2021 HIGHLIGHTS

SCIENCE AND TECHNOLOGY ORGANIZATION




EMPOWERING THE ALLIANCE'S TECHNOLOGICAL EDGE

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FOREWORD

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THE NATO SCIENCE AND TECHNOLOGY ORGANIZATION
"EMPOWERING THE ALLIANCE'S TECHNOLOGICAL EDGE"

Figure 1: Dr Bryan Wells, NATO Chief Scientist.

Following in the wake of the past few years, 2021 has been an extremely successful year for the NATO Science and Technology Organization (STO). Building upon the experience and "lessons learned" of the first year of the COVID-19 pandemic, the STO network of over 5,000 scientists, engineers and analysts have continued to remain focused on delivering excellence for the member Nations of the Alliance and NATO.

The STO continues to support the Alliance in maintaining its technological advantage by generating, sharing and utilizing advanced scientific knowledge, technological developments and innovative exploratory methods.

This booklet illustrates how the STO Programmes of Work continue to deliver scientific excellence for member Nations and for NATO.

Over the past year, several initiatives were launched and activities carried out with the aim of involving more new people in the S&T network and strengthening the bond of those who were already involved: **maintaining the momentum** has been paramount. The STO remains focused on attracting young scientists, involving them in the network, and encouraging their participation in the Programmes of Work. Among the different initiatives that have been developed, I would highlight the creation of the STO peer-reviewed journal, which increases the attractiveness of STO research activities for young scientists and helps to increase their profile within the scientific community at large.

Advice to leadership remains vital for facilitating NATO's high-level decision-making. Recent deliverables in this field include the first "Chief Scientist Report" on the science underpinning the integration of women into the armed forces, as well as research on the possible future scenarios arising from COVID-19. Such reports provide leadership with the means to make the right decision to enable the Alliance to maintain its advantage and address threats informed by the best scientific advice.

STO work also reflects the NATO high-level policy initiatives that will mark the path of the Alliance for the years to come.

At the 2021 NATO Summit held in Brussels in June, NATO Leaders agreed on the **NATO 2030** agenda to strengthen the Alliance over the next decade and beyond. This agenda stems from a forward-looking process initiated just a year earlier by Secretary General Jens Stoltenberg, laying out his priorities for NATO 2030: making sure NATO remains strong militarily, becomes even stronger politically and takes a more global approach. In this context, STO has also worked on defining how best to support and benefit from DIANA (Defence Innovation Accelerator for the North Atlantic) to boost transatlantic cooperation on critical technologies by engaging with academia and the private sector.

Partnership has always played a key role for STO in expanding its network and enriching it with new knowledge. In 2021, Japan joined the STO as an Enhanced Opportunity Partner (EOP), expanding the group already made up of Australia, Finland and Sweden.

At the Brussels Summit in June, Allies also agreed to aim for NATO to become the leading international organization when it comes to understanding and adapting to the impact of climate on security, and announced the endorsement of an Action Plan to implement the NATO Agenda on Climate Change and Security. Accordingly, the Centre for Maritime Research and Experimentation (CMRE) has increased its commitment to monitoring the maritime environment in the context of climate change.

The statistics on our two Programmes of Work demonstrate the scale of our efforts. Over the course of 2021, we had more than 300 activities underway, ranging from major research programmes to horizon scanning and lecture series, as well as cooperative demonstration of technologies.

This booklet demonstrates the very high quality of work that was done in 2021, and which continues to be done, within NATO S&T, and it shows how committed we all are to carrying out our work in the best possible way and making it relevant for future decisions by NATO and Allied Nations.

Dr Bryan Wells

NATO Chief Scientist
STB Chairman

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MAINTAINING THE MOMENTUM

DISRUPTIVE TECHNOLOGY TABLE-TOP EXERCISE

In February 2021, the STO ran its first virtual Disruptive Technology Table-Top exercise (D3TX), a significant event building on the Disruptive Technology Assessment Game (DTAG) and the S&T Trends 2020–2040 report previously developed by the STO. The exercise acted as a precursor to the STO's annual Plans and Programmes Workshop (PPW) and brought together communities of interest from across the STO, NATO and European Union (EU) Military Staff, and the wider NATO enterprise. Players participated in two afternoons of engaging gameplay, exploring the impact of emerging and disruptive technologies (EDTs) in operational scenarios designed to align with NATO's three core tasks (collective defence, crisis management and cooperative security) and operational or enterprise capabilities. The event was opened by the Director-General of the International Military Staff and attracted over 180 participants. These participants were divided into sixteen syndicates, each interrogating the campaign phases of a single scenario. The design and findings of the D3TX have since garnered considerable interest from a range of NATO communities, with the Office of the Chief Scientist briefing the C3 Board, the Directors of the International Military Staff, and the Committee on Counter Proliferation among others on the outcomes of the exercise. The exercise helped inform two further days of productive PPW discussions, in which the findings of the game were used to evaluate gaps and opportunities in the 2021 STO Programme of Work. Finally, the D3TX output significantly supported further analysis activities such as the EDT Implementation Strategy.

REACHING OUT

The STO has reached out to the NATO and Alliance innovation communities for increased situational awareness, fostered impact and enhanced collaboration.

In addition to innumerable activities at the panel level, strategic engagements within NATO include the D3TX itself, as well as briefings by the Chief Scientist or members of the OCS to the MC, DPRC, CNAD, C3B, IMS, the Secretary-General's Advisory Group on Emerging and Disruptive Technologies, and the Parliamentary Assembly.

Engagements with partners include senior EC leadership and participation in EDA S&T forecasting activities. Outreach with civil society also grew this year with presentations at TIDE Sprint, and notable briefings by the Chief Scientist to Georgetown University on AI and a virtual event (Minnesota Star Tribune) on climate change involving the Canadian PERMREP.

Industry is an important partner and contributor to Alliance R&D. As such, the STO continued its engagement with industry, including very useful engagements with Nokia, Boeing and Rolls-Royce.

SCIENCE & TECHNOLOGY BOARD (STB) PROGRAMMATIC DEEP DIVES

With the intent to strengthen the programmatic dialogue between the Panels/Group/CMRE and the STB, a set of eight virtual Programmatic Deep Dives were held in the May - July 2021 timeframe.

The Programmatic Deep Dives offered the Panels/Group/CMRE the opportunity to inform the STB about the current state of their respective Programmes of Work, to highlight topics of interest and to strengthen the programmatic exchange between themselves and the STB.

The Deep Dives were a great success and the STB Chair intends to replicate the format. The meetings allowed for good exchanges between the STB and the Panels/Group/CMRE, including requested STB guidance on specific questions posed by the them.

YOUNG SCIENTISTS

Young talent has always been a focus of attention for the STO, NATO and its members in general. The contribution and impact of young scientists in maintaining NATO's competitive edge is crucial. The STO continues to be committed to encouraging the next generation of S&T scientists. The involvement of tomorrow's scientists in S&T and Defence issues will ensure the development and adaptation of NATO's knowledge and expertise to future challenges, ensuring the technical edge of the Alliance. The STO has organized several events including the "Early Career Scientist" and "Shaping the Future of S&T: Young Scientists in NATO."

The Early Career Scientist Event took place virtually during the spring STB meeting in March 2021 and involved 18 young scientists nominated by the NATO member Nations, the Chairs of the STO Panels and Group, and CMRE. During the event, these young scientists took the floor to share their experiences within the S&T community. They advised the STB with short presentations, making their contribution to maintaining NATO's scientific

Figure 2: Dr Bryan Wells, NATO Chief Scientist, along with the Young Scientists and some of the STO staff in a group photo after the event Shaping the Future of S&T: Young Scientist in NATO held on the 14th December 2021 at the headquarters.

and technological edge. Different topics were covered on a spectrum ranging from "military applications and possibilities of 5G" to "Artificial Intelligence for military simulations," and "the use of analytical games as a knowledge acquisition tool" to "Big Data Analytics/Operational Analysis."

