Technology Forecast 2021 – Military Utility of Future Technologies

Foreword

The Systems Science for Defence and Security Division at the Swedish Defence University (SEDU) has since 2011 conducted Technology Forecast upon request from the Swedish Defence Materiel Administration (FMV). The objective is to assess the chosen technologies' potential future military utility for the Swedish Armed Forces (SwAF) within a set timeframe.

Due to the Corona pandemic, the Technology Forecast seminars were conducted via a digital platform. In the absence of physical meetings the digital seminars provided the opportunity for more people to attend, independent of the geographical location of various divisions or agencies.

Project management

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Report summary

For the purpose of Technology Forecast 2021 five reports from the German Fraunhofer Institute were chosen by FMV (and SwAF) and given to Systems Science for Defence and Security Division to analyse and assess within the timeframe up to 2040.

The following research reports were reviewed by the working group at SEDU:

- Adversarial Machine Learning
- High Entropy Ceramics
- Large Unmanned Underwater Vehicles
- Living Sensors
- Machine Learning in Materials Development

The aim of the Technology Forecast seminars and the finished product, this report, is to assess the potential military utility of the reviewed technologies and how they may contribute to the Swedish Armed Forces' operational capabilities based on the presented concept(s) and scenario(s).

The military utility is categorised by one of four assessments: Significant, Moderate, Negligible or Uncertain.

The following technologies were assessed to potentially have significant military utility:

- High Entropy Ceramics
- Machine Learning in Materials Development
- Adversarial Machine Learning

The following technology was assessed to potentially have moderate military utility:

- Large Unmanned Underwater Vehicles

The following technology was assessed to have uncertain military utility:

- Living Sensors

The project group 2021 consists of:

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Abbreviations and definitions

AI – Artificial Intelligence

AM – Additive Manufacturing

AML – Adversarial Machine Learning

APT – Advanced Plant Technologies

ASW – Anti-submarine Warfare

CAD – Computer-aided Design

CBRNE – Chemical, Biological, Radiological, Nuclear and Explosive

C2 – Command and Control

DARPA – Defence Advanced Research Projects Agency

DOTMLPFI – Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities, Interoperability

DTAG – Disruptive Technology Assessment Games

DVL – Doppler Velocity Log

ECCM – Electronic Counter-countermeasures

EDF – European Defence Fund

EM – Electromagnetic

FMV – Swedish Defence Materiel Administration (Försvarets materielverk)

FOI – Swedish Defence Research Agency (Totalförsvarets forskningsinstitut)

GBAD – Ground Based Air Defence

HEA – High Entropy Alloys

HEC – High Entropy Ceramics

ICT – Information and Communications Technology

INS – Inertial Navigation System

ISR – Intelligence, Surveillance and Reconnaissance

LIDAR – Light Detection and Ranging

LUUV – Large Unmanned Underwater Vehicles

M – Mach

ML – Machine Learning

MUAFT – Military Utility Assessment Method for Future Technologies

PALS – Persistent Aquatic Living Sensors

R&D – Research and Development

ROV – Remotely Operated Vehicle

SEDU – Swedish Defence University

SwAF – Swedish Armed Forces (Försvarsmakten)

SWOT – Strengths, Weaknesses, Opportunities, Threats

TF – Technology Forecast

TRL – Technology Readiness Level

UUV – Unmanned Underwater Vehicles

XLUUV – Extra Large Unmanned Underwater Vehicles

ZTA – Zirconia-toughened Alumina

The MUAFT[1] Methodology

The method used for the execution of the Technology Forecast seminars and the following report is the Military Utility Assessment Method for Future Technologies – MUAFT.

This section of the report describes the MUAFT methodology and provides commentary on the execution of Technology Forecast 2021. Next, the assessments of the technologies in question and the subsequent evaluations by the reporters each form one chapter in the report.

Central for the evaluations of each technology is the chosen definition of military utility. For the purpose of the MUAFT method and the execution of the Technology Forecast-project at SEDU the following definition is used:

> *The military utility of a certain technology is its contribution to the operational capabilities of the SwAF, within identified relevant scenarios.*[2]

The MUAFT method, originally inspired by NATO's DTAG, is designed to be a cost effective alternative used in a smaller context and with a more limited budget. As a result, on one hand this requires the project group to be large enough to include valuable competences to assess the technologies' contribution to military capabilities, i.e. their potential military utility. On the other hand, the size of composed project group has to fit the given budget.

Methodology:

The process for Technology Forecast starts with the selection of technologies to assess. The selection is made by an expert group composed of personnel from SwAF's and FMV's respective R&D departments. The scientific reports describing the technologies are distributed to SEDU and the Systems Science for Defence and Security Division. The reports are then assigned to different employees at the Division. The assignments of the reports are based on the participating employees' special expertise and interests. Together with the project management the participating employees – the reporters – constitute the project group.

The reporters review their respective technology report and step into the role of an advocate for that specific technology, promoting its use. The reporters prepare for

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[1] The methodology is described in more detail in Andersson, K., Lundmark, M. and Silfverskiöld, S. (2019), *The Military Assessment Method for Future Technologies*, Report, Swedish Defence University, Stockholm. The methodology has been reviewed in Silfverskiöld, S., Andersson, K., Lundmark, M., Does the method for Military Utility Assessment of Future Technologies provide utility?, *Technology in Society 67,* 2021.

[2] For a more detailed description of *military utility,* see Andersson et al., Military utility – a proposed concept to support decision-making, *Technology in Society 43*, 2015. Figure 1 further elaborates the concept.

the first seminar by writing a memo. The memo contains a summary of the technology, the reporter's created conceptual technical system(s) for military use as well as the scenario(s) in which the system(s) may be used by the Swedish Armed Forces in the given timeframe.

At the first seminar the project group and invited participants discuss the information provided by the memo and assist the reporter in modifying the systems and scenarios and provide input on the suggested SWOT-analysis, capability impact assessment and the assessment of footprint according to the DOTMLPFI. After the seminar the reporter writes a preliminary report. The report is distributed to the group in preparation for a final seminar.

At the final seminar the objective is to reach consensus on the potential military utility of the technology in focus. This is achieved by using a variant of the Delphi method where the group brainstorms, discusses and votes until they agree to a satisfactory degree. The need for military R&D is also discussed. Conclusions on the potential military utility are drawn and documented as either *significant*, *moderate*, *uncertain* or *negligible.* The recommendations to the military actor, here the Swedish Armed Forces, are usually divided into three categories; exploit the technologies that provide potentially significant military utility, monitor those with moderate or uncertain military utility and the advice not to invest in those with negligible military utility.

Each reporter's final report follows to the subsequent structure:

1. Introduction with a description of the technology's past, present and future state, and Technology Readiness Level (TRL).
2. The technology's possibilities and constraints.
3. Suggested military use.
4. Assumptions for the scenario.
5. Presentation of one or two *scenarios* (based on the above assumptions) where the technology is applied in a *concept system* that would best or most likely be of use for the Swedish Armed Forces in the year 2040.
6. A SWOT-analysis regarding the use of the technology in the assigned scenario(s).
7. Assessment of the technology's capability impact.[3]
8. Assessment of footprint.
9. Assessment of the need for military R&D.
10. Finally, a discussion and conclusion regarding the technology's future development, capability impact and military utility.

[3] The impact on one or several of the Elements of Combat Power in Swedish doctrine: Effect, Mobility, Sustainability, Command and Control, Protection, Intelligence and Information

The reports are then included in the final product, this report.

Due the Corona pandemic, work and seminars within the Technology Forecast project were conducted via a digital platform. A variant of the Delphi method was used where the poll function on the digital platform enabled voting. For the execution of TF 2021 this meant that people had the opportunity to join the seminars from different agencies and locations.

It has been identified within the project that it is important to have a broad mixture of people with various competences and expertise attending the seminars and discussing the technologies. The digital execution of the TF-seminars made it possible for the project management to invite additional personnel from other divisions of SEDU as well as from FMV, FOI and SwAF. Diversified attendance provided great value and insight to the seminars.

Based on the lessons learned from this year’s TF-project the MUAFT methodology will be further developed.

