BeFo

STIFTELSEN BERGTEKNISK FORSKNING
ROCK ENGINEERING RESEARCH FOUNDATION

AUGMENTED ROCK MECHANICS REALITY

Catrin Edelbro
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BeFo Report 213

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Förstärkt bergmekanisk verklighet

Catrin Edelbro, Itasca Consultants AB

Robert Ylitalo, CGI

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PREFACE

During a lunch-presentation at the Luleå Science Park, a project from Kiruna named the "Hidden city" was presented in 2018. This projected considered Augmented Reality (AR) and visualization of water pipes underground. As these pipes are invisible from the surface, in the same way as underground excavations are, the project idea about augmented rock mechanics reality was born. The purpose of this pilot study was to investigate AR technology and increase the knowledge regarding how AR can be used for rock mechanics purposes.

Daily, new technology connected to the rapid development in the IT sector reach us. And we should use and develop these tools where we see benefits. The research program 2021-2025 at BeFo invites to such utilization and this project is a good example if and how new IT tools can improve our processes. We can achieve this by working with people from other fields and with different skills. As in this project, where the rock mechanics engineer together with the expert in other technologies, in this case AR, takes a step into something completely new.

The planned activities of the project were a workshop, literature and case study review, study visits and interviews. The project started November 15, 2019 and the first reference group meeting was held November 26, 2019. The reference group provided input on the project and on the planned workshop at the second meeting held January 20, 2020. The reference group to this project consisted of: Mats Svensson (Tyréns AB), Henrik Ljungberg (Skanska Sverige AB), Sayidali Ahmed (Trafikverket), Tristan Jones (LKAB), Lars-Olof Dahlström (Golder Associates AB/LTU), Jekaterina Jonsson (Geosigma), and William Bjureland and Per Tengborg from BeFo.

The workshop with nearly 40 participants was held in Stockholm on February 4, 2020. Unfortunately, the planned study visits during the spring were cancelled due to the COVID-19 pandemic. The visits were replaced by open-ended qualitative interviews with people working in the role as rock mechanics engineer. Totally 20 interviews were performed. The results from the interviews together with results from the workshop have shown a common trend of suggestions on how AR could be used in a rock mechanics perspective.

The project was funded by BeFo, the Rock Engineering Research Foundation. We hope this report can be the basis and guide regarding what to focus on when developing AR in the field of rock mechanics.

Stockholm January 2021

Per Tengborg

FÖRORD

Vid ett lunchföredrag på Luleå Science Park, år 2018, presenterades ett projekt från Kiruna benämnt "the Hidden city". I projektet nyttjades förstärkt verklighet (AR) för att visualisera vatten- och avloppsledningar under mark. Eftersom dessa ledningar är lika osynliga som tunnlar under mark väcktes projektidén om förstärkt verklighet inom bergmekanik. Syftet med denna förstudie har varit att undersöka dagens teknologi inom AR och öka förståelsen kring hur vi kan nyttja AR inom bergmekanik.

Vi får dagligen ny teknik som har koppling till den snabba IT-utvecklingen och där det finns fördelar för branschen ska vi utnyttja och utveckla dessa verktyg. BeFos FUI-program 2021-2025 bjuder in till det och detta projekt är ett gott exempel på att undersöka om och hur nya verktyg inom IT kan användas för att förbättra våra processer. Det kan vi endast förverkliga genom att jobba med folk från olika områden och med olika kompetenser. Som i detta projekt, där bergmekanikern tillsammans med experten inom annan teknik, i detta fall AR, tar kliv in i något helt nytt.

De planerade aktiviteterna i projektet var workshop, litteratur- och praktikfallsstudie, studiebesök och intervjuer. Projektet startade 15 november 2019 och det första referensgruppsmötet arrangerades den 26 november 2019. Referensgruppen gav input till projektet och den planerade workshopen vid det andra referensgruppsmötet den 20 januari 2020. Referensgruppen för projektet har bestått av: Mats Svensson (Tyréns AB), Henrik Ljungberg (Skanska Sverige AB), Sayidali Ahmed (Trafikverket), Tristan Jones (LKAB), Lars-Olof Dahlström (Golder Associates AB/LTU), Jekaterina Jonsson (Geosigma), och William Bjureland och Per Tengborg från BeFo.

Workshopen, med nästan 40 deltagare, arrangerades den 4:de februari 2020 i Stockholm. Tyvärr kunde inte de planerade studiebesöken genomföras på grund av COVID-19 pandemin. Besöken ersattes med kvalitativa intervjuer med öppna svarsalternativ. Totalt intervjuades 20 personer som arbetar som bergmekaniker eller motsvarande. Resultat från intervjuer och workshop har visat på en samstämmig syn och förslag på vad man vill använda AR till inom bergmekanik.

Projektet har finansierats av BeFo, Stiftelsen bergteknisk forskning. Vi hoppas att rapporten kan användas som underlag vid fortsatt utveckling och forskning av AR inom bergmekanik.

Stockholm i januari 2021

Per Tengborg

SUMMARY

As a rock mechanics engineer your main task is to ensure the stability of rock excavations. In that role you investigate, measure, observe, and interpret geomechanical information, which is relevant for the stability. An improved safety, a better basis for decision making, and more objective assessments could be the result if the real-world view could be enhanced and improved with important and necessary information from a rock mechanics perspective. Augmented Reality (AR) is a relatively new and exciting technology, which provides a real-world view with additional, computer-generated enhancements. This report presents the results from a pilot study of the use of AR in the field of rock mechanics. The focus of the study was on examples on how AR can be used, from a rock mechanics perspective.

To capture the need from the industry a workshop was arranged and complemented with open ended qualitative interviews. Nearly 60 people responded and identified underground excavations and utilities, geological information, geomechanical model, rock support and reinforcement, results from analysis, measurements, as important objects to enhance in the real-world view. Almost all respondents wanted to use AR for visualization of weakness zones and structures. Using AR as a communication tool and for navigation and safety aspects was also highlighted. However, the vision was to visualize real-time analysis results in the field underground and to be able to do real time adjustments of the design. Future tunnel inspections were suggested to be more strategic and based on the scanned version of the completed tunnel including information of weak zones and complex areas.

This report introduces cases linked to the development of AR in fields related to, or relevant for, rock mechanics of underground excavations. Cases where VR and AR technology are used in mining for communication purposes and for tunnel inspections are presented. The development of AR solutions that enhances reality with 3D geological data for open pits and rock slopes is described as ongoing research. The state-of-the-art of AR as a technology is presented.

Based on the pilot study and the status of the AR technology, the world of rock mechanics could greatly benefit through its use. According to suppliers of technology and researchers in the field, the most difficult issue to solve at the moment is the localization and positioning for underground excavations. The identified low-hanging fruit for near future studies and implementation of AR in rock mechanics is therefore visualization for rock slopes. While AR is currently in its early stage and come with limitations, most of these limitations will likely be overcome within the next few years.

Keywords: Augmented reality (AR), visualization, rock mechanics

SAMMANFATTNING

En bergmekanikers huvudsakliga uppgift är att säkerställa konstruktioners stabilitet. I den rollen undersöks, mäts, observeras och uppskattas geomekanisk information som underlag för stabilitetsanalys. Förstärkt verklighet (AR) är en relativt ny och spännande teknologi som förstärker verkligheten med datorgenererade data och objekt. Om verkligheten förstärktes med nödvändig och relevant bergmekanisk information skulle resultatet kunna vara en säkrare arbetsmiljö, bättre underlag för beslutsfattande och mer objektiva bedömningar. Den här rapporten presenterar resultaten från en förstudie som berör AR inom bergmekanik. Målet är att ge konkreta exempel på hur AR kan användas ur ett bergmekaniskt perspektiv.

För att identifiera branschens behov utfördes en workshop samt kvalitativa intervjuer med öppna svarsalternativ. Totalt har nästan 60 personer medverkat i förstudiens aktiviteter och deltagarna har identifierat närliggande konstruktioner under mark, geologisk information, geomekanisk modell, bergförstärkning, resultat från analyser och mätningar som de viktigaste sakerna att förstärka verkligheten med. Majoriteten av deltagarna önskar använda AR för att visualisera svaghetszoner och strukturer. Att använda AR för kommunikation, navigering och säkerhet var också efterfrågat. I framtiden vill deltagarna kunna nyttja AR för att förstärka verkligheten med resultat från analyser och samtidigt kunna göra förändringar av designen i realtid. Framtidens tunnelinspektioner föreslogs vara mer strategiska och baserade på inskannad information av den färdiga tunneln tillsammans med verklig placering av svaghetszoner och komplexa passager.

I rapporten finns praktikfall beskrivna, vilka länkar till utvecklingen av AR inom områden som är relaterade eller relevant för bergmekanik. Praktikfall som beskriver hur VR och AR används inom gruvsidan för kommunikation och för tunnelinspektioner finns presenterade. Utvecklingen av AR system som kan förstärka verkligheten med geologisk data i 3D för dagbrott och bergslänter beskrivs som pågående forskning. Möjligheterna och begränsningarna med befintlig AR teknik beskrivs.

Baserat på denna förstudie anses AR vara till stor nytta ur ett bergmekaniskt perspektiv. Däremot är tekniken ännu inte mogen att användas full ut under mark med hänsyn till dess begränsning med positionering. Den "lågt hängande frukten" för fortsatt arbete och implementering bedömdes vara tillämpningen av AR på bergslänter. AR är en relativt ung teknik som har sina begränsningar. Den pågående teknikutvecklingen medför en stor potential för användandet av AR inom undermarksbyggande.

Nyckelord: Förstärkt verklighet (AR), visualisering, bergmekanik

CONTENTS

1. INTRODUCTION

1.1 Background

Rock mechanics connects to everything that is built underground and is used in mining, civil, and petroleum engineering. As a rock mechanics engineer your main task is to ensure the stability of rock excavations. In that role you investigate, measure, observe, and interpret geomechanical information, which is relevant for the stability. At the planning stage the ground conditions and behaviour are interpreted based on results from pre-investigations. The rock reinforcement, geometries, excavation method, grouting, etc., are designed based on the interpreted ground conditions. The design is verified during excavation by measurements, multiple rounds of investigations and field observations. Hence, more information about the ground is gathered during the different phases when constructing in rock.

An improved safety, a better basis for decision making, and more objective assessments could be the result if the real-world view could be enhanced and improved with important and necessary information from a rock mechanics perspective. Field studies, where the digital model, results from numerical modelling or the scanned environment is visible, could give an important contribution to excavation underground.

Augmented Reality (AR) is a relatively new and exciting technology. As AR may be used in combination with or mixed up with Virtual Reality (VR), Mixed Reality (MR) or Extended Reality (XR) it is important to explain (Figure 1) and define the terminology, as follows (modified from the Franklin Institute, 2020):

- Augmented reality (AR)

  Provides a real-world view with additional, computer-generated enhancements. As an example, this could be in a tunnel environment in which the user can virtually enhance what can visually be observed by adding digital objects.

- Virtual Reality (VR)

  An interactive, computer-generated depiction of a real or artificial world or activity. An example of this could be a computer-generated tunnel in which your simulated self can move around and interact with the virtual machines and tools or the simulated selves of others like you.