Figure 3: Mr Paolo de Heer receives the NMSG Young Scientist Award 2021 from Chair of the NMSG Awards Committee, Mr Niels KRARUP-HANSEN, at the NMSG Symposium on "Towards Training and Decision Support for Complex Multi-Domain Operations" held in Amsterdam (the Netherlands) on 21–22 October 2021.

The hybrid event "Shaping the Future of S&T: Young Scientists in NATO," held on 14 December 2021, in accordance with the STO vision and the communication campaign #WEARENATO, hosted a Panel of six renowned NATO Young Scientists. The event took place at NATO HQ but had attracted hundreds of participants connected worldwide. It was a unique event that saw the NATO Chief Scientist engage side-by-side with the next generation of scientists in a discussion about the STO Collaboration Network and how Young Scientists play a key role in shaping the Alliance's technological edge in the coming decades. As a result, the initiative achieved its aim of informing and attracting the next generation of scientists to STO's collaborative network.

Each year the STO Panels and Group individually recognize the exceptional contributions of their young scientists to the technical activities under the STO CPoW through the Young Scientist Awards. This programme is designed to encourage participation and networking for promising and talented young researchers in the STO community.

Figure 4: Students tutored by CMRE's Scientist presenting the results of the BARLAMARE Project during the SEAFUTURE 21 Convention in La Spezia, Italy.

In 2021, there were six recipients of the award:

- Dr. Norman Hopfe (DEU) – Applied Vehicle Technology Panel
- Dr. Joseph Coppin (GBR) – Applied Vehicle Technology Panel
- Dr. Boris Kingma (NLD) – Human Factors and Medicine Panel
- Paolo De Heer (NLD) – NATO Modelling and Simulation Group
- Prof. Dr. Gabriele Rizzo (ITA) – System Analysis and Studies Panel
- Dr. Elisa Giusti (ITA) – Sensors and Electronics Technology Panel

Areas of research for the 2021 award winners include cognitive and imaging radar, quantum computing, rocket propulsion, wind tunnel modelling, military operations in extreme weather, and strategic foresight analysis

CMRE's Science, Technology, Engineering and Mathematics (STEM) educational and outreach programme has continued during the COVID-19 pandemic by participating in the "GIONA Project," a multidisciplinary initiative led by local schools aimed at promoting environmental awareness among students aged 14 to 19.

In 2021, the work on Bio-Acoustic Research to Learn About the MARine Environment (BARLAMARE), in collaboration with the Province of La Spezia School Office, the Cinque Terre National Park, the Aquarium of Genova, and the University of Pavia, evolved with the adoption of cloud technology in response to the challenges posed by the COVID-19 pandemic. The project was conducted remotely using a cloud platform to analyze data collected during previous sea trials, in a secure and flexible way. The students were able to connect from home and collaborate in a virtual space, sharing their scripts and results. Tutoring sessions with CMRE scientists were conducted using video tele-conferencing.

In October 2021, the students presented the results of their work during the 7th Edition of SEAFUTURE 2021, an international business convention for maritime technologies, held inside the La Spezia Naval Base. During their presentation, the students recalled the milestones of the project since its start in 2018, and proposed a follow up soundscape monitoring activity, using Artificial Intelligence technologies to correlate the variations of the acoustic environment with climate changes.

In addition to the activity with high schools, CMRE supported the "GIONA Project" during the sea trial campaign, which brought more than 300 secondary school students onboard the Pandora schooner. CMRE personnel embarked with the students to talk about topics such as oceans and climate, while teaching them how to spot and recognize the numerous cetaceans that populate the waters of the Ligurian Sea.

Figure 5: CMRE's Head of Research Department (Dr. Sandro Carniel) on a boat trip with young high school students from the "GIONA Project."

STO PEER-REVIEWED JOURNAL

The STO has recently launched a new peer-reviewed journal entitled "NATO STO Review."

Publishing articles in well-known journals that have a high impact factor is a major attraction for scientists, particularly young scientists, who are looking for recognition of their scientific work. Although there are many publishing opportunities, it is not always easy to reach such journals and, even when it is, the costs can be prohibitive.

The NATO STO Review journal will provide this opportunity, and at the same time, it will make the STO Collaborative Programme of Work (CPoW) more attractive for our scientists, by helping them to increase their exposure within the scientific community at large.

Figure 6: NATO STO Review.

NATO STO Review is an online journal of publicly releasable articles with content connected to the work of the STO. The articles, free of costs, undergo a rigorous peer review process primarily from scientists within the NATO S&T community. The journal is further complemented by articles of a more general nature aimed at demonstrating the STO's value and overall scientific advice.

The aim is to reach a level of scientific content that will have this impact factor and relevant citation index level. The journal as a whole carries an e-ISSN, with each paper having a Digital Object Identifier (DOI), and registered in respected scientific journal databases. Building a significant "impact factor" for the journal will take several years.

We have now released the first online issue containing a number of peer-reviewed papers from recently held STO Events.

The *NATO STO Review* can be accessed at the following web address: **https://review.sto.nato.int**

ADVICE TO LEADERSHIP

INTRODUCTION

The intrinsic relationship between the conduct of science, progressive technological development and the consequent provision of advice makes them inseparable from each other. Evidence of this combination underscores how relevant and essential 2021 activities were to decision makers. These include the assessment on COVID-19, the publication of the Women in the Armed Forces research report, and a deep dive on EDTs.

COVID-19: CHIEF SCIENTIST'S CHALLENGE – ONE YEAR ON AND SAS-169

On 2 April 2020, NATO Foreign Ministers tasked the NATO S&T community to take concrete measures to "… harness our medical, scientific, and technological knowledge and resources to help deliver innovative responses" to the COVID-19 pandemic. With the pandemic persisting over 2021, the STO continued to refine and exploit S&T to support this request. Among a number of activities, two stand out in particular for 2021. First is the forecasting of the mid- to long-term implication of COVID-19 as part of SAS-169. As a Chief Scientist challenge, SAS-169 completed and published a study on "The Military Impacts of COVID-19 on the Alliance: Challenges and Opportunities." As a follow-on, the OCS facilitated and moderated a workshop between SAS-169 and the Secretary-General's Policy Planning Unit (PPU). This very successful workshop was built upon the advice contained in the SAS-169 study. Second, following up on HFM activities to understand and provide advice on COVID-19 disinformation, a book titled "COVID 19 Disinformation: A Multi-National, Whole of Society Perspective" is being edited and prepared for publication with a chapter co-written by the NATO Chief Scientist and an introduction by the Deputy Secretary-General.

WOMEN IN THE ARMED FORCES: THE FIRST NATO CHIEF SCIENTIST RESEARCH

In May 2021, the first NATO Chief Scientist Research Report was published on the topic of Women in the Armed Forces. This consolidates the findings of twenty years of STO collaborative research related to the employment of women in the armed forces. The report was commissioned to share with the wider NATO community the findings of STO gender research and support NATO's commitment to gender equality and women's inclusivity across Alliance structures and in national armed forces.

The report identifies four central themes that capture the current key areas of research: employment and integration, sexual violence and harassment, kit and equipment, and health. Overall, the research described in the report provides a solid framework for ensuring informed and evidence-based decisions are made on the optimal effectiveness and employment of women in the armed forces.

Highlights from the report include:

- The design of military kit and equipment can affect women's performance and safety in core tasks.
- Supportive, committed and sustained leadership is critical to the successful integration of women.
- Operational effectiveness can be enhanced by the participation of women in combat teams.
- Questions of sex and gender need to be mainstreamed in S&T research.