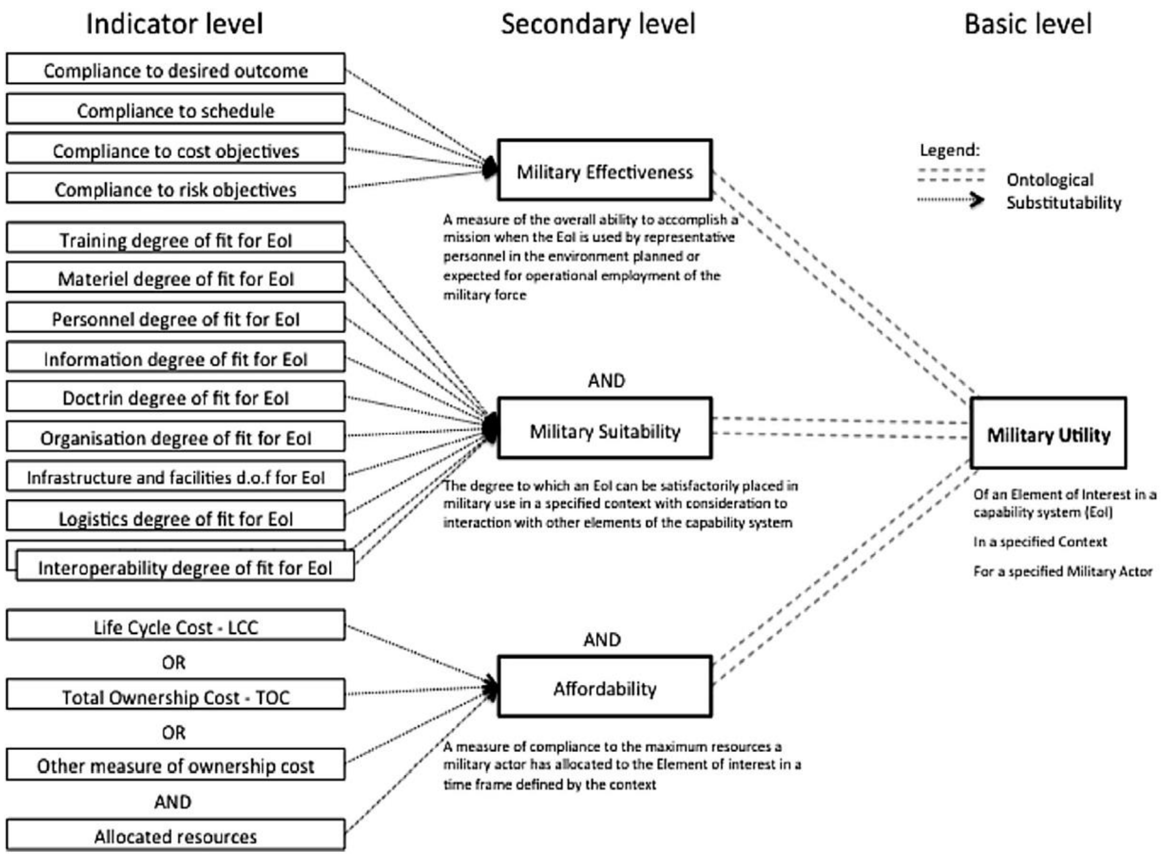

Figure 1. *Military utility* consists of Military Effectiveness, Military Suitability and Affordability. The Military Effectiveness dimension (level) corresponds to *Assessment of capability impact* in the MUAFT method while Military Suitability and Affordability corresponds to *Assessment of footprint.*

Technology Forecasts

Adversarial Machine Learning

Reference [1]: Ruhlig, K., Thorleuchter, D., *Adversarial Machine Learning*, Fraunhofer INT, Euskirchen, Germany, Dec 2020.
Referee: Marcus Dansarie, Lt (Navy), MSc, PhD student

Introduction

Over the past few years, machine learning (ML) systems such as deep neural networks, have surpassed human abilities in a number of tasks. One example of this is distinguishing targets from decoys and noise in sensor systems. Adversarial Machine Learning (AML) is a set of tools and techniques for defeating or tricking ML systems. With very small changes to the inputs of ML systems – unnoticeable to humans – the outputs can change drastically. For example, by adding crafted noise to an image of a school bus, an ML system can be tricked into classifying it as an image of an ostrich. Other examples include stickers attached to a stop sign, that causes ML systems to classify it as a speed limit sign and 3D printed objects that can cause similar effects regardless of the viewing angle.

Identified possibilities and constraints

The following possibilities and constraints were identified in the report:

Possibilities:

- Countermeasures against detectors in next-generation sensor systems.
- Obstruction of ML-based analysis of remote sensing data.

Constraints:

- Dependent on accurate intelligence on adversary systems.

Suggested military use

Current camouflage patterns are designed to make vehicles and soldiers hard to detect for humans. Future camouflage patterns may also incorporate AML technology in order to prevent detection by ML systems. AML-based camouflage can also be designed to create other effects in ML systems. For example, it might be possible to design camouflage patterns that cause ML systems to make faulty classifications of vehicles. This may turn out to be even more powerful than just making military platforms hard to detect.

A somewhat similar use is AML-based countermeasures. It is likely that many, if not most, target seekers in future missiles, torpedoes, and similar weapons will incorporate ML technologies for target detection and tracking. Today, many platforms employ soft-kill countermeasures such as chaff, flares, or active jamming systems to prevent the seekers from succeeding in guiding the weapon towards its intended target. Future active countermeasure systems could make use of waveforms specifically designed to cause misclassification or loss-of-tracking in ML-based seekers.

Assumptions

The concept scenario is based on the following assumptions:

– None identified.

Concept systems and scenarios in 2040

All major platforms are painted in camouflage patterns that, in addition to working as traditional camouflage also make use of AML technology. The AML-enhanced patterns are specifically designed to prevent correct classification by ML systems, thereby forcing manual classification of each detected target by a human. This negates the positive effects of ML systems.

AML pattern decoys are also available. They may be very simple, such as sheets of printed fabric that can be rolled out on the ground. The patterns printed on them are tailored to cause detection of a certain type of platform when remote-sensing data from satellites and aircraft are processed by ML systems.

Countermeasure systems on platforms such as warships and aircraft also employ AML technology to maximize the efficiency against weapons systems that use ML-equipped target seekers.

SWOT-analysis

Strengths: • AML camouflage and countermeasures may be very efficient – even in situations where traditional camouflage is useless.	Weaknesses: • Dependent on good intelligence on adversary ML technology. • AML camouflage may require changes in physical design of platforms, which could affect the signature with respect to other sensors or technologies.
Opportunities: • Counter-adversarial-ML systems (cf. ECCM) could be developed to detect counter-ML camouflage with very high	Threats: • AML camouflage and countermeasures can potentially be defeated or even be used to detect the unit if the ML system is trained with AML

probability/efficiency. • If the ML-model used by an adversary can be retrieved somehow (intelligence, destroyed equipment recovered from battlefield, etc.) it could be possible to build tailored countermeasures that are very efficient.	data. • Camouflage that works very well against ML-systems may not work at all against humans and traditional sensors, and vice versa. • It may be very hard to verify the safety and security of own ML-based systems. Current frameworks for ICT security do not incorporate the new risks introduced by ML technology

Assessment of capability impact

The primary impact of AML systems is in protection of military platforms. This is enabled by both passive and active technologies based on AML. The use of AML technologies for information operations may also be possible.

AML technologies are in many ways natural continuations of traditional camouflage and countermeasure technologies. The introduction of ML technologies in sensor systems requires and adaption of the traditional techniques to the new threats.

The ability to deceive ML-based classification and identification systems brings with it issues with respect to the law of armed conflict. It is almost certainly not permissible to knowingly cause a military platform to be classified as, for example, an ambulance by an enemy sensor. Other types of deliberate misclassifications may or may not be allowed depending on circumstances.

Counter-adversarial-ML systems may come to be a particularly efficient defence against AML technology. They may function similarly to home-on-jam systems in surface-to-surface missiles, where the missile simply flies towards the jammer when it detects jamming, thereby turning a countermeasure system into a homing beacon. Similarly, counter-adversarial-ML could be used to detect AML camouflage in situations where platforms with traditional camouflage are not detectable. This means that AML technologies could end up being double-edged swords.