- Mixed reality (MR)

  Combines elements of both AR and VR and provides an interactive view of combined real-world and computer-generated elements. In mixed (or merged) reality, the contents of the virtual and real world interact by putting virtual reality content through real-world movie sequences. This could, for example, be a real-time view of a tunnel in which a virtual bolt interacts with the real bolting machine. Since it is interactive, the virtual bolt follows the movement of the bolting machine.

– Extended reality (XR)

  XR is an umbrella term that covers all of the various technologies that enhance our senses. Hence, it includes Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR) technologies (as well as IoT "Internet of Things" and BIM "Building Information Model").

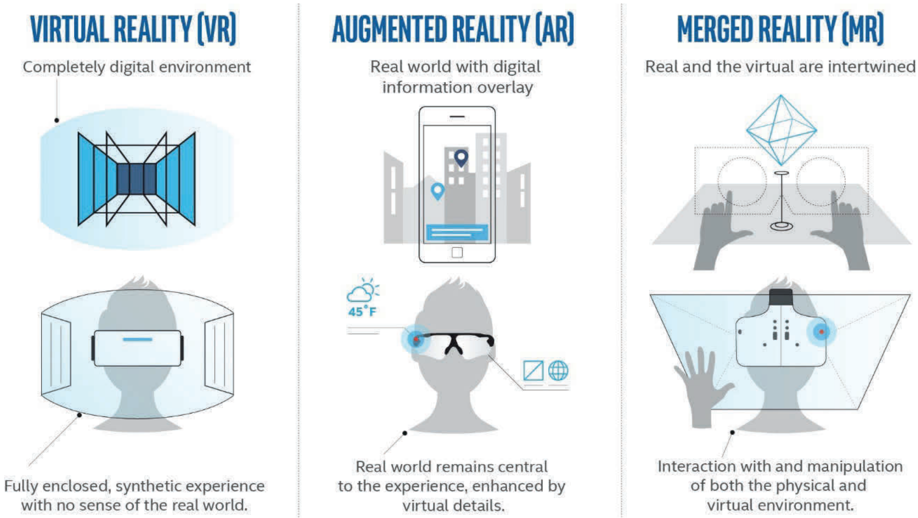

Figure 1. Schematic graph of the difference between VR, AR and MR (Cardinal, 2017).

In this work all the above terms are of interest and they are covered under the term "augmented reality". Hence the AR combines the real world with computer generated enhancements or objects. AR is a way to view and interact with applications and to display information and grab inputs from the user. Using sensors, AR devices can also detect information about the environment.

1.2 Objective and scope of work

The purpose of this pilot study was to investigate AR technology and increase the knowledge regarding how AR can be used in the field of rock mechanics. The aim is to give examples on how AR can be used, from a rock mechanics perspective.

To achieve this, the activities in this project comprised literature and a case study review, a workshop, and open-ended qualitative interviews. The pilot study is an analysis of needs of AR in the field of rock mechanics and a step forward regarding communicative and sustainable building underground. The result highlights needs and implementation of AR within rock mechanics and opens for continued research and development in the field.

This work does not go into detail in other systems and technologies supporting AR with information, such as photogrammetry, unmanned aerial vehicle (UAV (drone)), measurement while drilling (MWD), laser scanning, BIM etc.

2. METHODOLOGY

2.1 Literature and case study review

A comprehensive literature review has been conducted using Internet searches in Google, on-line literature databases (Scopus, Web of Science, Google Scholar, etc.), and publications available at Swedish universities. The state-of-the-art review is mainly based on experience from research and innovative work within the field of AR technology. The focus of the case study review was application of AR in underground excavations. Published cases primarily from Sweden but also international cases were collected as part of the review. Some of the identified cases were further investigated through interviews.

2.2 Workshop

In order to capture the need from industry a workshop regarding "Augmented reality in rock mechanics" was arranged in Stockholm on February 4, 2020. Nearly 40 participants (consultants, clients, contractors, researchers, manufacturers) attended and actively discussed and responded during the workshop. The workshop included a mix of lectures and group discussions. The discussions were held in both Swedish and English.

In order to obtain state-of-the art as well as examples of possibilities and limitation when using AR in field, three inspiration lectures were given. Robert Ylitalo at CGI introduced the state of XR today and inspired with the Hidden city case (CGI INC, 2019), see section 5.2.3. Tobias Kampmann at Luleå University of Technology presented research linked to visualization of geological models using VR and AR. Kristofer Björkström at Bjorkstrom Robotics presented tools, techniques, and their solution for using AR in field. The full program for the day is attached in Appendix 1.

2.3 Open-ended qualitative interviews

A total of 20 open-ended qualitative interviews were conducted with people working as rock mechanics engineers or similar. The respondents were from different areas (mining, tunneling, energy) and in different roles (design, excavation, client/owner, academia), as follows:

- Three from mines (client/owner).
- Two from the Swedish Transport Administration (client/owner).
- Two contractors in civil engineering (excavation).
- Ten consultants (design – for all types of underground excavation).
- Three researchers and teachers (academia).

The gender of respondents was five women and fifteen men. Nineteen were from Sweden and one from Norway. In addition to the above, separate open-ended qualitative interviews were performed with people working with implementing digitalisation, AR, and artificial intelligence (AI) in mines.

3. THE SUGGESTED USE OF AR IN ROCK MECHANICS

3.1 Results from the workshop

During the workshop, discussions were held in groups and thereafter presented verbally. The discussed subjects were:

- How AR can be used when excavating underground. Give example of professions that would benefit from using AR for underground rock excavations.
- Give examples on how AR can be used for underground excavations from a rock mechanics perspective.
- Opportunities and threats with implementing AR from a rock mechanics perspective.

As a summary from all groups the following examples of when to use AR in rock mechanics were presented (see also Figure 2):

- To observe changes with time, which could be important for studies regarding deformation, stresses, shotcrete, rock support etc. In this sense, the AR is useful for inspections, maintenance, and rehabilitation.
- Use AR for forensic analysis after e.g., a fall of ground. Using UAV (drone) investigations, scanning data and/or photos, see pile of rock, structure change, bolt length, etc.
- Real-world tunnel view added with selected parts of the computer-generated geomechanical model in 3D (e.g., large-scale structures, geology) would be a benefit during rock mechanics field studies, such as tunnel mapping or monitoring.
- To have the real-world view integrated with real time measuring (e.g., smart bolts, photogrammetry, MWD) and monitoring results would increase the understanding of the rock mass as well as provide a good background for decision making.
- In mining, it would be a benefit to study different layouts and use the 3D model combined and added with geomechanical information. This could for instance be used when evaluating the best position of a planned tunnel or suggest excavation steps or method. (In tunnelling necessary objects from the BIM model could be enhanced and visible in field.)
- In mining, seismic events and their location are of great importance. AR could be used to give a better visualization of the location of seismic events.

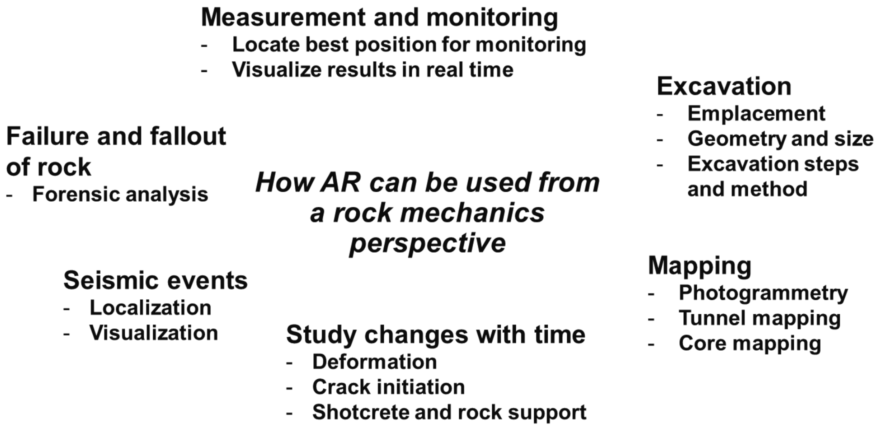

Figure 2. Example of areas in rock mechanics where *AR* could be a benefit based on the results of the workshop.

Other examples were also given, which would benefit the rock mechanics work, but also other areas or processes within underground excavation, as follows:

- By using AR, everyone can see the same information. Hence, it could be used as a communication and decision-making tool in the field and at the office.
- Preferably a tool to be used in all phases of an underground excavation — from pre-investigation/exploration to maintenance of a completed underground excavation.
- Drilling machine operators can use AR to combine the real tunnel with computer generated objects, such as structures and drilling plan. This would help to place and orient the drilling in a more optimal way.
- If the scanned tunnel is visible for the operator of the haulage equipment it would increase safety in case of fire accidents.

According to the presentations from the group works, real time information is required in order to use AR for decision making. Hence, the 3D models need to be intelligent and it must be possible to add any necessary data from a user perspective.

All participants also agreed that the implementation of AR in rock mechanics should start in a small scale and with something specific ("low-hanging fruit"). Based on results and interpretation, the need and development for other areas should be stated before a continued implementation. The identified challenge with implementing a VR/AR environment was connected to required input data and amount of output data.

3.2 Results from open-ended qualitative interviews

Relatively few of the respondents had thought of AR as a supporting technology from a rock mechanics perspective. The designers could see a great potential of using AR in their daily work, while the contractors could see less benefit in their role. Based on all interviews, structures and weak zones seemed to be of greatest interest to visualize in an interactive view. The respondents could also see the large benefit of using AR as a communication tool. In the future, the most benefit of using AR is to visualize data from field investigations and perform real-time analysis (such as wedge and stress analysis) that would result in an adapted solution for rock reinforcement. Several of the respondents answered that in the near future, AR should have a great potential for strategic tunnel inspections. The suggested "low-hanging-fruit" for a continued work was the visualization of mapped structures in rock slopes.

A general and schematic view of what information and objects the respondents would like to visualize in AR in the different phases of tunnelling design and excavation is presented in Figure 3. The AR environment should be continuously improved and updated with more information during the subsequent phases.

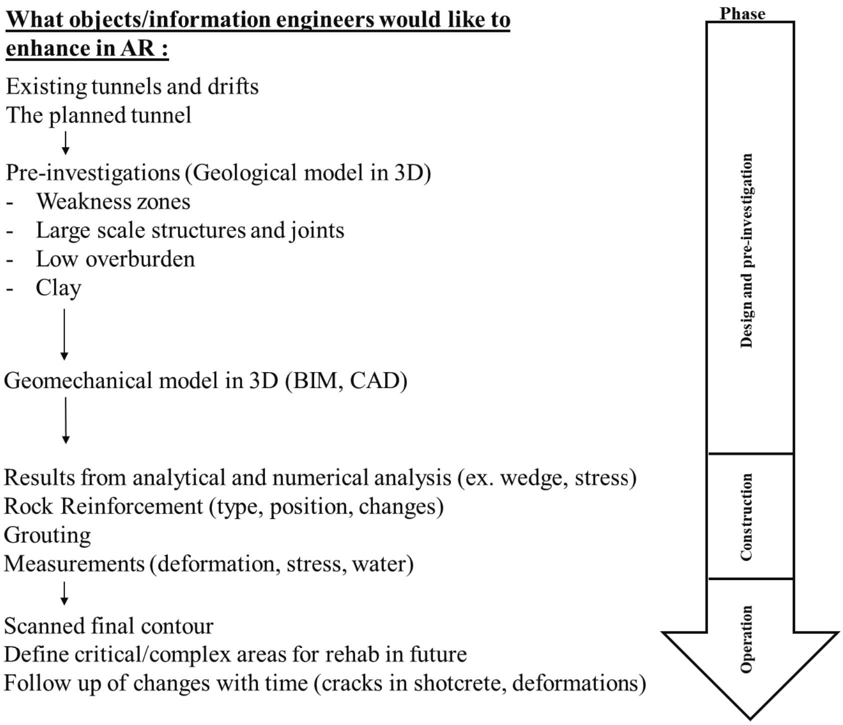

Figure 3. Schematic view of what the respondents would like to visualize for the different phases in tunnelling design and excavation.