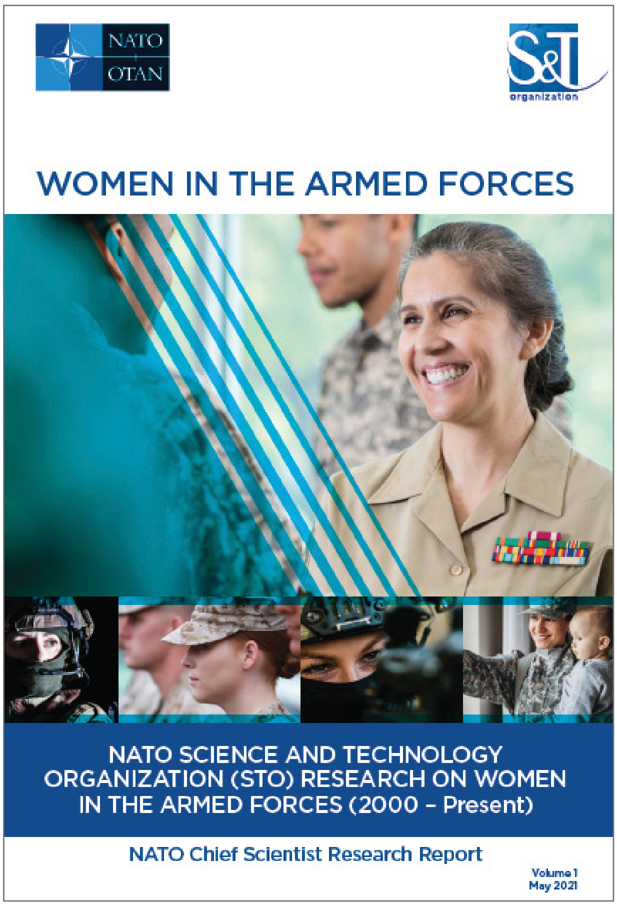

Figure 7: The first NATO Chief Scientist Research Report, on the topic of Women in the Armed Forces.

An accompanying post-publication webinar was hosted to discuss the report and its findings. This event brought together colleagues in NATO, scientific researchers, and academics for an in-depth and insightful discussion, with an audience of around 150.

SPECIFIC ADVICE TO THE DPRC ON EDTs (AUTONOMY, QUANTUM AND WEAK TECHNOLOGY SIGNALS)

EDT IMPLEMENTATION STRATEGY – DPRC TASKINGS

In March 2021, DPRC assigned several significant pieces of work to the STO. These included a review of the research conducted in the field of autonomous technologies and quantum technologies, a "technology watch" report identifying technological weak signals, and a contribution to an S&T red picture detailing the S&T developments in adversary and competitor states. The latter two tasks were the most considerable, prompting the Office of the Chief Scientist to collaborate with a range of partners, including experts in the nations, academia, and NCIA. The reports produced in response to these taskings materially contribute to NATO's broader understanding of the EDT landscape, pointing to early S&T trends, the state and rate of innovation beyond the Alliance, and the advances already made by the STO in its research on quantum and autonomous technologies. Moreover, the efforts made in response to these taskings will serve as the foundations for institutionalized capabilities within NATO for S&T forecasting and S&T intelligence. The key findings of each of these reports will be integrated into a final report delivered to the DPRC in early 2022. In addition, the STO is supporting the delivery of a series of workshops on biotechnology, which will socialize a NATO audience to the latest scientific and technological developments in this field.

NATO 2030

S&T organization

NATO 2030 is the vision of an alliance stronger together and fit for the future, the mission that represents the commitment of leaders to help shape NATO, and the reaffirmation of the common purpose of collaboration inherent in the Alliance and all its Partners.

This vision has triggered a mission agenda that aims to strengthen and prepare NATO for future challenges. This mission agenda is identified in nine proposals of interest around: deeper political consultation and coordination; strengthened deterrence and defence; improved resilience; preserving our technological edge; upholding the rules-based international order; boosting training and capacity building; combating and adapting to climate change; the next strategic concept; and investing in NATO. The STO has taken action on several of the agenda's proposals, developing NATO's Allies and Partners network and stressing the importance and sustaining the technological edge accelerating the adoption of EDTs.

CMRE INITIATIVES (HN-NREP21)

Climate change and its security implications are of growing importance to NATO Nations. The Centre for Maritime Research and Experimentation (CMRE), NATO's only research laboratory, has an impressive history of climate and oceanographic research. As a result, CMRE is exceptionally well-positioned to support NATO 2030, building on world-class research capabilities and pioneering studies conducted in the Arctic and Mediterranean regions.

The changing geopolitical landscape has led to CMRE renewing its focus on the Arctic. This region is also suffering rapid and profound transformations due to climate change and global warming. Responding to these changes and building on its multi-decadal expertise, in 2021 the CMRE successfully implemented an Arctic Science and Technology Strategy, a document designed to reshape our understanding of the future security space in the Euro-Atlantic zone, and in the Arctic region in particular.

CMRE is highlighting its role as the NATO research "hub" capable of collecting, quality checking, analyzing, and sharing climate and oceanographic data to better understand climate dynamics and their effects on security. In 2021, CMRE conducted sea trials and the deployment of two deep-water moorings, instrumented chains capable of collecting temperature, salinity, current velocity and acoustic data.

The preliminary results have significantly added to our understanding of the acoustic environment in the Arctic region. Massive amounts of warm

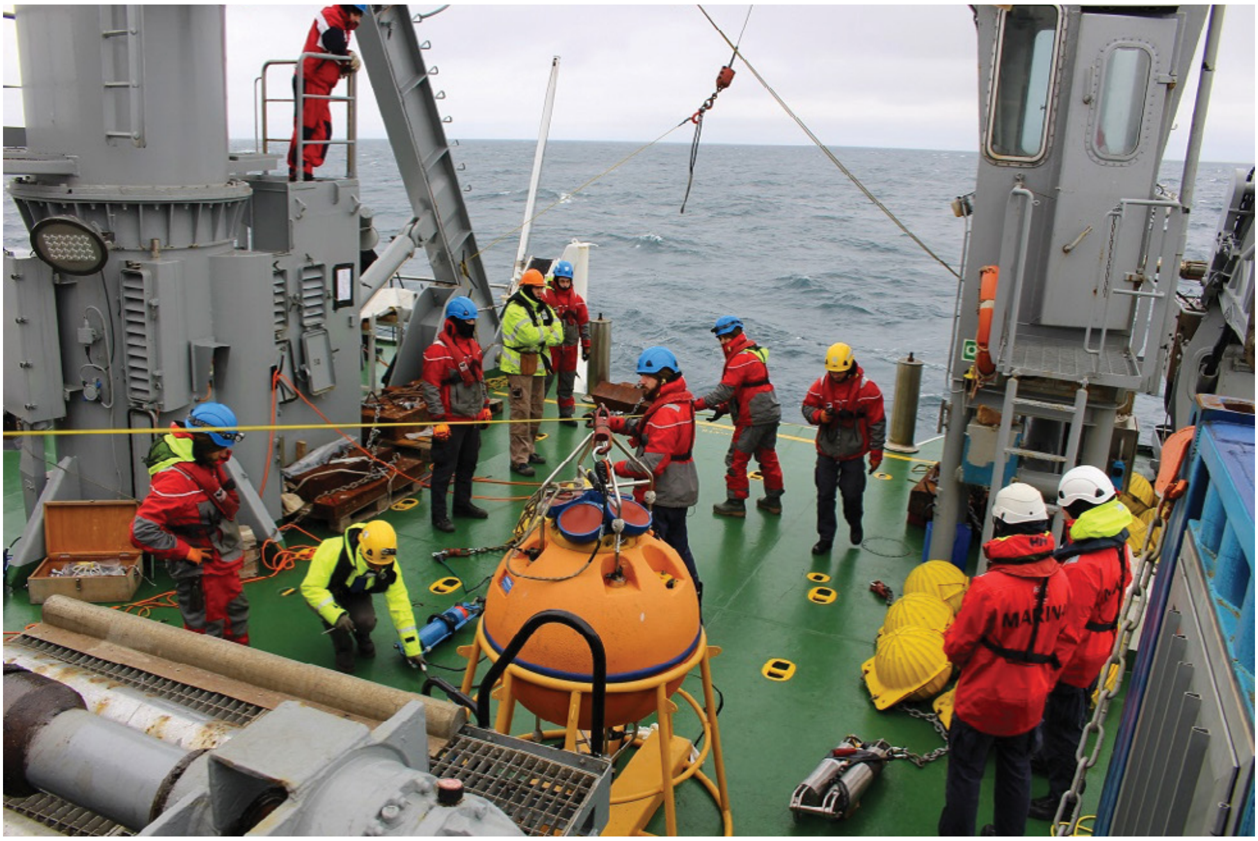

Figure 8: Deployment of a CMRE oceanographic mooring from the deck of NRV Alliance during NREP 21 campaign.