Assessment of footprint

Influencing factor	**Footprint**
Doctrine	None identified.

Organization	Organizational units that keep AML libraries updated and perform related intelligence work are required.
Training	None identified.
Materiel	The physical design of military platforms may have to be adapted in addition to just changing the camouflage.
Leadership	None identified.
Personnel	ML expertise is necessary to keep AML libraries updated and to produce necessary intelligence.
Facilities	None identified.
Interoperability	None identified.

Assessment of the need for military R&D

Results from civilian R&D will likely be applicable, but military use will also require R&D concerning the use of AML technologies in that context. Apart from the primary results, military R&D will also serve to build organizational understanding on how AML technologies can be used and what risks are associated with using ML in military systems.

Conclusions on military utility and recommendations

Adversarial machine learning technologies can have significant military utility, provided that current generations of machine learning technologies become prevalent in military sensor and weapon systems.

High Entropy Ceramics

Reference [1]: Brandt, H., *High-Entropy Ceramics - Designing Randomness at the Atomic Scale*, Fraunhofer INT, Euskirchen, Germany, Dec 2020.
Referee: Kent Andersson, Lt Col (Air Force), PhD

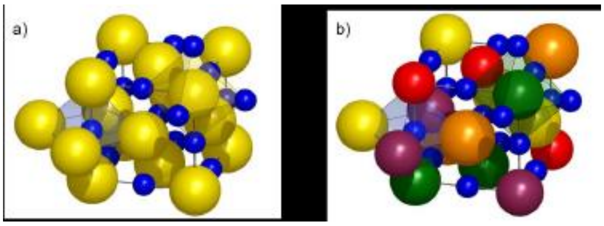

FIGURE 1 FROM THE REVIEWED REPORT SHOWS A SINGLE COMPONENT NITRIDE TO THE LEFT, E.G. LaN AND TO THE RIGHT A MULTI-COMPONENT SOLID SOLUTION OF FIVE METALS ON THE METALLIC SUB-LATTICE (LIKE IN HEC, THE REVIEWER'S REMARK). BLUE IS FOR NITROGEN. [1, P.3]

Introduction

The report describes traditional ceramics as crystalline, inorganic, non-metallic materials, typically composed of compounds between metals (or semi-metals) and non-metals. They obtain their characteristic hardness and thermal properties only through a temperature treatment after shaping the raw material at room temperature. Conventional high-performance ceramics are described as either extremely clean single component systems or heterogeneous multi-material mixtures of different ceramic phases in specific proportions (e.g. zirconia-toughened alumina, ZTA). Since ceramics are compounds with strong ionic or covalent bonding between the atoms they can also be characterized as brittle. In many applications this is a disadvantage as compared to metals, which are ductile.

However, research into a new class of materials known as High Entropy Ceramics (HEC) recently started to draw serious attention. This type of material becomes "stabilized by entropy", i.e. it finds an energetically stable structure by mixing at least four different components in roughly equimolar proportions. The first example in the report is (Mg, Ni, Co, Cu, Zn) O synthesized in 2015 from five different oxides. As opposed to traditional ceramics of multi-phased crystalline structure, HEC forms a solid solution throughout the entire component when heat-treated, resulting in a material with a single-phased, metal-like lattice structure – if the processing parameters such as pressure and temperature are right. Thus, under the right conditions they thereby obtain more stable phases than their respective component materials by them-selves. Oxide-based HEC is one sub-category while Carbides and Borides form other – and the list is growing. The initial research shows HEC specifically has potential for use in extreme environments due to superior mechanical properties, including enhanced fracture toughness, creep-resistance, wear-resistance, and oxidation-resistance. “Their stability under extremely high temperatures makes especially the carbides and borides with very low thermal conductivity, inheriting the high elastic modulus and hardness of the components, promising candidates for thermal insulation materials in aerospace and automotive applications such as satellites, spacecraft and gas turbines” [1, p.3].

The potential of oxidic HEC is first expected to be exploited in various areas of the energy sector, like solid-state electrolytes in high-temperature fuel cells, in solid-state and thin-film batteries, to realize ultra-fast charge/discharge rates in solid-state energy storage devices, for further miniaturization of electronic circuits and capacitive sensors, for increasing the energy and power density of very large capacitors, and as catalysts for photo-induced chemical reactions such as water splitting for clean hydrogen production. Oxidic HEC is also considered as electromagnetic wave absorbing materials, which have a strong EM absorption capacity and a wide absorption bandwidth.

There is an “enormously large number of possible chemical compositions, if the development of new ceramics now only has to take restrictions with regard to phase stability into account” [1, p.4]. This is why the report suggests that material development supported by machine learning is an especially interesting line of development. It seems the periodicity of the material makes it possible to predict characteristics of a material through “thermodynamic modelling and high-throughput experiments”. Thereby making it possible to explore HEC-space using computational design techniques.

In 2040 only HEC-borides, oxides and carbides are assessed to have reached TRL 9.

It seems the interest in this new highly dynamic research area appears to have been primarily motivated by military applications. Bibliometric analysis of HEC shows the most intense research takes place in China, followed by the USA. In USA there are various military funded projects, but these often have linkage to publicly funded research. “In Europe, Germany and Great Britain are leading, roughly on a par with India. Sweden follows in eighth position together with France and Japan.” [1, p.8].

Owing to the observed superior properties, result is first expected in areas where high development cost does not deter development, like in space travel.

There are competing technologies in so called architectured materials and in High Entropy Alloys (HEA). Some research is looking to join these fields in order for to increase the tunable potential in the characteristics of these materials even more.

“A kind of gold-digger mood lets expect new findings at a rapid rate.” [1, p.10]

Identified possibilities and constraints

This is a new research area and it seems potential possibilities are great, but research is mostly on a basic level. Among possible HEC materials the borides, oxides and carbides are best explored so far and the possibilities and constraints identified are therefore referred to these.

Possibilities:

- Obtaining bulk components or coatings with significantly enhanced mechanical properties as compared to traditional ceramics, including resistance to fracture.
- Obtaining multi-material compounds with tailored mechanical, thermo-electrical and electro-optical characteristics.
- Obtaining components with ceramic properties through a simpler process, without the need to form the component before heat treatment, perhaps allowing additive manufacturing for example.

Constraints:

- Coatings are applied using magnetron sputtering, also known as physical vapour deposition. This process takes place in a vacuum chamber which limits the size of coated components and also the rate of processing.
- The number of degrees of freedom in designing materials of HEC-type, in choosing constituent materials and processing parameters, makes an enormous design space to explore. In order to take advantage of the potential there is a desire to use AI to aid research and development.
- Characterization techniques to evaluate the structure in new materials is an additional critical parameter and a research area.
- High development cost.

Suggested military use

The following military uses of high entropy ceramics are suggested in the reviewed report:

- Thermal insulation materials in aerospace and automotive applications such as satellites, spacecraft, or gas turbines.
- Components durable to extreme environments, like in space or hypersonic applications, or/and in ramjets, rocket engines or gas turbines etc.
- Armour for vehicle and personal protection.
- Transparent electromagnetic wave protection in the electro optical wavelength band, for sensors, or absorption materials (for signature applications, reviewer’s remark).
- One specific use proposed is to protect communication and sensor satellites in low orbit from cosmic radiation, temperature extremes and debris impact. These satellites are suggested to support communication, navigation and precise targeting in areas of the world where no terrestrial networks are available.

But there are also dual-use applications:

- Protective coatings for mechanical wear.
- High-temperature fuel cells.
- Solid-state and thin-film batteries.
- Miniaturized electronics.

Assumptions

In the Fraunhofer INT report on *hypersonic propulsion* in 2017 the assessment was that in 2035 hypersonic air breathing propulsion would be possible using combinations of rocket engines, ramjets and scramjets. Heat resistant, low weight, and load bearing construction materials and protective coatings for front edges of the air intake, the fuselage, and hot components in the engine were considered critical. [2, p.11]

The concept scenarios are based on the following assumptions:

- HEC-borides and carbides has reached their extreme heat resistant and mechanical properties anticipated.
- HEC-oxides has reached its thermo-electrical properties anticipated for to realize visions for energy storage and miniaturization of electronics.
- The other critical technologies necessary to realize air breathing hypersonic propulsion have also reached maturity.