In the pre-investigation and design phase, it was suggested that the engineer should have an interactive view with all nearby tunnels, pipes and other underground utilities. Some respondents commented about accidents connected to drilling and not knowing about position of underground excavations and utilities. As example, a hole from the surface was accidently drilled into the tunnel at Södra Länken in Stockholm in January 2012. One bus and two trucks hit the drillrod. According to the drilling operator, there were no maps showing the tunnel underground (Sveriges Radio, 2012). In the U.S., there are problems associated with underground gas pipelines. Fenais et al. (2020) discuss the possibility to visualize underground utilities in order to avoid accidents and injuries when excavation workers hit gas pipelines. If the nearby and planned tunnel are enhanced in the real-world view, it could be used as support in decision making for the pre-investigation program.

It was also suggested to fill the AR environment with results from pre-investigations. As the weak rock areas are of great importance for the stability, the respondents wanted to enhance the real-world view with weakness zones, large scale structures, and joints, as well as overburden and clay. In general, they wanted to augment the reality with all data from the pre-investigation phase and the virtual geological model in 3D. The geological model could then be combined with interpreted stresses, topography etc., and transformed into a virtual geomechanical model of the tunnel.

During excavation of the tunnel, the respondents wanted to overlap the reality in field with the virtual interpreted geomechanical model. The planned theoretical geometry could be compared to the actual contour. Results from analytical, empirical, and numerical analysis should also be visible to be able to see the potential depth of wedges as well as stress tensors. The respondents wanted to be able to stand in the tunnel, with the above information enhanced, and verify the technical design solution. Since more information about the ground is gathered during the excavation phase, it should be possible to update and revise the AR environment with actual ground conditions. Hence, results from e.g., real time mapping, MWD, and testing in field, was suggested to be visible in an interactive view. By using the information above the respondents saw the potential for more strategic decisions regarding where and what type of measurements should be performed during excavation. The position and type of measurements as well as the results from measurements was desirable to add as enhanced objects.

Position and information of type of rock reinforcement as well as position of grouting holes was relevant information to visualize for some of the respondents. Especially for the contractors, laser or optical scanning of the rock surface as well as scanning after shotcreting could help to construct the support according to design. It also seemed interesting to use the AR technology to follow changes, such as cracks in the installed shotcrete or concrete arches.

In the operational phase, the AR technology could be used for strategic inspections in documented complex areas. The scanned contour of the completed tunnel could form the basis for follow-up of changes, such as deformations, failure and fall of ground, during operation. Monitoring of rock bolt condition was suggested to be visualized during the operational phase.

Outside of the general view of what the respondents would like to visualize in a rock mechanics perspective, there were other comments, such as:

- Be able to visualize seismicity and seismic events in the mines.
- The AR technology could be used for learning and improved understanding. The benefit would be both for new employees as well as for seniors to get a deeper understanding of the rock mass behavior. For example, visualizing nearby excavations which have failed or grown in size (such as ore passes) would increase the understanding of the failure observed in the actual drift.
- Use AR for simulation of mining/excavation stages and steps.
- Parallel with all the phases of underground constructing a risk analysis is performed. Some respondents commented about the potential of using AR as basis and support in the risk management work.

Beyond what the respondents would like to visualize from a rock mechanics perspective, they commented about the potential of using the VR and AR technology as a communication tool. In the different phases of the excavation there are various roles that could benefit of greater knowledge in general about the underground excavation as well as specific rock mechanic information. Especially complex geometries and areas with weak rock mass are important to communicate. A schematic example of who the respondents would like to communicate with in the different phases is shown in Figure 4.

The other potential use of AR was mainly linked to safety. This included: (i) to use the AR technology for navigation (as GoogleMaps) underground and for evacuation and safety purpose, (ii) to see the position of the nearest safety chamber was desired, and (iii) to visualize areas and boreholes where the blasting has failed and where explosives could be left in the holes.

An outstanding thought about the future was the possibility to use VR/AR and AI technology to create a communicative effective "platform" for design. The designer should be able to ask questions about ways to design, standards, size and precision of equipment, etc. The continuously updated "platform" should provide answers based on knowledge from several previous worldwide designs.

Some of the negative issues with implementing AR as a technology concerned:

- If there are problems today with understanding the 2D construction drawings, why should we implement a new technology that will make it more complex?
- A physical 3D model of a mine or tunnel is more worth as a communication tool than VR and AR.
- The BIM have not yet a clear role in underground excavation despite many years of implementation. Why should this new technology be easy to implement?

- Data is a fresh product that gets old. How will this new technology consider that?
- It is difficult for the skilled workers to use this type of technology. Hence, the development and implementation should focus primarily on the designers and the management and engineering roles.
- It will be too much information. It will be difficult to find out the important parts.

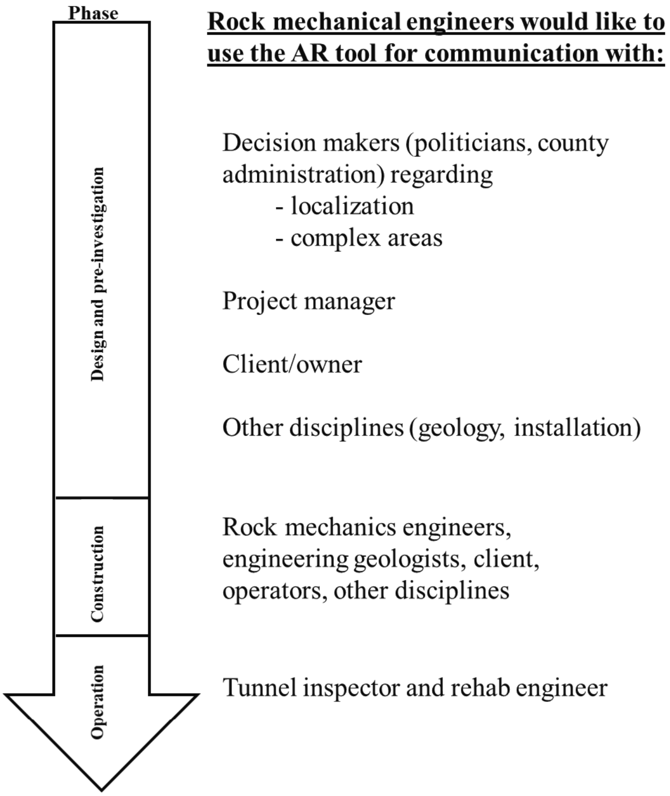

Figure 4. Schematic view of who the rock mechanics engineer would like to communicate with in the different phases of an underground excavation.

3.3 Summary of use of AR in rock mechanics

Based on results from the workshop and the interviews there were common objects and information that the engineers would like to visualize. From a rock mechanics perspective, they wanted to enhance the real-world view with the following information/objects:

- Underground utilities and nearby excavations as well as the planned and designed excavations.

- Geological information (rock types, structures, weakness zones, clay etc.).
- Interpreted and computer generated geomechanical model (geological information, overburden, topography, interpreted stresses etc.).
- Results from analytical, empirical and numerical analysis (e.g., wedges, rock mass classification interpretations, and stress tensors).
- Rock support and reinforcement (position and type of bolts, follow changes with time such as crack initiation in shotcrete).
- Real time measurement results (from e.g., extensometers, inclinometers, smart boltss, photogrammetry, MWD, etc.)
- Final rock- and inner contour of the excavation.
- Fall out of rock and seismic events.

From a communication and safety perspective, they wanted to use the AR technology for:

- Communication with stakeholders, clients, decision makers, project managers, other disciplines, and other engineers within rock mechanic.
- Navigation and evacuation tool underground.

4. STATE-OF-THE-ART OF AR TECHNOLOGY

4.1 Current AR/MR Devices

There are currently four major players in the realm of augmented/mixed reality. Apple's ARkit, Google's ARCore, Microsoft HoloLens, and Magic Leap. It is better to think of them as two different categories, as ARkit and ARCore are platforms for mobile devices like phones and tablets, while HoloLens and Magic Leap are headsets.

Generally speaking, ARkit and ARCore are very similar, the major difference being that ARCore tends to lag behind the features of ARkit slightly. Magic Leap and HoloLens are also similar devices. Currently, the HoloLens 2 outperforms the Magic Leap One in terms of specifications, but they both function in much the same way.

Microsoft is currently the leader when it comes to AR/MR headsets, and this trend is suspected to continue. They are already leveraging the power of their Azure platform with HoloLens, and offer a range of products and sensors using the same base technology and are targeting industry more than Magic Leap.

4.2 What AR/MR can do right now

4.2.1 Digital twins as proxies of physical objects

One of the most powerful applications of AR/MR technology is the use of digital twins. A digital twin is simply a virtual copy of a real-world object that is in some way connected to the real-world object. In AR/MR apps, one can create the illusion that the user is interacting with the real-world object by placing a virtual "proxy" copy (sensors) in the same spot. The virtual object is invisible to the user, and all of the interactions the user experiences as being made on the real-world object are being performed on the proxy. This kind of proxy copy is referred to as a digital twin.

A simple usage case of this is placing a virtual post-it note inside a room. For example, a user has an application ("app") that holds a 3D model of a large room that has been 3D scanned. The app can place this model accurately on top of the real-world room, and as the user walks around the room they could tap a wall or surface and leave a post-it at that location. The note would not be associated in any way with the physical room, nor would it attempt to place the note based on the physical location of the user. Instead, it would simply leave a note at that location on the digital twin. With this method, once the app correctly places the digital twin in the room the note will appear in the same location.

The above is a very static example, but digital twins can be used more dynamically than that. Data can be streamed from real-world objects to their digital twins. For example, a "smart" pipe that carries water could send data from its sensors to an AR/MR application. By tapping on this pipe, it could display the streaming data as an informative panel to the user. The user can monitor the status of the pipe, such as temperature, flow, pressure, etc. all through a simple tap gesture.

Digital twins can also provide guidance to the user. Imagine an engine being displayed on a table. Instead of displaying a panel with information, tapping on specific parts of the engine could spawn a 3D model of the engine to the side and show a step-by-step tutorial of how to replace that particular part to the user. This coupled with remote assistance would make for a very powerful learning tool.