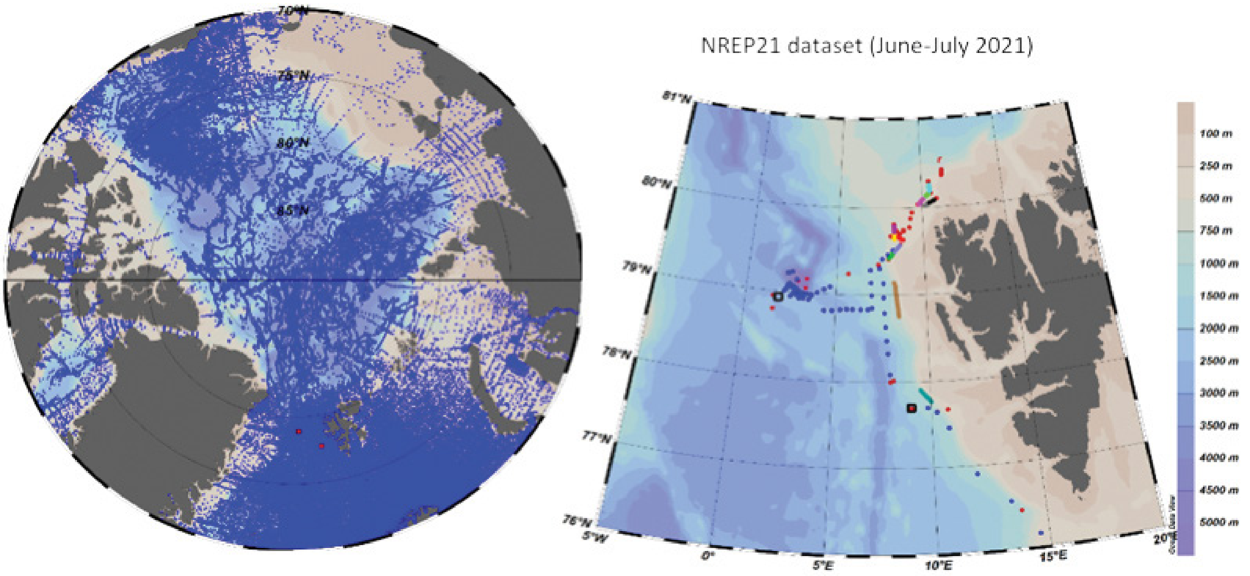

Figure 9: Oceanographic data collection from NRV Alliance in June 2021, off the Coast of Svalbard Island, during the NREP-21 Sea Trial. Red (blue) dots correspond to (conductivity-Temperature-Depth (CTDs) casts. Solid lines represent the Underwater-CTD trajectories. Black squares indicate mooring locations.

freshwater discharged by melting ice sheets has profoundly changed the character of Arctic water masses and, together with them, our traditional views on their dynamics and sound-velocity. This climate evolution, in turn, suggests a significant impact on Anti-Submarine Warfare operations in the Arctic and North Atlantic. Analysis of NREP21 data will be combined with historical ones.

As NATO moves forward to address climate and security challenges, CMRE is extending its current capacity, expertise, S&T network and capabilities. CMRE seeks to evolve to serve as a central body for NATO research in maritime environmental change, embedding new dedicated scientific programmes and producing tailored analyses essential to the operational success of the Alliance.

STO PARTNERSHIP EVENT

The STO looks back on a longstanding tradition of engaging Partner Nations in its Programme of Work and in the deliberations of the STB. After the pandemic had temporarily limited opportunities for these vital collaborations, the STO set up a dedicated outreach event to re-energize its partnerships, which are, and will continue to be, vital for the way the STO works.

In November 2021, the STO held its first Partnership Event at NATO HQ in Brussels. Aimed at Partner Nations' most senior political and military representatives to NATO, the programme provided an overview of STO activities, particularly emphasizing the mutual benefits for Partners and Allies alike.

In his opening address, the Deputy Secretary-General, Mircea Geoană, highlighted the particular relevance of international collaboration among Allies and Partners in NATO Science & Technology (S&T), emphasizing how they are working together on key technologies for our common defence and security.

Traditionally, the STO's outreach to Partners supported NATO's objectives of establishing and strengthening relations. Partnerships therefore focused on building defence capacity, and even more so on developing military capabilities and enhancing their interoperability. The NATO 2030 initiative pushes for maintaining NATO's technological edge and for expanding NATO's partnerships, and thus highlights a new challenge for S&T collaboration: setting international norms for emerging technologies. Building on NATO's values of democracy, individual liberty, the rule of law, and human rights, such norms should be developed and implemented together with likeminded international Partners.

As the NATO forum at the intersection of S&T and partnerships, the STO is well-positioned to support this ambitious agenda.

In addition to the Deputy Secretary-General, the event included a Partner's perspective from the Director-General of the Swedish Defence Research Agency (FOI) , complemented by presentations from the Director of the STO Collaboration Support Office (CSO) in Paris, the Director of the STO Centre for Maritime Research and Experimentation (CMRE) in La Spezia, and the Office of the Chief Scientist in Brussels. The

Director for Security Policy and Partnerships from the Political Affairs and Security Policy Division of the NATO HQ International Staff provided an overview of the wider NATO Partnership structure.

ACCELERATING THE ADOPTION OF EDTs

Emerging technologies are changing the nature of peace, crisis, and conflict. NATO Allies can no longer take their technological edge for granted. In recent years, NATO has stepped up its work on emerging and disruptive technologies, which includes adopting an implementation strategy to ensure NATO's edge in seven key disruptive technologies (artificial intelligence, data and computing, autonomy, quantum-enabled technologies, biotechnology, hypersonic technology, and space). The STO continues its research, technology development and analysis in support of this objective (see Figure 10), while at the same time exploring new directions in S&T, which may enable the EDTs of the future.