Concept systems and scenarios in 2040

Concept system 1: Hypersonic air to ground missile

Thanks to advanced HEC materials this missile can be constructed lightweight and compact enough to be airborne. This is necessary in order for to be able to launch the missile at a speed of > M 1.5, in turn necessary in order for its own hypersonic air breathing propulsion system to be effective. The on board data links, computers, sensor systems, navigational aids and homing systems benefit from heat resistant, durable and miniaturized electronics developed using HEC technology.

Scenario 1: Baltic Deterrence

Having this hypersonic air to ground missile and detailed intelligence, perhaps from a partner country's low orbit satellite systems, Sweden now has the capability to strike ground or sea targets within minutes from decision at very long range. Due to the hypersonic speed (10M+) of these weapons, ground or sea based air defences now have the short end of the stick, and this has altered the behaviour of Russian air, ground and sea units in the Baltic Sea to less aggressive. A missile launched on altitude above Stockholm hypothetically reaches its target on the east shores of the Baltic, with precision, in about one minute.

Concept system 2: Reusable hypersonic aircraft for ISR

Manned or unmanned hypersonic aircraft for surveillance or reconnaissance made possible by the HEC-advancements described above.

Scenario 2: Collecting intelligence strike mission

The reusable hypersonic aircraft executes quick, timely, flexible aerial reconnaissance as compared to satellites, and is less endangered by air defences than other aircraft. It can provide early warning or important intelligence for the Swedish Common Operational Picture. In combination with the first scenario it can support the attack mission with target intelligence for precision strike.

SWOT-analysis

The following strengths, weaknesses, opportunities and threats with *Hypersonic air to ground missile* in the *Baltic Deterrence* scenario were identified at the seminar:

Strengths: • The design allows an airborne missile with the possibility to exploit air breathing hypersonic propulsion for speeds of 10M+ and long ranges, i.e. a contribution to capability for air to surface offensive operations. • "High ability to penetrate a dense air defence." [3] • "High kinetic energy in target impact." [3]	Weaknesses: • Complicated production techniques. • High development cost. • Requires timely target intelligence to be fully exploited in tactical or joint operations. • Hypersonic speed on low altitude to reduce GBAD threats will produce plasma anomalies in the surrounding air on account of the heat from friction. This will make conditions for IR-based final phase sensors very difficult. Perhaps the only option is to navigate using Inertial Navigation Systems.
Opportunities: • With suitable military strategic doctrine it is a contribution to deterrence. • A systems effect in the affordability	Threats: • "Hypersonic speeds will not reduce the sensitivity for many types of countermeasures, for example electronic jamming and

dimension, as explained by Amann: "Since saturation of air defence appears not to be necessary, a fewer number of missiles could be launched for achieving the desired effect. That would in turn mean that the number of launch platforms might be reduced significantly and thereby reducing logistic needs and increase availability for other tasks."[3]	decoys."[3] • Potential adversary use will require the development of countermeasures.

The following strengths, weaknesses, opportunities and threats with *Reusable hypersonic aircraft for ISR* in the *Collecting intelligence strike mission* scenario were identified at the seminar:

Strengths: • The design allows a reusable aircraft for ISR missions at hypersonic speed, and is thus a contribution to surface reconnaissance and surveillance from the air. • This system complements the use of hypersonic missiles in the deterrence scenario. • As compared to low orbit satellite systems, this mission can be launched to provide timely information when needed. • The hypersonic speed ability increases survivability.	Weaknesses: • Hypersonic speed will produce challenges for sensors, see above, and non-traditional mission profiles for entering and leaving the area of interest. • Despite superior material characteristics, these extreme missions will likely require extraordinary maintenance.
Opportunities: • HEC-materials might also be used for signature reduction purposes in the electro optical wave bands, but perhaps also at radio frequencies, further increasing survivability. • To overcome the challenges for on-board sensors the vehicle could be equipped with parachuted one-time-use sensors.	Threats: • A potential adversary use will require the development of countermeasures.

Assessment of capability impact

High Entropy Ceramics is a cross cutting technology with potential use as supporting technology in a multitude of different military and civilian applications. This assessment focuses on the two scenarios described above.

The Hypersonic air to ground missile as depicted makes a significant contribution to capability for air to surface offensive operations (the Effect element), since there seems to be no countermeasure. This assessment is consistent with earlier results: "The review group is unified in the belief that future hypersonic missiles can increase mission effectiveness. This analysis is shared with for ex Jon Hyten, commander of U.S Strategic Command, who has stated that USA has no defence against such weapons (CNBC, 2018). Development is ongoing, e.g. in April 2018 Lockheed Martin was awarded a contract to build hypersonic conventional strike weapons for the US Air Force (CNBC, 2018)." [3]

The Reusable hypersonic aircraft as depicted makes a significant contribution to capability for air to surface surveillance and reconnaissance missions.

Possible alternative scenarios identified during the seminar focused on different armour applications, possibly for weight-critical situations, like protecting helicopter crews or in personal body armour. However, this use was not considered as disruptive.

Assessment of footprint

The following list is a compilation of anticipated footprints on capability development if the technology in focus is to be used as described.

Influencing factor	**Footprint**
Doctrine	There is a strategic impact on the doctrine from hypersonic air to surface missiles, since there is no obvious countermeasure. There are parallels with the development of nuclear weapons.
Organization	Difficult to assess. Tactical effectiveness increases since there is no need to saturate the protective systems around the target. This could either be used to downsize the organization to reduce cost, or it could be used as a force multiplier to increase effectiveness.
Training	Some, there will be a need for new tactical procedures and mission profiles.
Materiel	These weapons come at high cost and a likely scenario is that there will be only a few missiles available, for strategic

	use. That is, there will probably still be a need for the legacy systems. Development will require multi-lateral cooperation, especially on low TRL-levels. Some doubts regarding the weight of a hypersonic missile with the performance described in scenario 1 led to a discussion on whether the missile might be too heavy for a JAS 39 Gripen Aircraft.
Leadership	None identified.
Personnel	Some, new technical systems and tactics will render new demands for education and training.
Facilities	None identified.
Interoperability	Development will require multi-lateral cooperation.

Assessment of the need for military R&D

This technology supports, and might even be critical, for enabling hypersonic air-breathing propulsion and hypersonic missiles, which in turn by many is assessed to be a disruptive technology. Great powers like China, USA, France and Great Britain are at the forefront.

The seminar believes Sweden could benefit from a strategic agreement with partner countries in order to follow the development and build knowledge.

Conclusions on military utility and recommendations

The High Entropy Ceramics (HEC) technology was assessed to have significant military utility in 2040. However, the final seminar touched upon a few factors contributing to uncertainty in the assessment.

First, there was a methodological discussion due to the fact that the HEC-technology in this scenario context is an enabling technology to hypersonic propulsion, which easily leads to a focus on the military utility of hypersonics. However, the seminar concluded (your author's perception) that as long as HEC can be considered a key-enabler to hypersonic propulsion, and, hypersonic propulsion itself has been regarded a technology with significant military utility, the method works. It should be noted that in the NATO report on Science & Technology Trends 2020-2040 the organization notes that some technologies have to be clustered in so-called convergent technologies to be interesting, one of them is called *Space-Hypersonics-Materials*.

Second, the results of this study indicate that hypersonic weapons have strategic implications comparable to nuclear weapons in some aspects. For example, there does not seem to be any known defence. The seminar could therefor anticipate political interventions in the use of these weapons, like a possible non-proliferation treaty. With such a treaty in place the first scenario in this memo becomes irrelevant and cannot be used to argue military utility. On the other hand, the second scenario still holds, and the seminar also came up with other uses of the technology, like coatings on missiles to protect against laser weapons.

Third, there were also discussions concerning doubts on the physical possibilities to design an aircraft-carried missile like the one in scenario 1. The seminar for example saw reason to believe that hypersonic weapons will have to trust on-board navigational aids for the end phase of an attack on ships, as illustrated in the scenario, and that this in turn will make necessary precision extremely difficult to obtain. The seminar decided to assume all other enabling technologies, including on-board navigation technology, will also have reached necessary maturity in 2040.

