerging trends is by no means complete, and there is a clear need for continued multi – and interdisciplinary networking. The topics described here already venture into the unchartered waters of basic, exploratory sciences that have the potential to support paradigm-changes in the cross section of future mining and ICT.

## The Project

EXTRACT-IT started on 1 November 2012 with an internal mindmapping exercise, that defined an initial pool of concepts that were used to start up discussions during the appraisal workshop in Leoben, Austria (6-7 February, 2013). The objective of this first workshop was to discuss emerging technological challenges but also to define the scope, issues and strategies for the Delphi survey, which is an interactive foresight technique that collects structured opinions from a panel of experts. The first round of the Delphi (25 April – 28 May, 2013) was designed to cut through all important ICT topics that were identified in Leoben. Experts participating in the second workshop in Brussels (12-13 June, 2013) were asked to evaluate the first round of the Delphi Survey and to think about the different speed and rates of technology transformation within the defined timeframe. During the evaluation, experts were asked to eliminate topics that fall into the category of "applied research" or topics that are already under implementation today. These inputs were then used to formulate pre-conditions for the second round of the Delphi (19 August – 16 September, 2013), which was used to "poll" the greater scientific community and collect structured opinions from those who could not participate in the project workshops. The input collected with the help of the survey provided a strong background for discussions and for the conversion of ideas into Call Topics at the final workshop in Puntagorda, Spain (10-11 October, 2013). Discussions during the final workshop focused exclusively on the selection and elaboration of topics that were considered neither too far-fetched (unlikely to occur within the defined timeframe of 2050) nor too trivial (already under implementation).

The resulting Call Topics represent high-risk/high pay-off research areas of exploratory character, with scientific interest at basic science level for ICT in the present and potential applications for mining in the future.

### Thematic Area I - “Evolution Underground”

Call 1 Bio-inspired underground technologies.
Call 2 Microbiology-Energy-ICT Convergence for machine autonomy.
Call 3 Underground machine evolution.

### Thematic Area II - “Resilient Artificial Ecosystems”

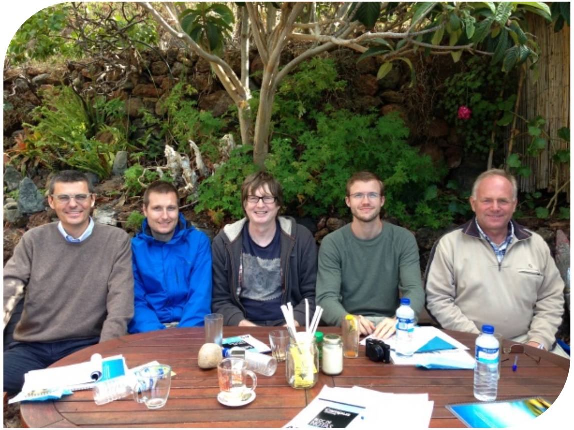
Call 1 Beyond pervasive adaptation.
Call 2 Machine-repairable machines.
Call 3 Heavy-duty swarm robotics underground.

### Thematic Area III - “Broadband through the Rock”

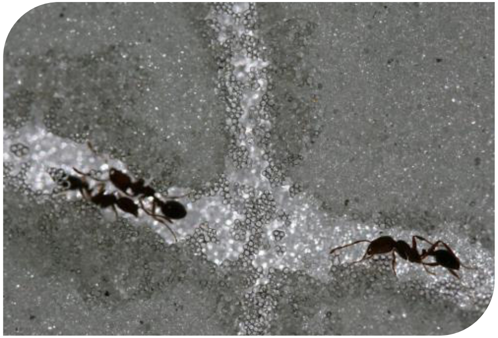
Call 1 Breakthrough data transmission technologies.
Call 2 Self-organised in-mine communication.
Call 3 SwarmCom.

### Thematic Area IV (2 Cross-cutting Calls)

Call 1 Smart Systems integration.
Call 2 Coordinating communities - Resilient Robotics for Future Mining.