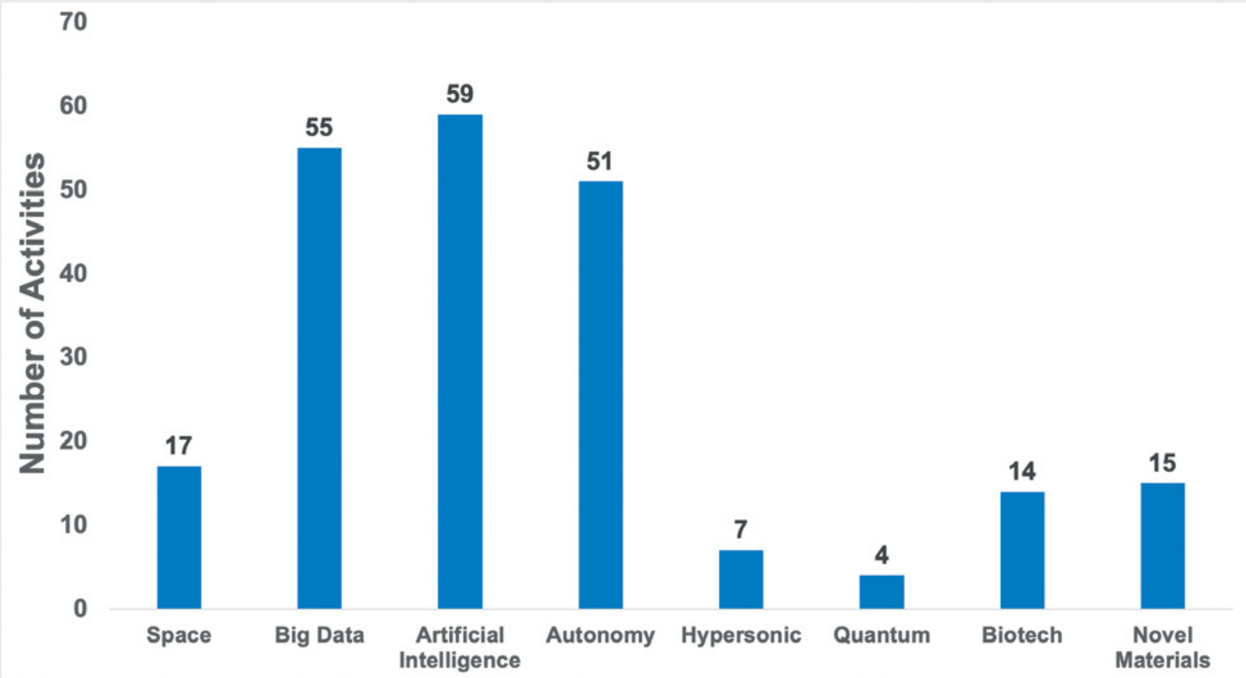

Figure 10: Alignment of EDTs with STO CPoW and STO CMRE PoW Activities as for 2021. [Please note that an STO PoW Activity can be aligned to more than one EDT (in particular for Big Data, AI and Autonomy)].

PROGRAMMES IN ACTION

Throughout 2021, NATO Allies reinforced their determination to preserve NATO's technological edge by supporting the development of Emerging Disruptive Technologies (EDTs), and to ensure Alliance interoperability, in order to maintain the credibility of NATO's deterrence and defence posture.

In addition, they also agreed to aim for NATO to become the leading international organization when it comes to understanding and adapting to the impact of climate change on security. An Action Plan was endorsed to implement the NATO Agenda on Climate Change and Security. STO has been particularly active in exploring how it can support the following areas: Cognitive Domain, Quantum Technologies, Space Technologies and Climate Change.

COGNITIVE DOMAIN

The Cognitive Domain is a new space of competition, beyond the land, maritime, air, cybernetic and space domains. Warfare in the cognitive domain mobilizes a different and wide range of strategies, tools, and techniques. It seeks to optimize human cognitive abilities to achieve advantage over a situation or adversary.

The STO is fully engaged in this research area through the STO Panels and Group to better understand the S&T aspects of this warfare, and to contribute to developing countermeasures to protect targeted individuals and groups of people. As an example, the Human Factors and Medicine (HFM) Panel and the Information Systems Technology (IST) Panel are currently conducting several activities on the subject, such as 'HFM-311 on Cognitive Neuro-enhancement Techniques and Technology' and 'IST-177 on Social Media Exploitation for Operations in the Informational Environment.'

QUANTUM TECHNOLOGIES

Next generation quantum technologies exploit quantum physics and associated phenomena at the atomic and sub-atomic scale, including quantum entanglement and superposition. These effects support significant technological advancements primarily in cryptography, computation, precision navigation and timing, sensing and imaging, communications, and materials.

The STO has supported quantum technologies in the past (SCI-058; SET-137) and particularly with the 2018 Von Kàrmàn Horizon Scanning on Quantum Capabilities for Sensing and Communication. The CPoW is currently engaged in this technology through the Systems Analysis and Studies (SAS) Panel activity (SAS-159) on 'How could Technology Development Transform the Future of Operational Environment.' In addition, the Sensors and Electronics Technology (SET) Panel is planning to conduct an activity (SET-264) on 'Quantum Position Navigation and Timing for NATO platforms.'

In the maritime domain, CMRE investigated Quantum Technology in projects funded by the ACT PoW. In the ASW context, capabilities of quantum technology magnetic sensors are being investigated, and a roadmap defining the integration of sensors in autonomous underwater systems and networks is in preparation. Quantum security and post-quantum cryptography are explored within the thematic area of underwater communication and network.

SPACE TECHNOLOGIES

In December 2019, the Heads of State and Government declared space as an operational domain for NATO. They recognized its importance alongside air, land, sea, and cyberspace domains, with the objective to keep the Alliance safe and to tackle security challenges while also upholding international law.

The STO is responding to these developments by creating a multi-year strategy for S&T development and conducting a comprehensive review of its Space S&T activities. In addition, the STO initiated a research activity for a proposed 3-ball NATO Collaborative S&T satellite constellation (12 - 27U) owned by the Nations as a testbed for collaborative S&T and experimentation for low-earth orbit (LEO), with a proposed launch date in 2024. The project is currently in the detailed project planning and systems engineering phase.

CMRE uses combination of space-based sensor technologies (e.g., Satellite Automatic Identification System (S-AIS), Synthetic Aperture Radar (SAR), Multi- and Hyper-spectral) with machine learning and artificial intelligence techniques, to improve global maritime surveillance capability. Among other satellite observations, Sea Surface Temperature (SST), sea-ice coverage and altimetry signals are used to improve the understanding of the oceans and to design proper algorithms for data assimilation, thus bridging the gap towards a "digital ocean" concept.

CLIMATE CHANGE

Climate change is a truly global problem, and its understanding and potential solutions go beyond the capabilities of a single nation. Consequently, climate change and its impact has become an increasingly important issue for NATO, resulting in a dedicated NATO Task force on Climate Change & Security.

The oceans are the largest components of the Earth's system that stabilize climate and support life, and it is therefore essential that NATO and the Allies understand the effects that climate change will have on our water masses, as well as the associated civilian and military threats and opportunities. As an example, in 2020 CMRE—with support from Allied Command Transformation—drafted its Arctic Science and Technology Strategy 2021–2030, with the aim of identifying aspects of environmental transformations already happening in the Arctic region and anticipating their impact on operations by NATO forces. This strategy provided the guiding principles for several 2021 activities at the CMRE.

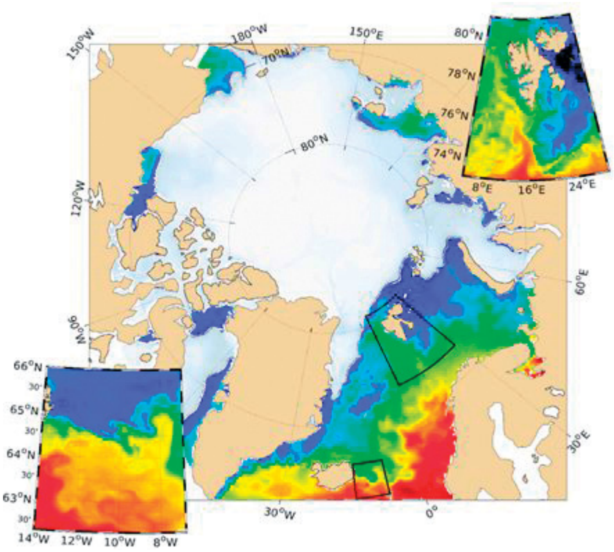

Figure 11: Summer sea surface temperature (colour) and sea-ice coverage as estimated by the ocean model used at CMRE. Note the two areas where high-resolution numerical models have been nested within the large-scale North Atlantic model.