Fourth, there are reasons to believe that the development of hypersonic weapons, including the development of high entropy materials, will be extremely expensive. On the other hand, having only a handful of these weapons might contribute to the threshold effect enough to reduce other capabilities. The affordability dimension was not investigated any further.

Given that the military utility was assessed significant, and that development of HEC for hypersonic applications are driven by the space and military sector, the Swedish Armed Forces should monitor this research area closely and perhaps liaise with partner countries investing in hypersonic R&D to build necessary knowledge – including possible concepts for to defend against hypersonic weapons.

References

[1] Brandt, H., *High-Entropy Ceramics - Designing Randomness at the Atomic Scale*, Fraunhofer INT, Euskirchen, Germany, Dec 2020.

[2] Nätzker, W., Huppertz, G., *Hypersonic Propulsion*, Fraunhofer INT, Euskirchen, Germany, Oct 2017.

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Large Unmanned Underwater Vehicles

Reference [1]: Gabel, O., Neupert, U., Lieder, E. *Large Unmanned Underwater Vehicles*, Fraunhofer INT, Euskirchen, Germany, Dec 2020.
Referee: Johan Granholm, MSc

Introduction

Large unmanned underwater vehicles have greater endurance, as well as larger payload capability, when compared with existing, smaller UUVs. The US Navy classifies LUUVs (Large Unmanned Underwater Vehicles) as having a hull diameter between 53 and 210 cm, and XLUUVs (Extra Large Unmanned Underwater Vehicles) having a hull diameter above 210 cm. It is also assumed that LUUVs will normally operate from a ship or submarine, whilst an XLUUV can operate directly from a land base. Both are within the scope of the report [1], and will henceforth be designated as *large UUVs*. An alternative designation is (X)LDUUV, where the D stands for *displacement*.

Large UUVs are assumed to have a degree of autonomous control beyond that of Remotely Operated Vehicles (ROV), which are in constant contact with another vehicle. This allows them to perform independent tasks; however, they are generally expected to team up with manned systems, similarly to comparable land and air unmanned vehicles.

Current status:

At the present, the United States as well as Norway are operating large UUVs.

These employ inertial navigation (INS) in combination with a Doppler velocity log (DVL). Such navigation technologies limit the length of independent missions, as the uncertainty of position increases over time.

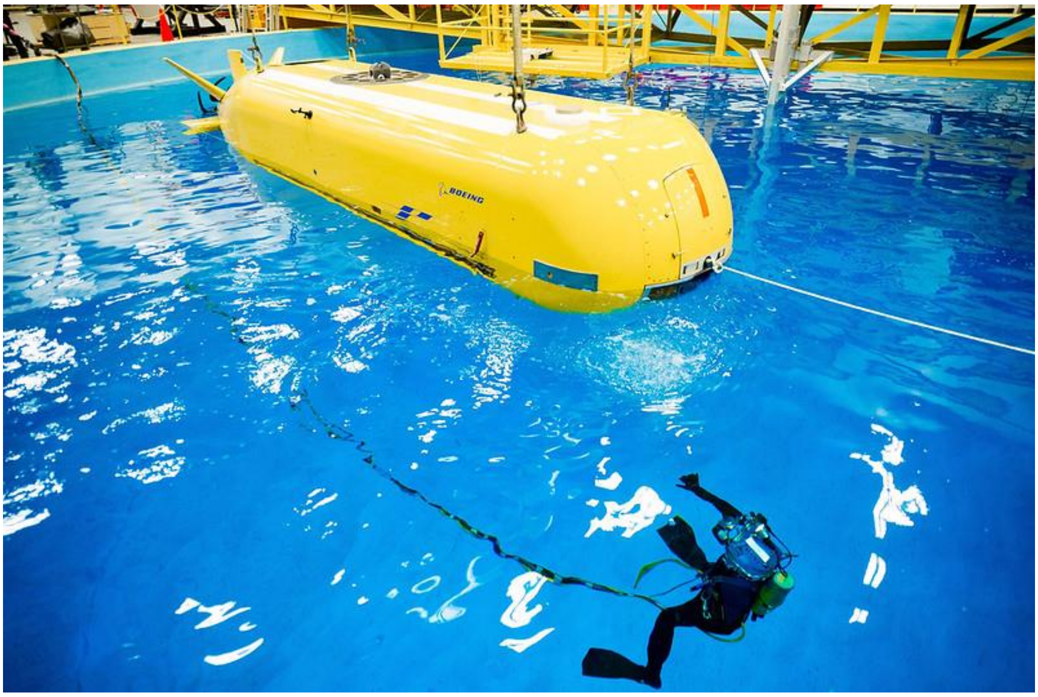

Figure: Boeing Echo Seaker LUUV. Source: The Boeing Company

In surfaced condition, these systems can communicate with radio based systems. Fully submerged, the only current means of communication is acoustic, which has relatively short range and very limited bandwidth. Both radio and acoustic signals are subject to detection and interception. An alternative is wire communication, which has been used for torpedoes since decades. This has a limited practical range.

The Norwegian system has electrical propulsion supplied from a lithium-polymer battery. Some of the US systems are is diesel-electric, which extends the range, but requires surfacing or snorkelling for recharging the batteries.

The Norwegian system is commercially available.

At least the United Kingdom, Russia, China and Germany have ongoing projects. There are at the moment no published proof of operation. These systems are assumed to use similar navigation, communication and propulsion systems, with the addition of hydrogen fuel-cells in the German case and nuclear propulsion in a Russian variant.

The German system is intended for civilian use.

<u>Predicted future status:</u>

Propulsion

For an unmanned vehicle, complexity and maintenance needs are critical properties.

The report predicts that lithium-based battery technologies will evolve further, as much higher energy density is theoretically possible. However, the step from batteries in small hand-held devices to operational propulsion batteries can take a long time.

Hydrocarbon fuels have a very high energy density. To avoid the problem of having to surface when recharging the batteries, closed cycle propulsion systems are being developed.

It is foreseen that solid oxide fuel cells will replace current fuel cell technologies, combining longer lifetime, fuel flexibility and lower maintenance needs.

Current fuel cells requiring hydrogen being stored on-board. Technologies extracting hydrogen from seawater could replace on-board storage.

Sea bottom recharging systems could be developed, where the large UUV could recharge without direct contact, through an electromagnetic field, similar to what is available for smartphones.

Nuclear propulsion is a technically feasible solution which would provide very long endurance.

Communication

When operating in a limited area, acoustic communication could be improved with a network of relay stations on the sea bottom.

An alternative for underwater communication could be optical communication. The report points out that this will require considerable research in several areas, including laser technology and biologically inspired photo sensors. Possible practical distance is not stated in the report.

Additional methods for communication through the surface, including one way communication where the submerged vehicle sends acoustic waves which causes ripples on the sea surface, These can then be detected and decoded from a flying platform. There is also research into optical transmission directly through the sea surface.

Navigation

Underwater navigation will depend on the combination of a number of different technologies.

A number of mathematical methods for improving navigational calculations are being developed. These will have very high energy requirements. That could be avoided by the development of quantum computers.

In addition to INS and DVL, geophysical navigation methods can be employed. These depend on both accurate mapping and on accurate sensors.

The report predicts that current accelerometers and gyroscopes will be replaced by quantum sensors with much higher accuracy.

For close range navigation, LIDAR and eventually quantum illumination can become available.

Identified possibilities and constraints

Possibilities:

- Large UUVs are generally cheaper in acquisition and operation. It is assumed that they will be more modular, allowing easier updates.
- This makes it easier to acquire more platforms, and they can be seen as expendable, as no crew is risked.
- Since no crew is present, missions can be longer, riskier, and more boring.

Constraints:

- The threshold for an adversary to take military action can be lower, for the same reason: no crew will be hurt.
- It will be attractive, and likely easier, to capture an unmanned system.
- An unmanned system is probably more vulnerable to cyber-attacks.
- Advanced mathematical calculations consume a lot of energy, which limits endurance.

Suggested military use

The following military uses of large unmanned underwater vehicles are suggested in the reviewed report:

- Maritime patrol.
- Reconnaissance missions for generating a dense situational picture.
- Protecting surface and underwater infrastructure.
- The deployment of sensors.
- Minelaying.
- Anti-submarine warfare, anti-surface and counter-land operations.