4.2.2 Above ground visualization with external GPS

Currently, none of the AR/MR devices come equipped with powerful GPS features. The accuracy of these devices can vary between a range of a few to several meters. While this is fine for most commercial applications it is not accurate enough for industrial purposes in most cases. To circumvent this problem, it is possible to connect these devices with external GPS systems to achieve better positioning.

In testing performed by CGI, they have been able to achieve a precision of around half a meter with a GPS system that uses readily available, over-the-counter parts and simple real-time kinematic corrections (RTK), and one can likely achieve greater results than that with this method. However, it is possible to boost precision even further by using GNSS-compatible equipment with high end RTK. With this level of industrial-grade equipment, one can achieve centimeter-level accuracy, which is enough precision to provide accurate above ground visualization of a mine below the user.

Using an external GPS, an AR/MR app can place a full-scale 3D model of a mining operation in the real world. The app can determine the height of the device based on readings of the ground and then place the mine below at the proper depth in relation to the device. Upon placing it, the application could track the user's position as they walk along the surface above the mine. In other words, it is currently possible to place a one-to-one digital twin of the mine in the real world.

Once the digital twin is in place, there are a lot of possibilities as to what one can do with it in an AR/MR application. One could scroll through vertical slices of the mine, much like an MRI scan, viewing only the portion that one wants. One could then place this swathe on the ground in front of others and take a virtual tour of the area above ground, or one could place markers or notes on walls and have that data be saved and accessed through other devices.

4.2.3 Below ground visualization with calibration points

Without the aid of GPS, AR/MR devices have a lot more difficulty with accurately placing 3D models and maintaining the accuracy of the model's placement when tracking. One method used to minimize error with placement is to set up calibration points. A calibration point is a small area where the user is directed to stand in the proper position and orientation. Once in place, the user will scan an image such as a barcode or QR code. The code provides the app with the position and orientation of their location, which is used to place the digital twin.

This method can place the digital twin of the mine accurately; however, its position is locked and will not be corrected. Imperfections made while the device or headset tracks its position in 3D space will lead to the digital twin not syncing up with the actual mine over time. This can potentially be overcome by having several calibration points, as well as options to manually calibrate the digital twin's position inside the app.

4.2.4 Indoor positional tracking

There are several different forms of indoor positional tracking technologies that can be, or have been, applied within the mining industry. Most, if not all, offer Application Programming Interface (APIs) or other ways in which an AR/MR application can communicate with other programs and units. The accuracy of each method varies, and they are largely not precise enough to calibrate the digital twin but could instead be used to display a localized map that shows the user's position, as well as other people, vehicles, and/or assets within the mine.

4.2.5 Visual data overlays and layers

The digital twin of the mine does not always have to remain invisible to the user. Sections of the model can be toggled on and visualized in different ways to give relevant data back to the user. These visual overlays could show displacement or strain within areas of the mine, offering a quick, visual method of displaying information. Tapping on areas could bring up more data and options as well.

It would also be possible to display a wireframe around the digital twin, allowing something akin to virtual x-ray vision. This type of feature would not just be limited to what is currently there. If there are plans and 3D models for new shafts, extensions to existing shafts, etc. one could have the ability to view them as well. This would allow users a feel for what is to come, and the ability to spot potential problems from a first-person perspective.

This type of data visualization is the true strength of AR/MR. Some concepts and a few ideas are described, but this is really just the tip of the iceberg. Much data that is generated could be used and converted into a visual overlay.

4.3 Limitations of AR

4.3.1 Visible light and positional tracking

Currently, AR/MR's positional tracking is done mostly through the visible light spectrum. The devices need at least enough light that a person can see comfortably, and the lighting should be as even as possible to allow for smooth tracking. If the lighting is too dark, tracking becomes impossible. If the lighting is not consistent it is possible for the device to temporarily lose track of where it is resulting in sluggish tracking, jittering holograms, and in the worst cases require recalibration via GPS or a calibration point.

The frequency of the lights can also affect tracking. The HoloLens cameras record at 30 frames per second, which is in sync with 30 Hz. If the HoloLens was in a room that was lit with a 50 Hz AC bulb, it would result in some frames receiving adequate light and others being more dimly lit. This is because there will be frames captured by the HoloLens that are not in sync with the lights, and on those frames, there will be less light compared to the others. Considering the standard for Sweden (and most of Europe) is 50 Hz, this is pretty much always the case.

With that said, this in itself is nothing to be alarmed of, as the tracking is still fine from testing performed by CGI on the HoloLens 1. It simply means that the tracking will likely be slightly less stable than it would be in the US or other countries with the standard of 60 Hz.

4.3.2 Processing power

Processing power is currently one of the largest limitations of AR/MR right now. Except for Magic Leap, all of the devices are more or less limited to mobile processors and GPUs. The Magic Leap is technically an exception here because it is connected to a processor unit called the Lightpack. Theoretically it could be switched out for something more powerful; however, to the authors knowledge they have not announced any alternatives to the standard Lightpack.

Currently, mobile devices overpower headsets when it comes to processing and graphics. There are two main reasons for this. First, phone models are updated with far more regularity, meaning that at least every year there will likely be a new more powerful model. Microsoft has only released the HoloLens 2 this past year, meaning that it has received one new model after four years. Similarly, the Magic Leap released in July 2018, and they have announced that the second model will ship in 2021.

The second reason why phones are more powerful is that the headsets render two separate images. It takes double the graphical resources to produce stereo images, which is still not taking into account the processes used to create the illusion of 3D holograms via stereo-images. The headsets' environmental awareness is more processor-intensive as well, as they produce a 3D mesh based on the environment, while ARKit and ARCore simply approximate vertical and horizontal planes. In summary, mobile devices can produce AR experiences almost up to the level of graphical fidelity as the latest mobile games, but this is not true for the headsets. That said, some mobile devices are now equipped with depth sensors, and it is suspected that they will be capable of more than just approximations soon.

Speaking from firsthand knowledge, the HoloLens 1 was never a graphical powerhouse, even shortly after release one could see that it had limited capabilities for rendering holograms. While it was still impressive at the time, it was not on par with the current generation of mobile devices. This is a more severe limitation than one might expect, as it affects development a great deal. To display effective holograms, one has to have a great deal of knowledge when it comes to optimizing 3D models and other graphical assets. It often requires a lot of work to implement these optimizations as well. One simply cannot take a CAD model and easily convert it into something usable on HoloLens 1. HoloLens 2, and perhaps even the Magic Leap, is likely to be powerful enough that these issues are not as problematic, but it will likely still be a concern. The HoloLens 2 does feature remote rendering via the Azure cloud, which would bolster its graphical capabilities in situations where latency is not as much of a concern, lessening this burden further.

4.3.3 Battery life (headsets)

Battery life is quite limited with all of the headsets. HoloLens 1 and 2 both claim to have two to three hours of battery life, while Magic Leap claims to have three. In practice, the HoloLens is more likely to have a battery life of 2 hours running more intensive apps, and Magic Leap is expected to be roughly the same in this regard.

On top of the short battery life, it takes about 2 hours to charge the HoloLens 1 on its charger. Without the HoloLens charger, charge times can be even longer due to it needing more amps and voltage for optimal charging than most USB charging cables can output, 18W of power (9V 2A). The HoloLens 2 has the same energy requirements, and will likely have similar charge times. No information could be found regarding the charge time of Magic Leap; however, its USB-C charger delivers 45 watts of power, meaning that it likely charges faster than the HoloLens.

4.4 Possibilities in the near future

4.4.1 Industry and commercial use

Currently, Microsoft has maintained its title as the leader with regards to MR headsets. With its release of the Azure Kinect DK, Microsoft plans to expand into producing high-quality depth sensors. Their target is primarily for industry, and they seem to be making a hard push to integrate AR/MR within as many sectors as possible as quickly as possible. Due to this, AR/MR will likely have its greatest impact within industry and that headsets like the HoloLens and Magic Leap will not be unusual within a few years.

On the commercial side, AR/MR has a lot of entertaining and useful features for commercial use. While mobile devices currently offer ARKit and ARCore, they are still not as aware of the environment as the current headsets. This limitation will not last for much longer, as more and more mobile devices are including depth sensors. Within the next five years, we will likely see a lot of features currently found in the headsets incorporated into mobile devices. However, due to how costly the headsets are, they will likely not catch on commercially outside of a niche market in the near future.

4.4.2 Depth cameras and sensors

More and more sensors and cameras are being produced that provides in-depth information about the environment that spans multiple techniques and technologies. Microsoft has Azure Kinect, Intel has their RealSense line of depth cameras, and Sony produces its line of DepthSense sensors for use in mobile phones and tablets. These sensors are cheaper than a headset but offer similar levels of environmental awareness. There are countless amounts of industrial and commercial uses for such sensors, and it is likely that they will become very common in the years to come.

4.4.3 Positional tracking improvements

As stated previously, AR/MR devices track the user's positions using visible light. Many other techniques and technologies are being developed that are not limited or hampered by low light conditions. Inertial tracking through accelerometers and gyroscopes, acoustic tracking or echolocation, magnetic tracking, and positional tracking through infrared and lasers are all being worked on. It is a matter of time before positional tracking is no longer bound by the visible light spectrum. As these alternative methods develop, they will also strengthen positional tracking as they can all be used in tandem to produce more accurate positional information.

4.4.4 Better onboard processing and cloud computing

The current limitations regarding processing power and graphical fidelity will fade over time. As AR/MR become more and more ubiquitous one can expect a steady stream of new devices that are up to date with the latest CPUs and GPUs. On top of this, cloud computing will become the norm as well. The HoloLens 2 already offers Azure Remote Rendering, which is a great way to circumvent the limited processing power of a headset, and this will likely be implemented in various ways amongst other headsets soon. Cloud computing is currently limited due to the strength and speed of your internet connection, but as time goes on that will improve as well.

4.4.5 Computer vision

The amount of understanding that a computer has with video input is increasing every year. While processing intensive, a lot of this can be offloaded to the cloud. Computer vision paired with AR/MR devices is extremely powerful, and a lot of what the current headsets accomplish with positional tracking is due to advancements made in computer vision. Much more can be said about the power of computer vision, but it falls outside the scope of this document.

5. CASE STUDIES

Augmented and mixed reality (AR and MR) is used only to a small extent in Sweden in the tunnelling and mining industry today. At the same time, it is thought to become a natural part of the future industry and developments within the area are progressing. This pilot study introduces cases linked to the development of AR in fields related to, or relevant for, rock mechanics. Hence, VR and other useful technologies are also included. Since several studies have been presented regarding AR within the field of building environment, a few of those are also presented here in order to give more examples and inspiration of use.

5.1 Mining and tunnelling

There are several papers and reports which discuss the future of mines and how AR can be applied and improve learning, safety and production in mining (see e.g., Bassan et al., 2011, Catalina et al., 2013, Durrant-Whyte et al., 2015, Jacobs et al., 2016, Society of Mining Professors, 2019, Buddhan et al., 2019). A few published cases or studies have presented the application of AR technology in mining. One such case is the RAG coal mining company in Germany, which has implemented AR for maintenance applications (Catalina et al., 2013). Hence the primary focus of implementing AR have been on rock engineering, the productional part, and the worker environment in a mine.