During 2021, a high-visibility workshop on the thawing Arctic ice was held at CMRE, attended by more than 100 participants. As a follow up, a Letter of Intent was shared among about 25 institutions, providing a firm basis for common activities in the Arctic region starting from 2022. To understand climate dynamics better, NATO needs capabilities to exploit environmental data at appropriate spatial and temporal resolutions, and CMRE is well-positioned to act as a hub capable of collecting, quality-checking, analyzing and sharing them. As a fundamental step in this direction, CMRE established the backbone of a permanent Arctic observatory during the Sea Trial Nordic Recognized Environmental Picture 21 (NREP 21) Arctic Campaign in the Fram Strait, to be maintained and enhanced in the coming years. This observatory consists of two deep-water moorings, instrumented chains capable of collecting data on temperature, salinity and current velocity. The data recently acquired in the Arctic region demonstrate that historical observations are now largely irrelevant for future operations. CMRE researchers and engineers are also looking at innovative ways for oceanographic data collection, an example being new small 'swarm' drifter technologies, and for injections of the large amount of collected data into state-of-the-art ocean numerical models. Coupled sea-ice ocean models, indeed, are a powerful tool in support of both short-range forecast for naval operations and scenario estimates in the Arctic region for long-term strategies development as well (see Figure 11).

CMRE is therefore extremely well-positioned to extend its capacity, expertise and capabilities and become the central body for NATO research into maritime environmental change.

NATO STO PROGRAMME OF WORK

NATO STO Programme of Work

INNOVATION FOR THE ALLIANCE

EFFECT OF ENVIRONMENTAL REGULATION ON ENERGETIC SYSTEMS AND THE MANAGEMENT OF CRITICAL MATERIALS AND CAPABILITY (AVT-293)

AVT-RTG-293 examined present and planned regulations to assess their impact on energetic systems for example through the EU REACH programme. It had become clear that the availability of energetic materials and related components was being affected by changes in environmental legislation and those effects across NATO needed to be understood. Active research options and programmes were reviewed to determine if they provide options for compliance. The Group also attempted to identify critical materials and to define routes for providing equivalent capability. Different national approaches were discussed, and the strengths and weaknesses assessed.

Hon. Prof. Adam CUMMING, GBR, University of Edinburgh

BACKGROUND AND MILITARY RELEVANCE

Energetic materials are a critical part of most munitions. They provide the impetus through gun and rocket propellants; the terminal effect through explosives, as well as a whole range of ignition and screening/signaling effects through pyrotechnic systems. Each of these applications contains a range of chemicals from the explosive molecules to binder and trace materials needed for effective and consistent operations. Changes in legislation are beginning to affect the availability of many of these materials, which because of their nature, can often be bioactive to such a degree as to now make them unacceptable for use. It is important to understand these risks and to plan for replacement where possible. This can become critical for military operations.

OBJECTIVE(S)

AVT-RTG-293 aimed to:

- Review regulations and future developments
- Identify short-term critical materials for immediate action
- Assess existing research activities for options for compliance with planned regulation
- Examine critically the data to satisfy regulations
- Propose research activities to cover gaps including possible further activities

S&T ACHIEVEMENTS

The RTG has identified areas of concern. They have also identified where there is a lack of understanding of the issues and little preparation for dealing with them. The Group did, however, begin to identify and list where action is being taken, and to identify many of the questions that will require answering. This should ensure that there is the possibility of avoiding critical shortages in energetic materials with its impact on capability. The action of the group has begun the development of an expert group for future NATO support.

> *Supplier capacity and capability. As a critical success factor, this is whether potential suppliers can and will deliver the requirements. Of course, ensuring supply chains are resilient and productive and that critical suppliers can continue to deliver is important more generally, and the extent to which the options may contribute to maintaining or increasing these aspects may be relevant to consider under the 'strategic fit' factor.*
>
> ***Defence and Security Industrial Strategy: A strategic approach to the UK's defence and security industrial sectors. March 2021***

SYNERGIES AND COMPLEMENTARITIES

The Group worked with other AVT activities, specifically AVT-243, and has links with AVT-311 on the availability of components for missile systems. Together they will provide a broader understanding of the issues. Links were developed with Munitions Safety Information Analysis Center (MSIAC). Their role on munition safety is relevant, as changes in the components may adversely effect safety and reliability. MSIAC are directly linked to the NATO Ammunition Safety Group. Some members of the Group were involved in the European Defence Agency (EDA) Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Group, which ensured that there was awareness of activities and developing policies outside NATO.

EXPLOITATION AND IMPACT

The final report is in preparation, covering the impact on NATO Capability with suggested remedial actions. The output of the Group will assist in the provision of accessible NATO expertise to assess current and future problems as well as devising priority actions. This will be developed through a Workshop in 2022.

CONCLUSIONS

Despite problems in obtaining information specifically related to particular IPR issues or military capability, the RTG has begun the process of ensuring that NATO has a robust awareness of likely problems and opportunities for the future. Those areas where there was little awareness have been identified and there is the possibility of education. Differences in policies have been seen and the overlaps between the USA, EU and elsewhere have been partially identified, though this is likely to be a moving target. This emphasizes the need to remain technically aware and updated.

APPLYING NEUROSCIENCE TO PERFORMANCE: FROM REHABILITATION TO HUMAN COGNITIVE AUGMENTATION (HFM -334)

Neuroscience is the study of the fundamental and emergent properties of neurons and neural circuits and the manner by which they relate to the biological basis of learning, memory, behaviour, perception, and consciousness. Applied neuroscience can be of vital importance in various contexts: in health, well-being, and training and in human performance. The concept of brain plasticity may help the armed forces to develop optimal personnel selection, training and clinical recovery through a systematic and integrated scientific approach, as well as optimally adjusting to the maturing brain of defence personnel.

Maj. Dr. Giorgio FANELLI, ITA, Military Psychiatry and Psychology Office Italian Army General Staff

BACKGROUND

The nervous system is a very complex part of the human body that coordinates actions and sensory information by transmitting signals to and from the brain at the periphery. The nervous system detects environmental changes that affect the body, and then works in tandem with the endocrine system to respond to such events, to such environmental stresses. Science has made significant progress in understanding how the brain works, but much still needs to be done.

Previous and ongoing STO activities have identified the importance of neuroscience in supporting Defence and security personnel when dealing with mental challenges. Such challenges include mental and emotional fatigue, cognitive workload, and stress. It is also recognized that the application of the principles and methods from neuroscience can provide opportunities to maintain, or increase, the well-being and efficiency of personnel.

MILITARY RELEVANCE

War is perhaps one of the most challenging situations that an individual can experience, and the challenges are exacerbated by the multi-faceted, changeable, and ambiguous contemporary operating space.

Neuroscientific knowledge and applications can benefit defence personnel through the operational cycle, of selection and training, during military operations, and in the aftermath, keeping defence personnel healthy and well, during and after service. Resilience to, or training to cope with stress, fatigue, and cognitive workload are of critical importance when operating in such complex environments, since they can impede performance and operational effectiveness, and can lead to major psychological disorders, including Post-Traumatic Stress Disorder (PTSD), anxiety, and depression. Similar challenges exist for other non-fighting military personnel such as first responders, police, firefighters, nuclear power plant workers, transport safety operatives, ISR operatives and maintenance crew. As such, in order to enhance the soldier performance and well-being, there is a fundamental need to understand the impact of stress, fatigue, and cognitive workload. Tools from neuroscience and neuro-technologies provide us with an unprecedented opportunity to study, characterize and even mitigate the negative effects of the above stressors to improve soldier performance.

OBJECTIVE(S)

This Symposium aimed to summarize the latest research activities on applied neuroscience in order to evaluate the advantages, challenges and ways of using neuroscience in general and neurotechnology in particular in the military context. The symposium was also essential to reactivate the network of collaboration and study within NATO while verifying a hybrid conduct methodology both in presence and remotely.

Neuroscientific knowledge and applications can benefit defence personnel through the whole operational cycle.

S&T ACHIEVEMENTS

The NATO Symposium on “Applying Neuroscience to Performance: from Rehabilitation to Human Cognitive Augmentation” was conducted in Rome, Italy on 11-12 October 2021 as we said in a hybrid modality. Nineteen papers were selected and submitted for presentation; ten presentations were delivered in person and 12 remotely. Three keynote presentations were given, at the beginning of the first day. In particular, Dr. Du Cluzel De Remaurin examined the construct of cognitive warfare “neuro-weapons” as one of tomorrow’s battlefields; Prof. Merzenich examined brain plasticity with a developmental perspective; finally, Prof. James Giordano, spoke about Neuroethics, and the risk associated with the use of brain sciences.