## Thematic Area I - Evolution Underground



Call 1 Bio-inspired underground technologies

Underground and burrowing animals demonstrate overwhelming superiority when compared to present-day underground mining equipment. They have evolved to feed, reproduce, form colonies and to manipulate the underground environment according to their needs. Their relative strength may exceed a hundred times the performance of the most powerful mining machinery, whilst they are energy efficient, self-organizing and able to navigate in subsoil environments. The objective of this Call is to map the underground animal kingdom (arthropods, worms, but also vertebrates) and develop dramatically new concepts for bio-inspired underground mining systems (including drilling, navigation, feeding, communication, actuation and collective behaviour) drawing inspiration from underground biology. Expectations from such novel systems would include increased flexibility and scalability of mining operations - not necessarily at ultra-depths, but in difficult formations, that are currently considered uneconomical.

Call 2 Microbiology-Energy-ICT Convergence for machine autonomy

Micro-organisms (bacteria and fungi) have demonstrated their potential in energy-harvesting for ICT autonomy. Bacterial bio-leaching of metallic minerals is a proven method for a range of minerals containing copper, zinc, nickel, molybdenum, gold, cobalt and other metals. Hydrothermal vents on the seafloor may offer new metal-processing bacterial strains that thrive in high temperature (80-100°C) hydrothermal fluids. Multi- and inter-disciplinary research is needed to develop hybrid collective systems, with symbiotic biological and mechatronic elements that generate their own energy via energy-harvesting while capable of producing valuable metals via bio-leaching in a symbiotic process. Research should be implemented in the cross section of microbial physiology (understanding bio-leaching coupled with bio-energy harvesting from mono- or mixed-culture microbial communities) and the disciplines supporting the development of energetically autonomous robotics. Such systems would require the development of a collaborative environment, in which ICT and microbiological agents co-exist and co-evolve. The symbiotic functions and long-term interaction of such bio-ICT systems need to be investigated with the help of natural analogues and simulations.

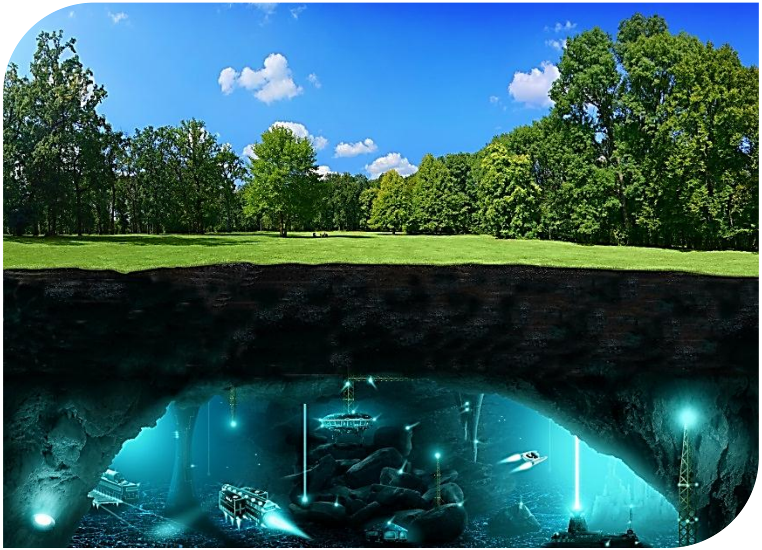
Call 3 Underground machine evolution

The development of Life on Earth demonstrates the ability of natural evolution to fill environmental niches with suitable designs. Artificial evolution can be expected to do the same much faster. A radically new evolutionary paradigm for engineering mining equipment is needed for working in previously unreachable environments. This paradigm should use artificial evolution to develop the hardware (the bodies) as well as the corresponding software (the minds) of machine systems. This could be realized through the conceptual development of a semi-closed ecosystem, where machines are subject to natural and artificial selection. Natural selection will guarantee adaptation to the given environment (i.e. ill-suited robots will “die”), while artificial selection will enforce human priorities. In such systems, underground machines will evolve in a controlled manner, facilitating on-demand evolution in real time and real space with a large degree of autonomy. This will lead to completely new kinds of systems where the design, the production, and the instruction (programming) of mining equipment are inherently evolutionary.