5.1.1 VR and AR technology for communication purpose

LlamaZoo have developed MineLife, a platform with AR, VR and desktop application for visualizing planning data. One of their cases is the Galore Creek project in northwest British Columbia where they developed a solution for better communication between internal and external stakeholders without having to travel to the site (LlamaZOO, 2020). They developed a 1:1 scale Virtual Reality digital replica of the Galore Creek development area. Geographic Information System (GIS), Digital Elevation Model (DEM), shape files, satellite imagery, UAV, photography, and other surface data including roads, infrastructure, government information such as waterways, mountain regions, and land holdings were integrated in MineLife. 60+ years and 393,000 meters of drill hole data (Figure 5) was visualized for the Galore Creek case.

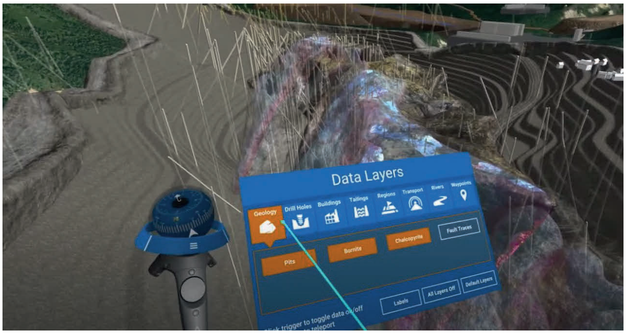

Figure 5. VR visualization of the mine project (LlamaZoo, 2018).

BGC Engineering used MR, VR and holographic images to communicate the life stages of an Alberta oil sands mine, emphasizing the environmental reclamation of the site in a unique communication format (Loook, 2017). The BGC Engineering AR software transforms data and plans into 3D models of the mine that can be viewed through HoloLens goggles. The tools have been used by community stakeholders in the Giant Mine remediation project (see Figure 6).

Figure 6. 3D-models of the Giant mine used as communication and discussion tool (CIM News Magazine, 2018).

5.1.2 Visualization tools for improved safety and increased productivity

In 2013 Mobilaris announced Mobilaris Mining Intelligence™ (Mobilaris, 2020) which addressed the industry need for increased efficiency and safety. Based on the continued need from industry, several products have been developed. The products include solutions for navigation (Figure 7), faster evacuations and safer daily operation, real-time information and data from production, machines, people, and vehicles. By knowing all assets of the mine and who is moving in what direction, you get an early warning before a potential traffic situation occurs. By collecting data in real-time from equipment, energy systems, people and vehicles it is possible to control emissions, electricity, and gas. Since all mines have different infrastructure for digitalization, the Mobilaris Mining Intelligence™ is technology-agnostic and a solution where planning data, machine production, maintenance and sensor data are integrated into one decision support system.

Example of mines where Mobilaris have made installations for safety and efficiency perspective are the Black Rock Mine in South Africa, Fosterville Gold mine in Australia, Kittilä Gold Mine in Finland, and in all Boliden Mines in Sweden and Ireland. At the Kiirunavaara mine, owned by LKAB, and Barrick mines in Canada, Mobilaris have installed real-time 3D visualization of people, vehicles, and equipment. The product for position of people in real time has also been installed at an UG Apatyt mine in Russia, the tunnel Förbifart Stockholm, owned by Trafikverket, and tunnels for underground water systems, owned by Stockholm vatten.

Figure 7. Navigation underground where every vehicle and position of equipment is visible in the mine (Mobilaris, 2020).

5.1.3 AR in tunnel inspections

Zhou et al. (2017) presents a method of implementing AR technology for segment displacement inspection in reinforced concrete segment tunnels. An AR-based system was established by superimposing BIM models onto a real structure. Due to the complexity of using GPS or location-based tracking technology underground a marker-based registration and tracking system was used as technology. Its precision met the requirement of the quality inspection. On-site experiments were conducted to evaluate the possibility, and to assess the advantages of the use of the developed AR-based system. The AR-based inspection system consisted of tracking, data acquisition, display, and interaction subsystems as illustrated in Figure 8. The live onsite scene could be captured by video camera, and the global coordinate and virtual camera coordinate could be acquired by a tracking subsystem. The virtual baseline model (3D CAD drawing) would be superimposed over an onsite image in real time. Then, the combined scene will be conveyed to the end users by a display subsystem. The key problem, according to Zhou et al. (2017) was the accurate registration of the transformation among three coordinates, which are camera coordinates, screen coordinates and global coordinates.

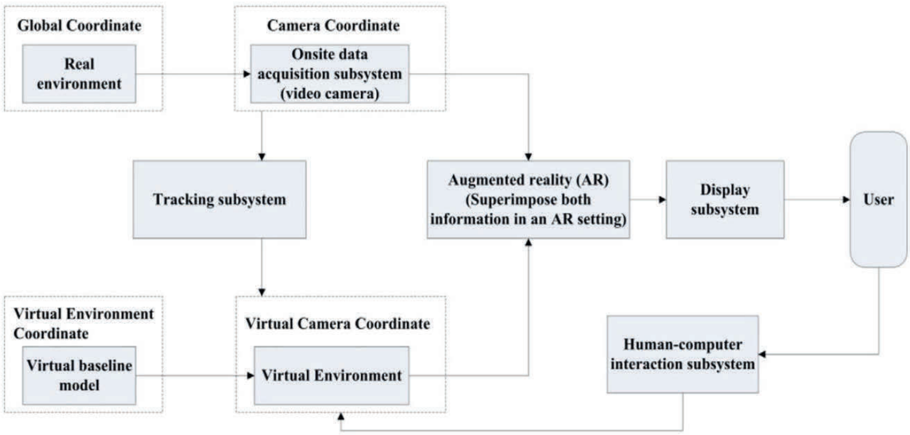

Figure 8. The Framework of the AR-based inspection system (Zhou et al., 2017).

The procedure for field inspection using AR technology is presented in Figure 9. In the procedure, the BIM models of the inspection items will be considered as the baseline models. Zhou et al. (2017) applied the AR technology for the metro tunnel across the Changjiang River in China. To diagnose the displacement between two segments, a marker was placed beside one of the segments. A virtual model was then registered over the real displacement. The virtual models for the segment displacement were created in AutoCAD with the same dimensions as the designed shield segment and its threshold. Those models were used as the baseline models. The CAD files were then converted to VRML ("Virtual Reality Modeling Language") files to be loaded in the AR system. The experimental results show that the AR-based system meets the accuracy and precision requirements for segment displacement inspection. The difference between a BIM depiction and the real view of the facility was measured and the segment displacement could be inspected. The system is thus found to be a promising inspection device for tunnel excavation.

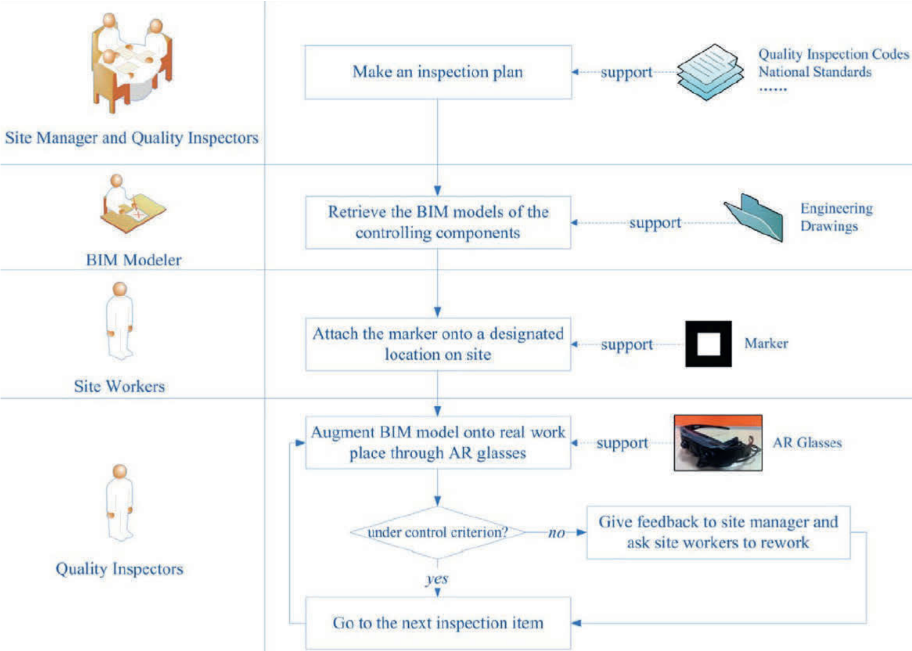

Figure 9. Roles and procedure for field inspection using AR.

5.1.4 Automation and robotization in the Kankberg mine

Boliden, together with Telia and Ericsson, have built a 5G network in the Kankberg mine in Sweden. The network will be used to develop new solutions for the mine in terms of automation and sustainability (Telia, 2019). Boliden actively works with robotization to increase productivity and safety in the mine and the 5G network is an important aspect of this. The networks short response time can meet the safety and work environment demands of the mine and, at the same time, ensure high production efficiency. The collaboration is a part of Telias 5G-partnership program as well as the EU-funded Sustainable Intelligent Mining Systems (SIMS) project.

The 5G network is especially developed to support automation and Internet of Things (IoT). With 5G networks both speed and connectivity are improved, which makes new innovations and applications possible. Modern mines are becoming more and more digitized.

"*The mine used to be like a black hole, but now we can see what is happening down there in real time. We can do things like controlling ventilation depending on where in the mine vehicles are located and whether or not they are operating, thus sparing the environment and conserving resources*"

/ Peter Burman (Boliden, 2019).

Ericsson have built a virtual replica of the entire Kankberg mine (Ericsson, 2018). The model is generated from point cloud data from LIDAR scans performed from self-driving vehicle, resulting in large amounts of data that continuously needs to be sent to the model. These large amounts of data require a 5G network with low latency to be able to update the model in near real time.

5G networks are powering modern technologies such as AR (Ericsson, n.d., Ericsson, 2016). The 5G network in Kankberg mine enables the possibility to explore AR in a mine environment, for example to explore a tomography of a rock face over time (Eriksson, 2018). In an intelligent mine perhaps rock bolts can be connected to inform rock mechanics engineers about events and changes in the rock mass.

5.1.5 VR for education and training

In 2007, a virtual representation of a longwall mine and transport roadway were set as a module for training and education in VR at the School of Minerals and Energy Resources Engineering at UNSW in Sydney (UNSW, 2020). Currently they have 20 modules available in the school, which can be visualized in a 3D theatre as well as in headsets.