SYNERGIES AND COMPLEMENTARITIES

Nations/organizations joined this activity were all NATO Nations, NATO Bodies, Enhanced Opportunity Partner (EOP), Istanbul Cooperation Initiative (ICI), Mediterranean Dialogue (MD), Partnership for Peace (PfP), Contact Countries, in accordance with Public Releasable level. Contributions from military operations and industry communities were welcome. There was also an important and productive synergy with H FM-311 and HFM-AVT-340.

EXPLOITATION AND IMPACT

The outcomes of the Symposium will address applying neuroscience and neuroscience technology in Defence and Security personnel, and other professionals who have to perform in complex, challenging environments.

The symposium influenced, in particular, the following four themes:

- Optimizing Personnel Selection and Training
- Enhancing Operational Performance
- Applied Neuroscience in Health and Well-being
- Enabling Technology and Methods

CONCLUSION(S)

In order to enhance the soldier performance and well-being, there is a fundamental need to understand the impact of stress, fatigue, and cognitive workload. Tools from neuroscience and neuro-technologies provided us an unprecedented opportunity to study, characterize and even mitigate the negative effects of the above stressors to improve soldier performance.

The concept of brain plasticity may help the armed forces to develop optimal personnel selection, training and clinical recovery through a systematic and integrated scientific approach, as well as optimally adjusting to the maturing brain of defence personnel.

The topics presented in this Symposium clearly demonstrate that outstanding recent work has been conducted in the field of neuroscience, which holds a great potential for application in the military field. The lectures covered the possible use of neuroscientific tools such as non-invasive stimulation techniques, biofeedback techniques, physiological assessment, Brain-Computer Interface, Virtual and Extended Reality, genetics, hyper-scanning, wearables, and interception enhancers for the screening, assessment, health

Figure 12: HFM-334 Symposium Participants.

promotion and prevention, and treatment for mental disease also. The Symposium testified that outstanding neuroscientific research is being performed of potentially relevant use for improving military personnel's performance on one hand and promoting military personnel's psychological well-being on the other. The importance of neuroscientific research in the military field is now a fact, also thanks to a wide range of experimental empirical research. As suggested by Professor Giordano on the discourse relating to neuroethics, "it will be important to ask oneself the right limits and the right questions before proceeding in unprecedented situations and with no return."

This science, and these new strategies for assessing and improving human performance abilities, could be transformational for military personnel and for mission fulfillment. It is important that this science perspective is taken seriously and exploited on the path for sharply improving both the health and the performance abilities of our mutually protecting armed forces.

M&S OF EFFECTS OF CYBER ATTACKS (MSG-ST-188)

ST-188 assessed the feasibility of producing a High Level Architecture (HLA) Federation Object Model (FOM) module for representing cyber entities, attacks, and effects to enable cyber training within NATO Mission Training through Distributed Simulation (MTDS). Member Nations demonstrated the application of the draft Simulation Interoperability Standards Organization (SISO) Cyber Data Exchange Model (DEM) as an enabler of the HLA Cyber FOM module. The 3-year follow-on task proposed by ST-188, MSG-200, has been approved and will commence in January 2022.

Dr. Bert BOLTJES, NLD, Toegepast Natuurwetenschappelijk Onderzoek (TNO); Mr. Dennis GRANÅSEN, SWE, Swedish Defence Research Agency (FOI); Dr. Katherine L. MORSE, USA, Test Resource Management Center (TRMC); The Johns Hopkins University Applied Laboratory (JHU/APL)

BACKGROUND

With the increasing focus on hybrid warfare and the battlefield reaching out into information space, many NATO members and partners have increased their funding to develop cyber capabilities. Natrually, also simulation and training of cyber capabilities have gained attention, yet many such venturs are performed in isolation. Since the cyber and kinetic battlefields are becoming increasingly entagled, ST-188 took the stance the training and simulation environment should reflect that, hence the need for the interoperable cyber simulations. Except with specially designed ad hoc interfaces, most exisiting simulation systems are unable to exchange information about a cyberattack and their impact on affected systems because there is no standard for the exchange of simulation data in the cyber domain. As such, standards for data models need to be developed to integrate and re-use cyber simulations.

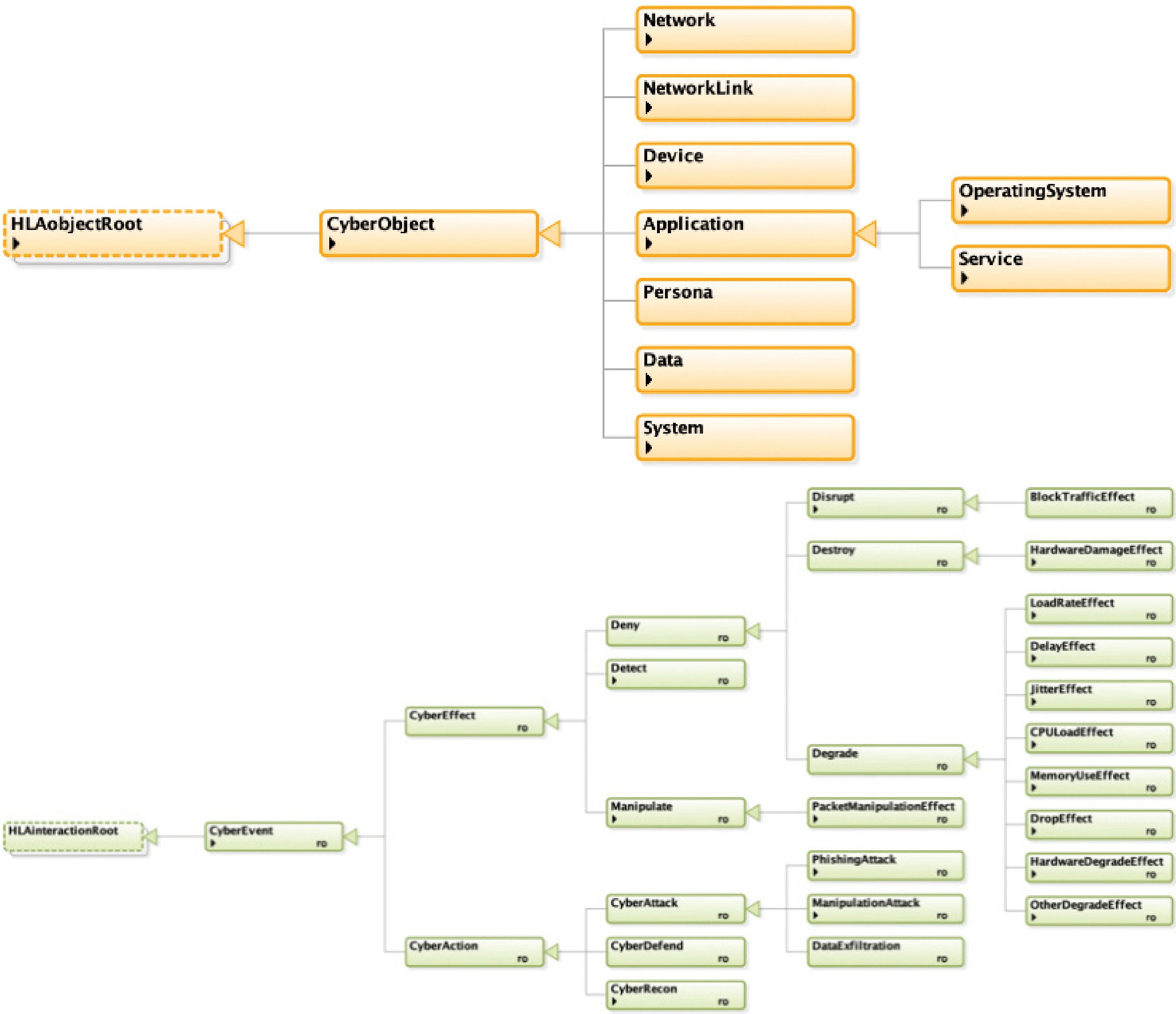

Figure 13: Draft of the Cyber DEM. At the top are the entities, on the bottom their possible interactions.