## Thematic Area II - Resilient Artificial Ecosystems

Call 1 Beyond pervasive adaptation

Latest developments in artificial collective systems point towards increasing the total heterogeneity, using functionally and structurally different robots, involving bio-/chemo-hybrid elements by combining chemistry, biology and mechatronics. Such diverse artificial systems will create artificial ecologies, where different types of artefacts and computational networks will collaborate, evolve and impact each other in achieving their goals, e.g. exploration, extraction and maintenance. These units must be capable of operating under sub-optimal conditions (while partially damaged) and capable of learning how to keep operating without using the damaged systems. Future robotics underground will thus require the development of new paradigms for lifetime learning and physical adaptation to changeable and unexpected working conditions beyond pervasive adaptation: they must be able to respond to individual failures and remain operational in environments where human supervision is impossible.



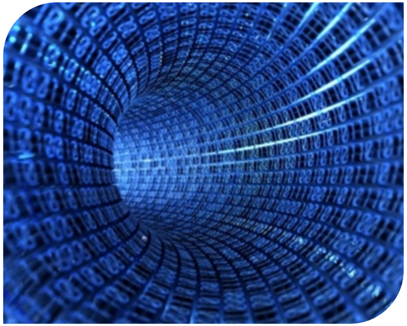
Call 2 Machine-repairable machines.

The production of machinery today is efficient. In contrast, the repair of machinery is expensive and labour intensive (e.g. vehicles, construction machinery, and mining equipment). This is undesirable and impractical in dangerous, hard to reach places where high levels of machine autonomy is otherwise desirable. The aim is to investigate and demonstrate how heavy-duty mining machinery can be designed to be machine repairable from the very beginning and how to develop the corresponding systems to perform these repairs automatically. This requires a paradigm change in how machines are designed and fundamental research is required in the area of damage-recognition and subsequent autonomous machine "surgeries" performed by specialized units. Tasks include the understanding of the general principles behind future automatic repair systems, taking into account their limitations and potentials. Further tasks are the development of the fundamental elements of machine repairable machines, including connection mechanisms, modularity and organization. This Call will develop the concepts for fundamentally new machine design approaches that will allow unsupervised machine maintenance during their operational phase.

Call 3 Heavy-duty Swarm Robotics underground

Once a mining/mineral extraction process requires more than a handful of vehicles to operate in the same area, their actions must be coordinated to enhance efficiency. At some point in the future, ecosystems of heterogeneous artefacts will implement autonomous mining solutions—possibly composed from reconfigurable or modular elements. Mining will thus require the deployment of self-organizing multi-agent systems, where each unit is a specialist in different challenges: exploration, cutting, transporting, communications, maintenance, etc. Through task allocation, the complexity of the individual agents could be minimized, and will be expected to manifest complex behaviour at systems level. Basic research is required for understanding swarm robotics in such real-life production ecosystems, where the unpredictable, harsh environment and the specific task requirements will open up new research challenges for robot team technologies, stability, controllability and overall resiliency.

## Thematic Area III – Broadband through the Rock



Call 1 Breakthrough data transmission technologies

Next generation communication solutions will be used in the "sense, communicate and control" smart mining paradigm. The challenges are: provide full coverage, connectivity of sensors with different bandwidth requirements, resilience, re-configurability, self-organization, self-healing and easy deployment in a harsh environment. Research is required at basic-science level for the development of radically new ways of providing data communication and localization capabilities directly through heterogeneous non-uniform materials and rock substrates via the exploitation of radio, seismic/vibrational, acoustic signals and high energy particles (such as neutrons).

Call 2 Self-organised in-mine communication

This Call supports the conceptual development of communication networks that provide a reconfigurable dynamic infrastructure for full connectivity between in-mine artefacts, humans and surface operation centres. The network concepts should make efficient use of the mine characteristics: completely new modes of radio propagation, waveguide propagation through tunnels, exploitation of metallic infrastructure used in tunnels, energy distribution, wiring, pipes, mine infrastructure and the orebody itself. The self-organised, self-healing in-mine communication network shall exploit means of communication in a hybrid approach: basic-research experiments for new radio bandwidths, ultra wide band

and mmWave radio, without excluding the use of wired solutions provided that they exploit existing or an easy-to-install infrastructure.