Assumptions

The concept scenarios are based on the following assumptions:

- The applied technologies have reached the maturity described in the report [1].
- In particular, new energy storage technology has increased endurance considerably.

Concept systems and scenarios in 2040

Concept system 1

A patrol LUUV, fully autonomous, with an endurance of 14 days submerged; patrol speed 2.5 kn. The electrical propulsion is supplied from lithium-ion batteries, in combination with solid oxide fuel cells. The LUUV has the ability to navigate with very high precision, without either transmitting or depending on external beacons. Regular reports are transmitted to airborne platforms. Short instructions can be received by long-wave radio. Stealth properties and behaviour are necessary mainly to avoid the system being captured.

The autonomy allows the LUUV to decide how to react to detected targets, i.e. to move outside of the patrol loop in order to further investigate.

The LUUV payload consists of passive sensors: acoustic, electromagnetic, magnetic et c. The LUUV capabilities are limited to detection and classification.

Scenario 1

It is assumed that an unknown entity may be preparing for future activities by deploying underwater systems in Swedish waters. Ten patrol LUUVS are constantly patrolling the Swedish coastline, seaward of the archipelagos. Every six hours a patrol report is transmitted to patrol aircraft.

When the adversary wants to move a system into Swedish waters, the critical point is before entering the archipelago. The LUUV discovers such a mission without being detected, and central command can act accordingly.

Concept system 2

A load-carrying LUUV, fully autonomous, with a range of 200 nm submerged at a speed of 10 kn. The electrical propulsion is supplied from lithium-ion batteries, in combination with solid oxide fuel cells. The LUUV has the ability to navigate with very high precision, without either transmitting or depending on external beacons. Reports are transmitted to airborne platforms. Short instructions can be received by long-wave radio. Stealth properties and behaviour are intended to avoid detection.

The autonomy allows the LUUV to decide how to avoid obstacles and threats during the mission.

The LUUV can carry and deploy payloads. The payload volume is 12 m^3.

Scenario 2

The LUUV is provided with a payload and a mission at a shore base. The payload consists of an underwater mine. The LUUV proceeds to a designated point where it deploys the payload on the sea bottom in a fairway in the archipelago. When 10 nm from the deployment point, it reports success of the mission. It thereafter returns to base.

SWOT-analysis

The following strengths, weaknesses, opportunities and threats with concept 1 in scenario 1 were identified at the seminar:

Strengths:	Weaknesses:
• Lower cost compared with manned submarines. • No crew that could be lost. • Longer missions possible with no crew. • Does not require recruitment of crew. • Manned submarines will be available for other missions. • Resistant to physical attack because of small size.	• Decision levels must be determined before mission. • Control is handed over to AI – can it be trusted? • Law and ethics are complicated. • Requires complex sub-systems to provide range and endurance. • Has high demands on logistic support systems.
Opportunities:	**Threats:**
• Can be used to develop and test sub-systems for other use. • Logistic support systems could be shared with other systems. • Should be able to detect being tampered with, and reporting this to home base. • Could be used as target for ASW training and exercises.	• System failure whilst on mission could result in loss/disappearance. • Tampering or capture by hostile party.

The following strengths, weaknesses, opportunities and threats with concept 2 in scenario 2 were identified at the seminar:

Strengths:	Weaknesses:
• Lower cost compared with manned submarines. • No crew that could be lost. • Does not require recruitment of crew. • Can deliver payload stealthily and in unsafe waters. • Resistant to physical attack because of small size.	• Decision levels must be determined before mission. • Control is handed over to AI – can it be trusted? • Law and ethics are complicated. • Requires complex sub-systems to provide range and endurance.

	• Has high demands on logistic support systems.
Opportunities: • Can be used to develop and test sub-systems for other use. • Logistic support systems could be shared with other systems. • Should be able to detect being tampered with, and reporting this to home base. • Could be used as target for ASW training and exercises.	Threats: • System failure whilst on mission could result in loss/disappearance. • Tampering or capture by hostile party.

Assessment of capability impact

The main impact will be in the following Elements of Combat Power:

Mobility – longer missions as well as missions to unsafe areas.

Sustainability – no need for crew survivability.

Intelligence and Information – sensors can be moved stealthily.

Assessment of footprint

The following list is a compilation of anticipated footprints on capability development if the technology in focus is to be used as described.

Influencing factor	**Footprint**
Doctrine	Intents with autonomous systems have to be clarified. Decision levels for the system have to be clarified. Laws and ethics for autonomous systems have to be considered.
Organization	Decision levels for the system in relation to higher levels have to be clarified. Logistic support may be impacted, unless the system is designed to use existing structures.
Training	Training should be based on similar roles for existing systems.
Materiel	Same requirements as for manned submarines.
Leadership	None identified.

Personnel	New categories are needed: - Service of the physical system (unless similar to existing systems). - Analysts for the data acquired. - Mission planners. - Decision rule makers – this will vary depending on mission type and purpose.
Facilities	New facilities for replenishing, mission programming and service will be required. They could be both mobile and stationary.
Interoperability	None identified.

Assessment of the need for military R&D

The seminar concludes that Sweden should not invest in military R&D for most of the technical areas, because of high costs, but also because considerable research is done by other actors, including civilian agencies. The exception is the area of acoustic communications, where ongoing Swedish research should be continued.

In some areas, including quantum sensors, there are ongoing or planned EDF (European Defence Fund) projects. Sweden should consider joining those projects, in order to secure access to the results, which would otherwise be very costly.

Further possible areas for research could be tactical applications of LUUVs, including the selection of power system solutions for various applications.

Conclusions on military utility and recommendations

The seminar discussions included the following statements:

- Other actors will employ long range/long endurance LUUVs, and achieve better situation awareness.
- Sweden cannot afford enough manned submarines, and LUUVs could fill some of the gaps.
- LUUVs could be used for high risk missions, as well as for long lasting missions.
- LUUVs could improve maritime security even in peacetime.
- Experience with using LUUVs could be used for developing and improving other systems, e.g. manned submarines.
- However, initial costs for introducing LUUVs could be punitive.

The military utility of the system was assessed to be moderate to significant.

The Swedish Armed Forces should, in addition to the identified R&D areas, monitor the evolvement of LUUVs continuously and, when systems with improved properties become available, assess if these match any identified missions or tactical applications.

Living Sensors

Reference [1]: Pinzger, B., Heuer, C. M., *Living Sensors: Novel concepts for bio-based sensor systems*, Fraunhofer INT, Euskirchen, Germany, Dec 2020.
Referee: Eva Lagg, PhD

Introduction

Research into living sensor technologies is generally pursued in the hope of gaining fast, sensitive, discreet and cost-effective sensor solutions. Living sensors (animals, plants and bacteria) may be categorized according to the degree of human intervention required for their use.

At the lowest level of intervention, the natural behaviour of the organism is monitored. A classic example is the coal mine canary. Threats to the environment by the release of harmful substances are often recognized by its effects on flora and fauna. DARPA is presently funding the program "Persistent Aquatic Living Sensors" (PALS) investigating if the natural behaviour of fish and other water-living organisms could be used to warn of the intrusion of (possible unwelcome) vessels. One important challenge is to differentiate behaviour changes caused by vessels from behaviour caused by other disturbances.

At the intermediate level of intervention, the organism (animal or insect) is trained to use its sensory apparatus to detect certain substances (such as explosives, narcotics or diseases). The use of sniffer dogs is well established, and more recently the use of rodents for detecting land mines was introduced. The range of substances these animals with sensitive noses are successfully trained to detect has increased over the years, and is nowadays even applied for medical purposes to detect diseases, such as cancer and covid-19. A more recent approach is the use of insects, in particular honey bees, for similar purposes. There is currently a project "Biological Methods (Bees) for Explosives Detection" financed by NATO. Bees are quick to learn (conditioning complete within 1-2 days), but sensitive to environmental conditions (such as low temperature) and short-lived if confined in a detection system (increased mortality after two days).