Within the SIMS project (SIMS, 2018) a VR environment has been developed, consisting of selected parts of a mine. The physical large scale VR environment is used for education in mining and rock engineering and is located at Luleå University of Technology (LTU). A study visit, see Figure 10, was performed to the virtual mine in which the user can walk around experiencing a mine and see on-going activities. The aim of the VR-mine is to give the user an experience of a field visit to a mine (Vallin et al., 2019). The project is funded by Horizon 2020, an EU Research and Innovation program. Among the partners are Epiroc, Boliden, LKAB, K+S, Ericsson, LTU, and RWTH Aachen University. The fully functional VR environment has been developed and tested in several contexts, such as conferences, exhibitions, and schools. It has also been used as a virtual field visit in introductory courses at LTU, thereby serving as a first underground experience for many students. Initial demonstrations have been completed with students at the university and mine workers at Kristineberg mine in northern Sweden (SIMS Project, 2019a). According to the project leader everyone has a positive attitude towards the VR environment and find the tool very educational. Today, the tool is aimed to be used in early education, such as elementary school, introducing how a mine works. Hopefully in the future, the tool can be developed to include more advanced elements (SIMS Project, 2019b). This could perhaps entail adding features that are valuable for rock mechanics engineers in the future.

Figure 10. Study visit in the VR environment at LTU.

Two VR learning systems related to rock engineering and mining education have been developed at Aalto University, Finland. The first system is the Virtual Underground Training Environment (VUTE) developed for the training of fracture mapping and rock mass characterization as part of Mining Education and Virtual Underground Rock Laboratory (MIEDU) research project (Janiszweski, 2019). The user is wearing a headset and the system enables remote visual inspection of the rock surface and virtual measurements of the orientation spacing, and roughness of discontinuities. The second VR learning system regarding how to identify rocks and minerals is currently being developed in the Educational Virtual Rock Collection (EDUROCK) research project.

VR-simulators are used to train operators in the different parts of the drill-and-blast cycle, such as grouting, shotcrete, bolting and machine scaling (Edvirt, 2020). Three of the topics (grouting, shotcrete and bolting) are certification courses for the Swedish Transport Administration. Other VR-simulators has, for example, been used for training in underground inspections, roof fall hazard assessment etc. (UNSW, 2010; Isleyen and Duzgun, 2019). The virtual reality simulation involves decision-making tasks for a particular scenario in which participants can experience creating a safe working environment in a timely manner (Isleyen and Duzgun, 2019).

For safety reasons a VR environment have been created for the new underground station Sofia at Södermalm in Stockholm (Nya tunnelbanan, 2020). The station will not include escalators when completed. Hence the only way for transportation and evacuation is by elevators. The VR environment will be used for studying the human behaviour during potential evacuations.

5.1.6 Ongoing research

A pre-study with the aim to explore which future systems and AR applications that are desirable by users and other stakeholders in the deep mining industry was performed during 2019 (SIP STRIM, 2019). The pre-study was done with a user-centred approach. Three companies teamed up for the study: Boris Design Studio, RISE "Research institutes of Sweden", and Mine Tec. The idea was to use their previous knowledge of personal safety and positioning system development together with AR technology to provide solutions for deep mines. The study resulted in four concepts, three of which focused on AR technology, see Figure 11. Based on the pre-study the team will move forward with the idea Speaking Robotics and apply for a pilot study (SIP STRIM, 2019).

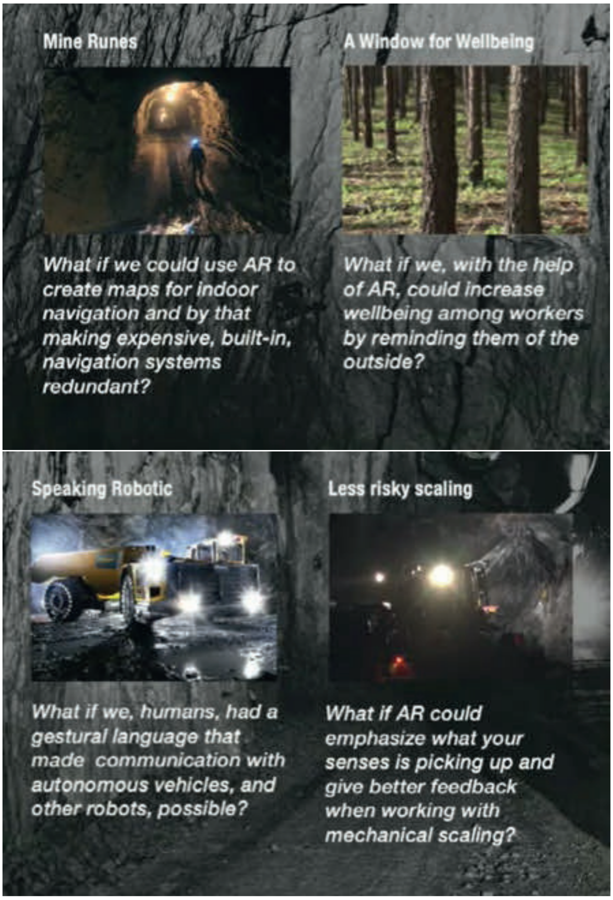

Figure 11. Ideas based on user-centred pre-study (SIP STRIM, 2019).

The Sustainable Underground Mining (SUM) project started in 2018 and is ongoing with partners from LKAB, ABB, Epiroc, Combitech, and Sandvik (SUM, 2020). Together, the five companies will set up a test facility where new technology will be developed and tested in a real mining environment, as well as in a virtual test mine. The test bed is being built in LKAB's underground mines in Kiruna and Malmberget. The goal of the cooperation is to find new methods and smarter solutions for mining operations of the future. Autonomous vehicles, electrification and automation as well as tests of new mining methods are in focus. The virtual test mine makes it possible to simulate data flows and scenarios that cannot be tested in the test mine. The establishment of the virtual test mine is planned for 2020-2022.

The SMIG (Integrated Smart Test environment for the mining industry) project, with financing from the strategic innovation program Swedish Mining Innovation and Piia, started in mid 2017 and ends mid of July 2021 (Swedish Mining Innovation, 2019). 11 partners are involved in the project and the SMIG testbed is for test and demonstration of intelligent mining technologies supporting innovation that are needed for the mining industry in the future. Example of results within the project so far is the field test of Fall of Ground sensors, digitalized ground support and virtual development of autonomous loading (Swedish Mining Innovation Program day, 2020)

The need in the mining and exploration industry for an improvement of workflows for visualization of geodata, as well as for more objective and accurate data and facilitated quality control has been identified within the Visual3D network of infrastructure (www.visual3d.info). The FARMIN project, with financing from EIT Raw Materials, aims to develop an augmented reality (AR) solution that visualizes 3D geological data and allows exploration and mining professionals to modify models in the field (Kampmann and de la Varga, 2019). The combination of geomodelling and AR technology will be based on GemPy, an open-source library for implicit geological modelling, developed by RWTH Aachen University, and rexOS, an AR operating system, developed by Robotic Eyes GmbH. The FARMIN project will run for three years and started in January 2020.

Simon Fraser University and the Engineering Geology and Resource Geotechnics Research Group has used MR technology on for instance landslides and open pits (Onsel et al., 2018). They are developing the application of state-of-the-art multi-sensor remote sensing approaches for investigation of high rock slopes. The remote sensing techniques include long range (up to 4 km) terrestrial laser scanning (TLS), high-resolution photography (HR), terrestrial digital photogrammetry (TDP), ground based and aerial structure-from-motion (SfM), infrared thermography (IRT), and hyperspectral imaging (HSI). As the multi-sensor remote sensing approach combined with MR/VR could improve the understanding of structural and geotechnical deformation, the application of VR and MR for data collection from site characterization was investigated by Onsel et al. (2019). In their work they demonstrated the use of a Microsoft HoloLens headset as it comprises a short distance 3D scanner useful onsite for data collection and mapping. EasyMap MR (EMMR) is a HoloLens application developed by SRK Consulting and Simon Fraser University. When the HoloLens user looks directly toward an object at a distance between 0.8 m and 3 m, the HoloLens scanner creates a mesh of the object with a resolution of ca. 5 cm. In the EMMR application, an orientation measurement tool was developed to determine the dip and dip direction of joint surfaces, see Figure 12. The orientation data can be displayed in real time on a stereonet.

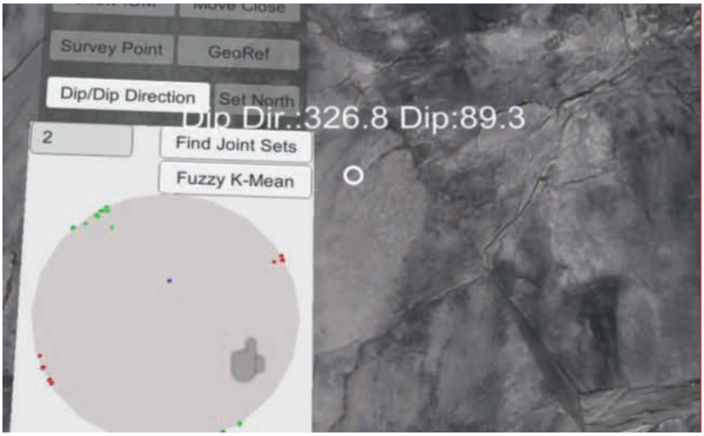

Figure 12. Joint surface orientation measurement in EMMR (Onsel et al., 2019).

5.2 Built environment

5.2.1 Example of AR technology in built environment

Several studies have investigated the possibilities of AR technology in the field of built environment (in e.g., Wang et al., 2013; Delgado et al., 2020). Primarily the advantages in efficiency and project management have been of interest. Pavlovic and Sundberg (2018) studied in which way AR can be valuable and create efficient processes during construction by avoiding expensive renovations and extended time frames. According to Pavlovic and Sundberg (2018) companies are facing large challenges in structuring existing data in order to be able to use these in AR applications. Knowledge and experience of the staff are other factors, which are important to consider during development of AR applications (Kjell & Silfersparre, 2017). AR have plenty of advantages and can add significant value to a project if developed further. However, no complete system exists on the market today, which is a viable investment.

Constructions sites are characterised working with two-dimensional drawings, here AR applications can be a valuable addition where construction workers easier can visualize the end-result (Pavlovic & Sundberg, 2018). The workflow will, in this way, become more efficient and work can carry on without interruptions. The largest advantages of AR can be found at the construction site (Kjell & Silfersparre, 2017). Site managers and construction workers can use head-mounted-displays to identify construction errors before building starts. It can also be used to visualize plans, both what is to be done and when to do things. AR tools can be used in later stages as well, for example during management of the building to identify locations of pipes and wires. Using AR at construction sites can also create opportunities for the client to envision the building requisites during the construction process (Pavlovic & Sundberg, 2018). This would open up for active participation by the client, who can be updated continuously on the project progression. If changes are necessary, all participants can be involved simultaneously, and new decisions can be arrived at quickly.

An up-to-date study regarding the use of VR and AR in built environment is performed by Delgado et al. (2020). By the summary of a questionnaire and a literature review, six cases were defined based on what the participants provided on how AR and VR is used in practice (Figure 13). AR and VR approaches for stakeholder engagement are mostly used. AR and VR representations can give consumers an opportunity to better examine built-assets at real-scale, in an immersive environment, and provide a better understanding than pictures or videos. As design support, AR and VR can help designers to identify the consequences of their design decisions and to have a better understanding of the final results. The main challenge of using AR and VR for design support and review include the difficulty to translate design changes to BIM models and to archive AR and VR outputs. A summary of the benefits and challenges of the six defined cases is presented in Table 1.