Call 3 SwarmCom

Underground robotic swarms will require secure, uninterruptable (redundant, parallel-processed and high-bandwidth) communication networks for swarms of robots to allow coordination, task delivery, monitoring and navigation. They shall meet the specific needs of underground mining swarms, be embedded, preferably powered by energy harvested directly from the environment and have self-healing/self-configuring properties. They shall fulfill the requirements of new generation robotic systems that may operate in (semi) autonomous mode. Future mines may be flooded or pressurized, in such a case new transmission methods should also be identified via basic research experiments. Fundamental new findings are expected in identifying the appropriate communication medium, the characterization of the communication medium, e.g. radio propagation, new transducers and antennas, physical layer algorithms, signal processing algorithms and new protocols. Research should address the use of multiple parallel solutions for achieving high aggregate transmission rates for in-mine broadband.

## Thematic Area IV (2 Cross-cutting Calls)

Call 1 Smart Systems integration

Basic-research is required towards the conceptual development of a “super-size” autonomous, adaptive production-system (communication, energy harvesting and storage, sensing, robotic solutions for transport, exploration, production, maintenance, etc) that actively participates in decision-making, eventually capable of planning itself. Machine teams may vary from a small number of co-operating robots (also co-operating with humans), to large swarms implementing tasks in a distributed fashion. Theoretical and practical advances in robot team technologies are required, building on conventional and non-conventional (e.g. bio-inspired, distributed/swarm) methods. This will require a profound understanding of the challenges of self-organization of artificial and hybrid systems where the system goals (as influenced by humans) and the optimization challenges will eventually become more complex than in their biological analogues. Advances are needed in adaptive self-modelling and optimization methods, including optimization of deployment of resources and exploration/exploitation trade-offs. Networking should be directed towards novel solutions to mine deployment and management, demonstrated in rich 4D simulation with key elements validated using available mining technologies and/or data resulting in new concepts in autonomous system control, optimisation and verification.

Call 2 Coordinating communities - Resilient Robotics for Future Mining

EXTRACT-IT has demonstrated that our quest for the production of minerals in challenging environments has the potential to fuel basic, exploratory research for minerals and ICT. A continuing coordination effort is needed that could mobilize even more new ideas and create new avenues for ICT research. Such action should support a paradigm shift in underground robotic design, making future systems more robust and energy efficient e.g. by outsourcing control to the physical level as it can be observed in nature (embodiment and MC). Multi-disciplinary coordination efforts are needed for energy (production, harvesting, distribution), energy efficiency, the development of novel sensors, high-temperature electronics and several completely new inter-disciplinary research domains (e.g. in the cross-section of geometallurgy and ICT).

## Final Notes

EXTRACT-IT represents a first step in the process that could boost European efforts in mining-ICT research of exploratory character. Such efforts will reside in the "exploratory science domain" and as such they are not directly driven by immediate industry needs in the present (but rather anticipated needs in the future), and pure scientific interest is the key driving factor. Clearly the path that may result in, for example, the deployment of novel bio-inspired mining systems, is a long one - if such development is ever realized on an industrial scale. But simply by going down this possible future path, entirely new research domains will be explored and developed, fuelling basic science in the present. The underlying research challenges are so profound that calling on such topics would contribute to the development of research areas beyond mining, eventually strengthening European research excellence in exploratory ICT. There is a vast array of exciting multi-disciplinary technological areas that could not have been developed into Call Topics within the short timeframe of the EXTRACT-IT project (12 months). The objective of EXTRACT-IT was merely to start up the dialogue and *"be the first step on the way towards future European scientific and industrial leadership in areas that today simply do not exist yet."*

The multi-disciplinary networking around mining and emerging ICT must continue.

## Acknowledgement

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## The EXTRACT-IT Partnership http://www.extract-it.eu

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