At the highest level of intervention, the organism's sensory properties are modified and/or enhanced. Plants and bacteria react to their surroundings, and their stimulus-response mechanism can be genetically modified and tailored to react to specific chemical compounds with detectable responses. DARPA is funding two such ongoing programs. "Advanced Plant Technologies" (APT) strives to develop genetically modified plants able to detect CBRNE materials, and "Bio Reporters for Subterranean Surveillance" intends to create bacteria that detect buried explosives, and another strand that signals events by emitting glowing light on the surface.

The Fraunhofer report concludes that "the value of living sensors for military operations seems doubtful" (p. 13), beyond their present use, one might add. Table 1 below, originally from the Fraunhofer report, displays the estimated technology readiness levels (TRL) for the coming 20 year-period of the identified potential applications of living sensor technology.

The use of detections animals is rather well-established across all identified fields of application, i.e. TRL is already high. The range of animals used for detection purposes may widen, and the range of substances detected in this manner as well. In a more long-term perspective, the use of detection animals would rather be expected to decrease, as the sensing capabilities of conventional non-living sensors is further developed.

The prognosis for the use of wild animals feels rather speculative. It is possible to argue for a somewhat higher estimate in the situation of today. Vegetation and wildlife are monitored even today, although not for the purpose of detecting infringements of territory. Whether this latter application will be the preferred means of surveillance in the future seems like a fairly open question. The rather high TRL estimated in 15 to 20 years' time may be overly optimistic.

Sensor plants require appropriate living conditions, and are, in general, slow to respond compared to other sensor systems. They may find their uses with time, but not necessarily in military applications.

Genetically modified bacteria appears most promising. The application of this technology is, however, greatly restricted by current legislation. Using free genetically modified bacteria as sensors will be difficult in the short-term perspective. With time and accumulated knowledge, this situation may change. In controlled environments, such solutions are more easily applied. One such application will be suggested as the concept systems analysed below.

Taxonomy	Designation Year	2020	2025	2030	2035	2040
A07.01, A07.02, A07.04, B06.13	CBRN-related applications…					
	…using detection animals	9	9	9	9	9
	…using sensor plants	3	3	4	5	*
	…using bacterial sensors	4	5	6	6	6
B06.17, C04.05	Environmental monitoring and decontamination applications…					
	…using wild organisms	4	6	6	7	8
	…using detection animals	9	9	9	9	9
	…using sensor plants	3	3	4	5	*
	…using free bacterial sensors	4	6	7	*	*
	…using contained bacterial sensors	6	7	8	8	8
C05.04	Medical applications…					
	…using detection animals	7	8	9	9	9
	…using bacterial sensors	4	6	7	8	8

Table 1: Short, summarizing evaluation of to where the Technology Readiness Level (TRL) sub-system's different technologies might have developed for different time intervals. Asterisks: Further readiness advancements in these fields would only make sense, if the regulations regarding the release of (genetically) modified organisms into the wild would be significantly relaxed. This appears unlikely. Colour codes: TRL 1-4 red, 5-6 yellow, 7-9 green. The term TRL is described in e.g. a report GAO-09-288, Appendix VI, on page 48-49. See www.gao.gov (GAO = United States Government Accountability Office). (From the Fraunhofer report [1]; Table 2 on page 6)

Identified possibilities and constraints

The following possibilities were identified in the report:

- CBRN-related applications using detection animals, sensor plants and/or bacterial sensors.
- Environmental monitoring and decontamination applications using wild organisms, detection animals, sensor plants, free bacterial sensors and/or contained bacterial sensors.
- Monitoring health and well-being of people (including medical diagnoses) using detection animals and/or (free and/or contained) bacterial sensors.

The following constraints were mentioned in the report:

- Living sensors tend to have short life spans, i.e. the time of use until the expiration date is rather limited. This is not easily compensated for by mass production.
- Living sensors are sensitive to environmental conditions.
- Living sensors, such as animals, plants and bacteria need nutrition.
- Living sensors may also require disposing of metabolic waste products.
- There is a lack of solutions to long-range collection of data from distributed living sensors.
- There are ethical and legal constraints on the handling of animals and release of biotechnologically engineered organisms.

Suggested military use

The following military uses of living sensors are suggested in the reviewed report:

- Living sensors might offer quick, sensitive and relatively cheap monitoring and detection solutions in various contexts.
- One example in the report is surveillance of marine environments where the natural behaviour of fish and other water-living organisms might warn of the intrusion of (possible unwelcome) vessels.
- Genetically modified plants and bacteria could be used in the search for chemical and biological agents as well as explosives.
- Living bacterial sensors, detecting inflammations and other biomarkers, could be made part of wearables of various kinds, monitoring personnel health.

Assumptions

The concept scenario is based on the following assumptions:

- The use of genetically modified bacteria encased in semi-permeable materials is accepted.
- Used products containing genetically modified bacteria can be safely disposed of.

Concept system and scenarios in 2040

Concept system: A system monitoring health and/or health hazards using genetically modified bacteria enclosed in semipermeable material.

Two scenarios demonstrate possible applications of the concept system.

Scenario 1

Genetically modified bacteria encased in semipermeable materials are used in wearables of various kinds, such as pieces of clothing, bandages and living tattoos, in order to monitor the health of personnel, as well as warn of health hazards in the environment. The reactions of this biological sensing equipment could be registered by some monitoring device and forwarded to commanding officers of other colleagues.

After use, the equipment is collected and disposed of in an appropriate and safe manner.

Scenario 2

Genetically modified bacteria encased in semipermeable materials are used to assess the quality of food, food ingredients, water and other drinks in the field, in cases where such assessments cannot be made by other means.

After use, the equipment is collected and disposed of in an appropriate and safe manner.

SWOT-analysis

A SWOT was performed for the concept system. The differences between the scenarios were deemed too small to merit separate analyses. The SWOT-analysis therefore addresses to both scenarios. The SWOT-analysis identified the following strengths, weaknesses, opportunities and threats with the suggested system monitoring health and/or health hazards using genetically modified bacteria enclosed in semipermeable material.

One potential threat is difficulties with acquiring an appropriate level of diagnostic specificity. Bacteria may react to a range of chemically similar substances. This could lead to undesired false alarms. The inner-body milieu is fairly well-known, and what kinds of substances that are released in case of illness. Health-monitoring applications are probably less problematic than monitoring environmental threats in air, water, soil or food products. A question is whether they will react faster than the owner of the body. People tend to experience, and report, bodily discomfort in response to health hazards. Monitoring equipment will not be of much use unless it may serve as an early-warning system.

Strengths: • Detection of infections, bodily reactions and health-threatening substances not detectable through other means.	Weaknesses: • Demanding routines for safe disposal. • Short life span.
Opportunities: • Comfortable and easy-to-wear health monitoring equipment. • A quick means to detect dangerous micro-organisms.	Threats: • Potential release of hazardous waste, in the form of genetically modified bacteria, through careless handling of used products. • The equipment might be too sensitive, posing too high demands on handling and storage to be successfully applied in a field setting. • Weak diagnostic specificity. • Slow response.

Assessment of capability impact

The primary impact is on force protection and endurance. With regard to the monitoring of potential health hazards, there is also a contributions to surveillance and intelligence.

If the registrations are forwarded, they might contribute to enhanced C2 capability, since soldiers unfit to continue with their present tasks could be identified and removed for treatment and recovery.

Assessment of footprint

The following list is a compilation of anticipated footprints on capability development if the technology in focus is to be used as described.

Influencing factor	**Footprint**
Doctrine	Limited.
Organization	Routines for safe handling of used products.
Training	The personnel will require instructions on how to safely dispose of used products. The personnel will also need to

	be able to correctly interpret the registrations made by the equipment.
Materiel	Special containers may be required for safe handling of disposed products.
Leadership	Limited.
Personnel	Limited.
Facilities	Probably limited, but could make demands on facilities for storage and proper handling.
Interoperability	Limited.

Assessments of the need for military R&D

The research reviewed by the Fraunhofer researchers, which shows some promise, is primarily applicable to problems shared by civilian society and the military. There appears to be no call for particular military research initiatives. The military may benefit from products developed for civilian use.

Conclusions on military utility and recommendations

As stated earlier, the value of living sensors in military endeavours, beyond the present use, is dubious. It seems likely that progress in the field of technical sensors will rather lessen than increase the need for living sensors. This ought to be a welcome development, since a challenge with living sensors is to keep them alive. It may be stretching the argument too far to claim that the future military utility of living sensors is negligible, but it certainly appears uncertain.