5.2.2 Building site of ESS in Lund

Skanska and Information Experience have been working together to develop a software that uses MR combined with Microsoft HoloLens. The technology was tested at the building site of ESS, European Spallation Source, in Lund, Sweden (Nohrstedt, 2017). During construction, the workers used the glasses to see the surroundings and a digital model of the construction, see Figure 14.

The digital model finds its position in reality through a physical marker at the site. By the marker, the planned design, such as rebars, appear at the correct location (Nohrstedt, 2017). The HoloLens is connected to a central database/system and can report and return data in order to do follow ups of the project. The software from Information Experience is used to assist in positioning of the HoloLens. The hypothesis was that this will lead to better project management and that one tool can be used for all project aspects — planning, construction and documentation. Trimble have worked with HoloLens 2 to develop a similar product called Trimble Connect (Trimble, 2020), see Figure 15.

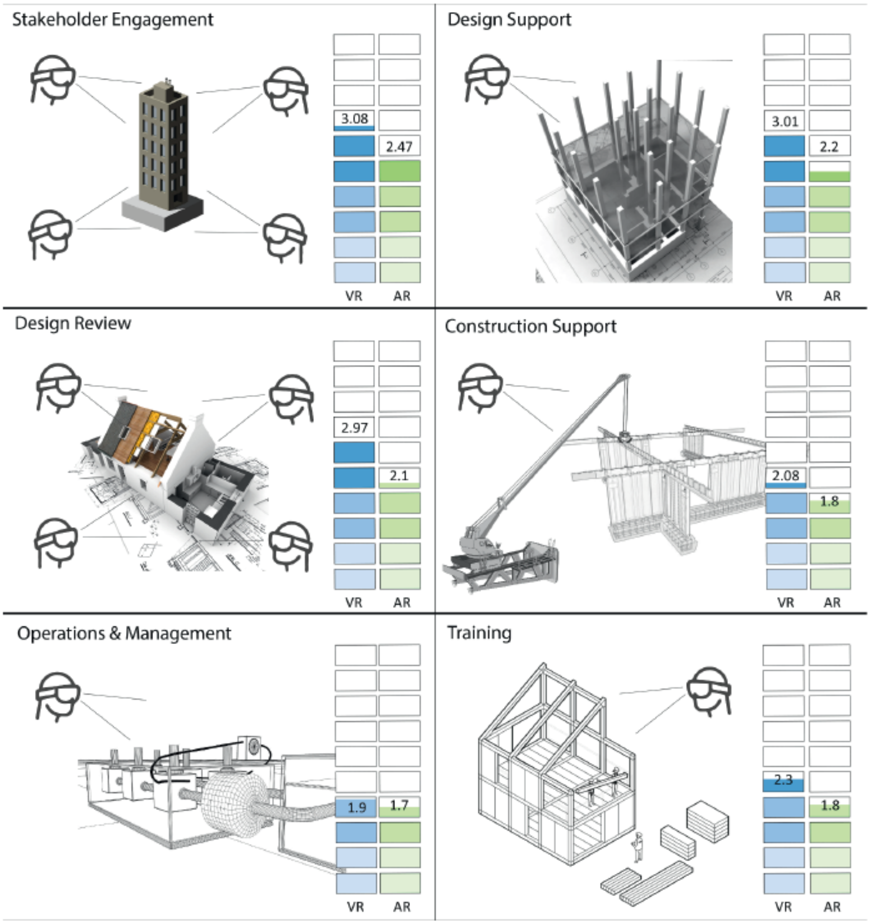

Figure 13. Six defined cases where AR and VR are used in practice for built environment (Delgado et al., 2020). The plots indicate the level of adoption in projects for the given use-case (1 = not used, 2 = early testing, 3 = basic implementation, 4 = partially used, 5 = fully implemented).

Table 1. The benefits and challenges per case together with the level of adoption according to Figure 13 (from Delgado et al, 2020).

Case	Main benefits	Main challenges
Stakeholder engagements	Timely feedback. Better: - requirement understanding, - contextual understanding, - impact assessment. Increased inclusivity. Improved user experience.	High investment (space and skilled staff). Not user-friendly. Uncomfortable. Isolation. Difficult to implement multi-user capabilities.
Design support	Real-scale visualization of designs. Better understanding of design impacts. Easier understanding of simulation results (airflow, people flow, etc.).	High investment (space and skilled staff). Difficulty in translating changes to BIM models. Difficulty of archiving AR & VR outputs.
Design review	Faster sign off. Efficient decision-making. Easier multi-disciplinary assessment.	High investment (space and skilled staff). Difficulty in translating changes to BIM models.
Construction support	Visual understanding of construction progress. Visual analyses.	High investment (number of devices and skilled staff). No safety-approved hardware. Low accuracy in tracking and mapping. Potential limited internet access. Short battery life. Difficulty of archiving AR&VR outputs.
Operations and management	Minimise travel. Reduce risk for technicians. Support maintenance. Better understanding of facility needs. Visual asset information in real-time.	High investment (number of devices and skilled staff). Lack of integration with other facility management systems. Accuracy and speed of updating information. Difficulty of archiving AR&VR outputs.
Training	Inexpensive and more effective training scenarios (safety and complex tasks). Simulations of large-scale operations. Mitigating risks due to staff turnover.	High investment (number of devices, skilled staff). Lack of experts to produce content. Lack of systematised evaluation processes. Lack of qualification standards integration.

Figure 14. Building site through the HoloLens glasses (Nohrstedt, 2017).

Figure 15. Using mixed reality at construction site (Trimble, 2020).

5.2.3 The Hidden city

To continue the safe growth and expansion of the Swedish mining company LKAB, the city of Kiruna with 18,000 residents is relocated 3 kilometers east. While new homes and a new city center are built, some of Kiruna's most historic buildings, such as the Kiruna Church, recognized as one of Sweden's most popular and beautiful wooden buildings, will be physically moved to the new city center. The relocation opens up for innovative approaches in city planning, maintenance and use of technology.

For Kiruna and many cities, maps and blueprints of underground infrastructure, such as public pipes and cables, can be inaccurate, outdated, or unavailable. A lack of useful data can directly impact the ability to maintain and install underground infrastructure. As a result, cities may waste excavation time or incur expensive damages from broken pipes or lines, resulting in service disruptions, traffic delays and detours, and considerable costs.

CGI considered the challenges associated with the move and devised a way for the city to gain a precise view of its underground infrastructure before digging. The city innovation office KSC was approached with a concept for using AR to digitally map, document, and interact with underground infrastructure (Figure 16).

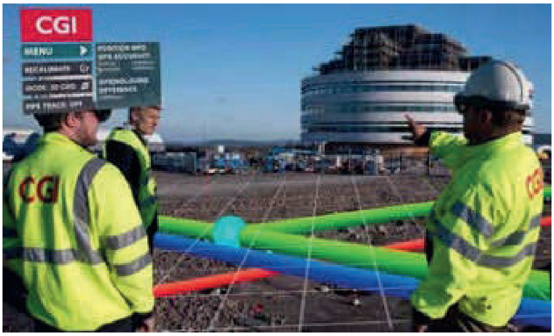

Figure 16. AR view of the underground infrastructure.

One key challenge was that AR technology had never been used outdoors before. To test the idea, CGI invested in a proof of concept named "Hidden City" as part of a CGI program that promotes the development of innovative ideas into real-world, practical, outcome-driven solutions. With both the city and CGI onboard, CGI technical experts began to envision a means to view and interact with the Hidden City

In March 2017, the CGI Hidden City team was challenged to "build a hole in the ground that does not exist". The technology vision combined GPS-enabled data sources and GIS data from the city, visualized through augmented reality (AR). The use of AR would enable Kiruna to view concealed or hidden infrastructure, such as underground pipes with cm-precision, see section 4.2.2.

CGI was already working with AR technologies, including Microsoft's HoloLens (cf. Chapter 4) that enables the wearer to interact with a holographic representation of an environment.

In September 2017, the AR platform, which integrated city GIS data regarding newly laid pipes supported by GPS positioning data for the new city of Kiruna, was ready for testing. Kiruna's Mayor and a GIS engineer, standing alongside the CGI team, donned HoloLens glasses. The test was a success, enabling an interactive, holographic view of the Hidden City beneath the street. As each person strolled outside the City Hall, they could view the underground pipes in three dimensions (Figure 17). This demonstration proved not merely HoloLens' ability to work outdoors, but also the city and CGI's vision for visualizing its data, enabling more precise and proactive city planning and public works management.

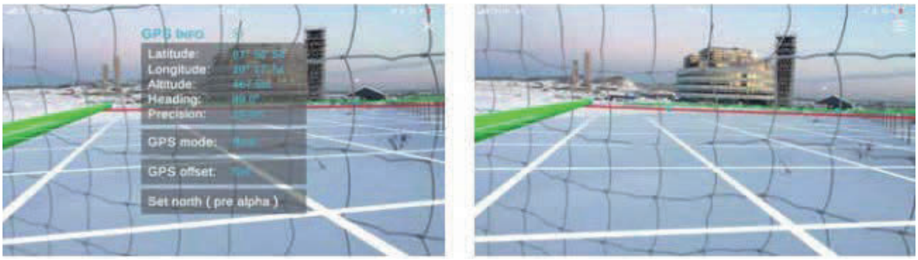

Figure 17. Example of view in the HoloLens.

The initial six-month effort was just the beginning for Kiruna and CGI. After the successful Proof-of-Concept (POC), the team immediately turned to additional use cases. Given Kiruna's subarctic climate, where snow can cover the ground for nine months of the year, even manholes can be difficult to detect. How could Hidden City be extended to support city workers in the field? Furthermore, how could the platform be extended to smartphones and tablets? In November 2017, CGI successfully tested the Hidden City concept using smartphone technology on iOS, offering great potential for increasing the speed and accuracy of city maintenance in the future.

6. COMPARISON OF SUGGESTED USE OF AR AND TECHNOLOGY USED IN TODAYS PRACTICE

A number of suggestions on the potential use of AR in rock mechanics were raised from the workshop and interviews. In order to distinguish between needs and items that would be easy to accomplish and those that would be difficult and time consuming for implementation, the suggested use was compared to existing cases and technology. According to this study the AR technology was suggested to be used for communication with clients, decision makers, other disciplines, etc. AR and VR as a communication tool for stakeholder engagement have been used for some published cases within mining (LlamaZoo, 2020; Loook, 2017). When using AR as a general communication tool there was no specific requirements on accuracy and precision of the visualization. It should be relatively easy to implement AR for general communication purposes due to the already existing cases and the requirement on precision.

Another request concerned navigation and evacuation underground. For example, Mobilaris (2020) are working with real-time 3D visualization which they have implemented in several mines as well as tunnels. The technology is not based on AR as such, however, it is an example of technology that already exists and fulfils the request. According to suppliers of technology and researchers in the field, the most difficult issue to solve at the moment is the localization and positioning for underground excavations (see e.g., Nikolakopoulus, 2019; Björkström, 2020, Ylitalo, 2020). Development work is required regarding positioning and visible light to be able to use AR underground.

In order to fulfil the request on enhancing the real-world view with underground utilities and nearby excavations, these need to have a position and must be possible to visualize. A relatively low-hanging fruit would be to scan all underground excavations and utilities in urban areas, so that these objects can be enhanced in the real-world view already in the feasibility study stage. However, there will still be underground excavations, e.g., those owned by the armed forces, etc., that cannot be visualized for security reasons.

Ongoing road and railroad tunnel projects uses the BIM technology for the planned and designed excavation. The underground excavation is visualized in 3D on the computer screen and if all objects are digital and carries individual information as well as their relation to other objects in the model it can be transferred to AR technology. To be able to stand on the ground surface and see the planned tunnel under one's feet seems relatively straightforward based on existing technology and cases (Zhou et al., 2017, Delgado et al., 2020).

In the FARMIN research project (Kampmann and de la Varga, 2019) the aim is to develop an AR solution that visualizes 3D geological data. Their main focus is on exploration, geology in large scale, and visualization from surface. Simon Fraser University (Onsel et al., 2019) have investigated AR as an application for data collection from site characterization for rock slopes. They comment that the HoloLens headsets allow for collection of data and perform data processing almost in real-time, following a seamless workflow that starts with the mapping at the rock slope, and is concluded on site with a complete rock mass characterization. For rock slopes, the development of AR technology is more straight-forward and easier to implement compared to underground excavations. Ongoing research in the field of enhancing geological information in the real-world view will naturally push forward the development work of AR. One issue that needs to be addressed and which was raised during the workshop was the standardization of data format and test methods in rock mechanics and rock engineering. The complexity, uncertainty and case-specific properties of rock mechanics might bring difficulty in establishing an efficient and generally acceptable system of standards.

The computer generated geomechanical model is based on the geological information plus information on overburden, topography, interpreted stresses, etc. The basis for the geomechanical model could be an object-based 3D or BIM model. An important issue is the real-time model modification. AR systems should be capable of proposing modifications to the existing virtual objects based on later field observations. The 3D/BIM and AR model needs to be linked in order to change both models in real time. Two-way modifications between AR and BIM models should be possible in real-time. As pointed out by Huang et al. (2021) the future trend of BIM in underground construction is big data analysis which requires machine learning and computer vision.

Rock mechanics numerical analysis is often performed in 3D and with CAD files as the basis for the models. The result is visualized in 3D on the computer screen and should therefore have a great potential to be transferred to VR and AR technology. The results of numerical analysis can be displayed intuitively by digital models (Zhu et al., 2011). However, development work is required in order to get real-time analysis result in an AR environment.

One of the roles as a rock mechanics engineer is to interpret and give suggestions on rock support and reinforcement. Since a couple of years back there are sensors developed for health condition of rock bolts (reviewed in e.g., Song et al., 2017). These sensors provide data that should be visualizable. Using data from drilling and bolting, the position and type of bolt could be visualized, and using data from scanning, the thickness of shotcrete would be able to visualize (see e.g., Savage et al., 2018). To capture changes with time, such as deformations and cracks in shotcrete, a high precision of the visualization is required, as the important number may be less than one mm for some excavations. Although laser scanning techniques show the potential for deformation monitoring, it is still difficult to monitor small deformations, and the system is limited to a precision of a few millimetres for both long-range and short-range scanners (Feng, 2012). By 3D laser scanning it is possible to have a 1 mm precision for a 30 km/h automated custom-built inspection of flat surface railroad tunnels (Laurent et al., 2014). The same precision and speed are not possible to be expected in mines and "non-prepared" tunnels. Still, the automated inspections together with a visualization in VR and AR could be useful for forensic analysis of fall of ground and seismic events in mines.

Visualization of results from measurements performed in the rock mass, such as extensometer and inclinometer installations, could be a basis for the verification of the technical solution and for increasing the understanding of the rock mass behaviour. It is possible to perform wireless tunnel monitoring where for example extensometers are connected to a central monitoring system. However further development is required in order to visualize the position and results as objects in an AR environment. Based on the state-of-the-art and the comparison of suggested use of AR in rock mechanics versus currently used technology, the proposed development work should focus on the AR system, the information model (e.g., extended BIM or geomechanical model) and its supporting data. A schematic view of the suggested development work for these three categories is presented in Figure 18.

Development of		
AR technology	Positional tracking Depth cameras and sensors	Positioning underground Longer battery life Processing power
Information model	Visualization of supporting data as objects.	Visualization and synchronization of real-time supporting data
Supporting data	Data for rock slopes, for example: - Geomechanical data - Computer generated slope - Rock support and rock reinforcement information - Wedge analysis results - Measuring results	Data for underground constructions, for example. - Position of underground utilities - Geomechanical data - Computer generated underground construction - Rock support and rock reinforcement information and data - Wedge and stress analysis results - Measuring results

Longer time for implementation ⟶

Figure 18. Suggested future development work.

7. DISCUSSION

AR as a technology cannot support us in geological uncertainties and with information that have not been measured. What makes AR so powerful are the other systems and technologies supporting it and the possibilities to visualize necessary and important information. In the end, an AR application is only as good as the data that supports it. Currently, the world of rock mechanics could benefit greatly through the use of AR technologies. The necessary pieces are already in place to provide scientists and researchers with valuable tools that could enhance and optimize their workflow. While AR technologies are currently in their early stages and come with limitations, most of these limitations will likely be overcome within the next five to ten years. One of the most important parts for a continued development is the acceptance of using this technology within the field of underground excavations. The AR technology must be accepted among the different roles and in the different phases of a project. Therefore, the client/owner of underground excavation projects has an important role in the acceptance and development of AR.

The requirement on precision and accuracy makes it difficult to implement for different purposes. Further research and development is required for cases where there is a high demand on accuracy and precision. AR and VR will not take off for underground excavations if the technology is not trustworthy. Inaccurate AR and VR tools that lead to errors and mistakes will not be adopted. If the AR system provides an indication of its accuracy regarding positioning and system information, then it is easier for users to trust the system, and they can take the necessary actions to manage that uncertainty. Thus, it is essential to have a clear indication of accuracy and a clear graphical representation of those metrics. Research on what are the best ways to visualize uncertainty in AR and VR devices and to calculate uncertainty in real-time are hence suggested. The continued research could, e.g., be linked to the ongoing BeFo project "Osäkerhetsmodeller för optimal resursanvändning i infrastrukturprojekt" (Svensson et al., 2018), or to other future projects.

By working towards an implementation of AR in the near future, one will be ready to take full advantage of it once it becomes an integral part of underground construction. The implementation of AR in the field of rock mechanics is suggested to initially start with cases of rock slopes in order to avoid the problems with positioning underground. The development regarding visualizing results from analysis and measurements is another suggested future work.

8. CONCLUSION

Based on the workshop, the interviews, case studies, and assessment of the state-of-the-art of the AR technology the following conclusions are drawn:

- In general, the suggested use of AR in rock mechanics concerns visualization of:
  - Underground utilities and nearby excavations as well as the computer generated designed and scanned finalised construction.
  - Computer generated geomechanical model (geological information, overburden, topography, interpreted stresses etc.).
  - Results from analytical, empirical and numerical analysis (e.g., wedges, *RMR*, *Q*-value and stress tensors).
  - Rock support and reinforcement (position and type of bolts, follow changes with time such as crack initiation in shotcrete).
  - Real time measuring results (e.g., extensometer, inclinometer, smart bolts, photogrammetry, MWD).
- AR and VR are used as communication tools for a few published cases in mining.
- According to suppliers of technology and researchers in the field, the most difficult issue to solve at the moment is the localization and positioning through visible light for underground excavations.
- Scanning all underground utilities and excavations, in urban areas, could improve strategies for the pre-investigation and design phase.
- A computer-generated underground excavation in BIM or CAD could, if transferred to AR technology, improve the design and excavation phase from a rock mechanics perspective. The BIM and AR model needs to be linked in order to change both models in real time.
- There are ongoing research projects with focus on visualization of 3D geological data and site characterisation data on rock slopes. This could improve the visualization of important geological data from a rock mechanics perspective.
- To the authors knowledge, there are no underground excavation cases that have used AR technology for visualization of:
  - the geomechanical model or enhanced reality with results from analysis,
  - bolt position, bolt type, shotcrete thickness and changes with time, and/or
  - results from measurements.
- Since it is difficult to monitor small deformations, the use of AR for deformation monitoring is currently limited.

This study has demonstrated that AR is not yet ready to be fully adopted in rock mechanics and for underground excavations. The required future work for the AR system is the development of positioning underground, high accuracy tracking, and processing power. From an underground perspective, a longer battery life is also desired. To function as a communication tool in large tunnel or mining projects the AR systems should guarantee multi-users and also multi devices.

Research efforts should focus on the integration and the graphical representation of BIM and/or geomechanical model data, sensor, measurement, and analysis data in AR.

Suggested near- future work of AR for rock mechanics is primarily on applying AR for investigations of rock slopes, in order to avoid the problems with positioning underground. A related work would be scanning and visualization of underground utilities and excavations in urban areas. In that sense, the AR technology could be developed for the visualization of underground excavations plus the planned 3D generated tunnel model.

More long-term future work should include development regarding visualizing real-time results from analysis and measurements. This work first requires integration of the visualization of BIM and/or geomechanical model data with the AR application followed by real-time two-way synchronization between model and application. For that purpose machine learning and computer vision can play an important role.

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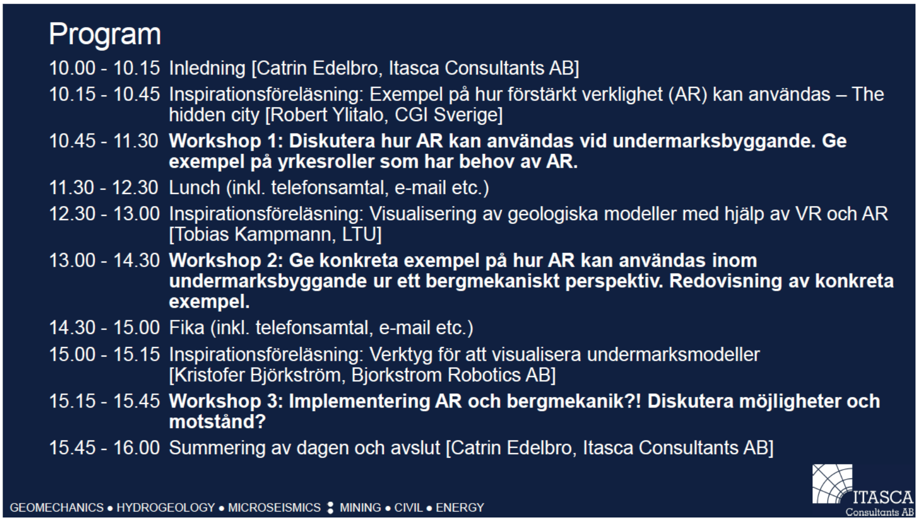
Appendix 1. Workshop program



Appendix Figure 1: Program of workshop "Augmented reality in rock mechanics" in Stockholm the 4th of February 2020.

BeFo
Box 55545
SE-102 04 Stockholm
info@befoonline.org • www.befoonline.org
Visiting address: Sturegatan 11, Stockholm
ISSN 1104-1773