Machine Learning in Materials Development

Reference [1]: Langner, R., *Machine Learning in Materials Development*, Fraunhofer INT, Euskirchen, Germany, Dec 2020.
Referee: Peter Bull, PhD

Introduction

Artificial intelligence (AI) is a widely used term that easily leads to associations to the supercomputer HAL 9000 that appears in 2001: A Space Odyssey by Arthur C. Clarke and Stanley Kubrick. In reality, however, AI is not as advanced today as the movie from 1968 predicts. According to Jordan [2] what is today labeled as AI is machine learning (ML). Machine learning is a field of science utilizing knowledge from several fields of science such as statistics and computer science. The aim is to design computer algorithms that can gather large amounts of data and process it in order to recognize patterns, to diagnose conditions, to make predictions, and to help make decisions.

Past state of the technology

The term artificial intelligence appeared in the 1950's quite possibly inspired by Alan Turing's "Imitation game" [3]. A short overview of AI history can be found in Jordan [2].

Present state of the technology

As stated above, AI is presently nowhere near as capable as computers portrayed in science fiction from the 1960's. In an interview Jordan says that the most important goal of machine learning and AI is not to imitate human thinking [4]. Machine learning can be utilized to collect and analyze vast amounts of data in order to find patterns that can be used to recommend courses of action. This is mainly what machine learning is used for today. As well as being a scientific field in its own right, its algorithms are successfully applied in several other fields of science. One example of which is materials science as described in the reviewed report [1].

Future state of the technology

The use of machine learning in development of new materials is basic research. This is underlined in the report [1] by the low technology readiness levels, TRL 3 – 4, of the different relevant sub fields. Machine learning in itself is estimated to have somewhat higher TRL of 4 – 6. Some caution is therefore necessary when trying to predict the future state of this technology. Large resources are being put into research and development of both machine learning as such, and the implementation of machine learning in development of new materials. Some areas of research that might produce interesting materials for the armed forces are energetic materials for e.g. explosives, super-hard materials for e.g. ballistic protection, and parameter control in additive manufacturing. The two former examples are of interest since they can produce materials that can be utilized in order to increase the performance of weapons and protection systems. The latter is interesting because when manufacturing metal parts with additive manufacturing, the process can be very sensitive to process parameters. Therefore, experienced operators might be required in order to manufacture high quality metal parts. With machine learning the need for experienced operators might be reduced. This can be utilized in a military logistics chain.

Identified possibilities and constraints

Possibilities:

- Materials can be tailored on a molecular level in order to achieve material properties that have previously been unobtainable.
- Vast amounts of material data can be gathered, processed, and analyzed in order to identify materials with certain properties.

Constraints:

- The Black box problem. It can be very difficult to understand how and why machine learning algorithms get the results they do. To understand this is crucial.
- Just because a material with very interesting properties have been identified, does not necessarily mean that it is possible to produce the material.

Suggested military use

The report suggests the following military applications of machine learning for materials development:

- Development of energetic materials for e.g. explosives.
- Development of super-hard materials for e.g. ballistic protection.
- Parameter control for additive manufacturing.

Assumptions

The concept scenario is based on the following assumption:

- CAD files containing the geometries of parts are readily available.
- Qualified process materials are available.
- The necessary equipment for additive manufacturing is available.

Concept systems and scenario 2040

Additive manufacturing with machine learning control

The Archer self-propelled howitzer is based on an articulated hauler. Steering is accomplished using hydraulic rams that bend the vehicle around a hinge-point behind its cabin.

During an exercise one of the gudgeon pins that fix the hydraulic rams to the chassis breaks. Because of redundancies the howitzer is still capable of moving, but not at its full capacity. It turns out that the repair unit does not have spare gudgeon pins, and even though they are commercially available, neither does the certified supplier. The repair unit does, however, have access to equipment for additive manufacturing of metal parts. Structurally loaded metal parts require heat treatment after they have been manufactured. In this case the part is manufactured, turned down to the correct size in a numerically controlled lathe, and heat treated. The manufacturing system has machine learning algorithms that ensure a sufficiently high quality of the gudgeon pin. It both controls the manufacturing parameters, and accurately predicts the amount of deformation caused by the heat treatment. The latter makes it possible to machine the gudgeon pin before heat treatment, and still achieve the correct fit and finish after heat treatment. When the part is finished, the Archer howitzer can be repaired in the field, and continue to participate in the exercise within a relatively short time.

SWOT-analysis

Strengths: • A manufacturing process that is less sensitive to variations in process material properties, and environmental factors. • An increased availability of the howitzer.	Weaknesses: • This is expensive specialist equipment that would constitute a high-value target. • Sensitive equipment that is difficult to transport and deploy. • Few parts are possible to manufacture using AM.
Opportunities: • Possibility to manufacture hard to get parts in a relatively short time. • Possibility to manufacture specialist parts in the field, or very close to it.	Threats: • Black box problem, the machine learning algorithm can recommend parameters that are counter intuitive and impossible to investigate. • Difficult to certify system for peace us.

Assessment of capability impact

Machine learning in materials development as treated here is basic research, and as such has limited capability impact. Products resulting from its application on development of e.g. explosives, materials for ballistic protection, or additive manufacturing, as mentioned in the scenario above, might have an impact. Because of the very low TRL for the fields in question it is impossible say if or when usable products are available on a sufficiently large scale.

Assessment of military effectiveness

Within the scope of the scenario described above, the military effectiveness of machine learning control algorithms for additive manufacturing of spare parts is uncertain at best. This is mainly because the benefits of additive manufacturing of spare parts are not entirely obvious, see e.g. [5, 6, 7, 8, 9, 10, 11, 12, 13, 14].

Assessment of footprint 2040

The following list is a compilation of anticipated footprints created by the use of machine learning in materials development to the factors DOTMLPFI (Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities and Interoperability) as well as the demands that are expected to be put on the SwAF R&D in order to facilitate the introduction of the technology.

Influencing factor	**Footprint**
Doctrine	Limited.
Organization	Limited.
Training	Operators have to be trained in using this type of equipment.
Materiel	Specialist equipment, and qualified raw material is required.
Leadership	Limited.
Personnel	Limited.
Facilities	Equipment for additive manufacturing can be placed in most workshops intended for making metal parts.
Interoperability	CAD systems and control systems must be compatible, both within the armed forces and with suppliers.

Assessment of military suitability

The suitability of these systems is uncertain, and to some extent dependent on whether they will be used in a forward operating base or in a centralized logistics hub. The equipment needed for additive manufacturing is made for being placed in a stationary workshop, and might therefore be easier to integrate in a maintenance organization if it is placed in a centralized logistics hub. Additive manufacturing of metal parts is a slow process that is very good for making parts that are impossible to manufacture with other manufacturing methods. This does, however, not mean that it is a suitable manufacturing method for any part. A work conducted for the Dutch Army showed that the amount of spare parts that were suited for additive manufacturing was very small [11]. Whether this also holds for the Swedish armed forces needs to be investigated before investing in this type of equipment.

Assessment of military affordability

The affordability, too, is uncertain. Equipment for additive manufacturing of metal parts is expensive. In addition, equipment for heat treatment and machining is required. Additive manufacturing can only be used for manufacturing of relatively small parts. It can therefore be argued that, based on statistics from maintenance history, a reasonably large stock of wear parts might be a more economical solution.

Assessment for the need for R&D

As pointed out above, the use of machine learning in development of materials is basic research. Whether the Swedish armed forces should commit itself to basic research is a question outside the scope of this report. What is important is to have the knowledge to understand how the use of machine learning can affect the development of materials, and also be aware of the black box problem and how to mitigate effects from it.

Conclusions on military utilities and recommendations

Machine learning in materials development might revolutionize how new materials are discovered and developed. However, since quite moderate TRLs have currently been reached in the fields of applications mentioned in the report, it might also just contribute to evolutionary steps rather than revolutionary leaps.

The use of machine learning in materials development in itself is assumed to have uncertain military utility. The results from its application on e.g. development of explosives, or materials for ballistic protection might have significant military utility. Therefore, it is important to monitor areas of application where even moderate improvements in properties can have significant effects.

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