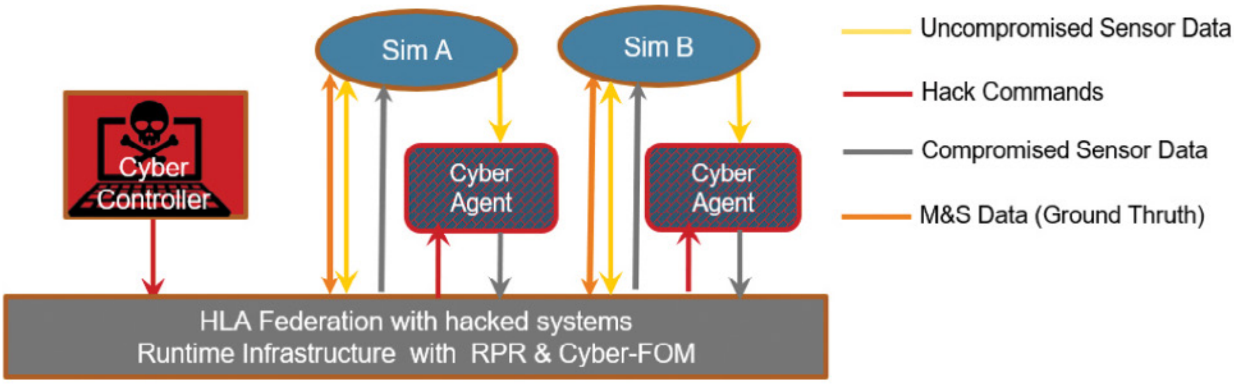

Figure 14: Basic architecture with cyber building blocks to introduce cyber effects into MTDS. Through the web-based Cyber Controller, the trainer gives commands to the Cyber Agents to manipulate sensor data.

MILITARY RELEVANCE

Cyber attacks are already a reality in contemporary conflicts and can be force multipliers for adversaries with little investment or risk. For cyber operation-related decisions to be relevant at the tactical, operational, and joint staff levels, their effects need to have an impact into current kinetic operations.

OBJECTIVE(S)

The main objectives of ST-188 were to:

a) collect requirements for a NATO Cyber HLA Cyber FOM module and test an initial, experimental version of such a module;

b) deliver initial implementation of the HLA Cyber FOM module, gateways, and tools to introduce effects of cyber events in NATO MTDS; and

c) deliver a concise technical report and a Technical Activity Proposal (TAP) for a follow-on three-year task group.

S&T ACHIEVEMENTS

ST-188 contributed use cases for the development of the SISO Cyber DEM (see Figure 12), which will produce an HLA Cyber FOM. Figure 2 illustrates a basic architecture with cyber components to introduce cyber effects into MTDS. TNO implemented this architecture as a prototype demonstration of the application of the draft SISO HLA Cyber FOM to training. More details on the use cases and the prototype can be found in report of ST-188.

SYNERGIES AND COMPLEMENTARITIES

Ten nations participated in this research task group. This diverse group contributed to the success of the activity and the high quality of the work. ST-188 also formed a close working relationship with the SISO Cyber DEM PDG.

EXPLOITATION AND IMPACT

A follow-on task group, MSG-200, has been approved to build upon the work of ST-188 including identifying more NATO-relevant use cases and guiding the continued development of the SISO Cyber DEM and a Cyber FOM module, corresponding to identified simulation needs on tactical, strategic and operational levels. The TAP also suggests an investigation of how to introduce effective and credible representations and GUI elements of cyber effects for multidomain MTDS and test environments.

CONCLUSION(S)

ST-188 laid the groundwork for successful development and deployment of an HLA Cyber FOM, which has significant potential to come to fruition under MSG-200. With close cooperation with the SISO Cyber DEM PDG, the results of MSG-200 have the potential to lead to a STANAG, enabling cyber simulation interoperability across NATO and its' partner organizations.

ELECTROMAGNETIC ENVIRONMENT SITUATIONAL AWARENESS (IST-146)

Military radio, Electronic Warfare and Radio Frequency sensor systems operate in a congested and contested electromagnetic environment. Aligned with the NATO Electromagnetic Spectrum Strategy, the IST-146 project was aimed at evaluating the operational benefits of Electromagnetic Environment Situational Awareness (EME-SA) and at evaluating the Radio Environmental Map (REM) technology.

Mr. Yvon LIVRAN, FRA, Thales Secure Communications and Information Systems; Mr. Paul HOWLAND, GBR, Defence Science and Technology Laboratory (DSTL)

BACKGROUND

Electromagnetic Environment Situational Awareness, under the name of Radio Environmental Map, has attracted a lot of attention in the wireless communications and electronic warfare research communities. It can be seen as a field of application for Big Data Analytics to enhance the Spectrum Awareness on the battlefield. The REM consists of a space-time-frequency database and a tool suite that can store and process the relevant information and derive representations of the Electromagnetic (EM) environment for electromagnetic operation situation awareness. The space-time-frequency database consists of information, such as spectrum sensor information, geographical features which characterize the terrain (and therefore the propagation), the available EM assets along with their activities, spectral regulations, locations, and relevant policies etc. EM assets include all emitters and receivers in the battlespace, intentional, unintentional, civil, blue or red.

MILITARY RELEVANCE

Management and access to the Electromagnetic Spectrum (EMS) are critical to achieving information superiority in military operations. The REM provides an enhanced capability to report to the military commander on situational awareness of spectrum in time, space, and frequency. EME-SA is a possible contributor to the NATO Electromagnetic Spectrum Strategy; it is an enabler for Command and Control (C2) of spectrum, dynamic Spectrum Management (SM), Electronic Warfare (EW) support for Common Electronic Order of Battle (C-EOB) and transmitter localization. It facilitates the optimization of spectrum usage in order to improve operational effectiveness by enabling dynamic management, coordination, and synchronization of spectrum usage. Such coordination may encompass several areas of responsibility and as such is critical during NATO coalition operations.

OBJECTIVE(S)

The main objectives of the IST-146 were: a) define a first model of REM and demonstrate the REM feasibility) b) demonstrate the REM benefits for NATO Command, Control, Communications, Computers (C4ISR) operations and systems and c) evaluate the gap between the existing legacy system and the future REM.

S&T ACHIEVEMENTS

The project team conducted studies of EME-SA including a potential architecture, test and simulation and validated its relevance and benefits through scenarios and vignettes and an operational analysis. The operational analysis established the importance of Electromagnetic Spectrum C2 (EMS C2) integrated with other C2 processes and identified key user benefits. The military functions that were addressed included transmitter localization and transmit power estimation, elimination of interference and jamming on the battlefield within and between allied forces, and support for real time establishment of the Electronic Order of Battle. The project proposed to turn the IoT-A reference architecture into a specific architecture for the REM unique to the Electromagnetic Spectrum domain. It defined the interfaces between the layers of the architectural model, the functional blocks within each layer, and decided on which interfaces and functions there will be need for standardization. Proposals for future evolution of the NATO electromagnetic operations and dynamic spectrum management in operations utilizing REM have been developed. The project identified the gaps between legacy system and EME-SA. It proposed an improvement roadmap for the evolution of EMS C2, the support of the battlespace data repository, the evolution of the organization of SM tasks and the evolution of SM Tools.

SYNERGIES AND COMPLEMENTARITIES

The association of research labs and institutes, industry, NATO head quarter representative and operational defence forces, representing 8 countries, has been very fruitful and efficient providing high quality of the work. Advice and orientation from the Spectrum & C3 Infrastructure Branch (SC3IB), ACO SM and the JEWCS have contributed to the success of the project. A presentation of the IST-146 project

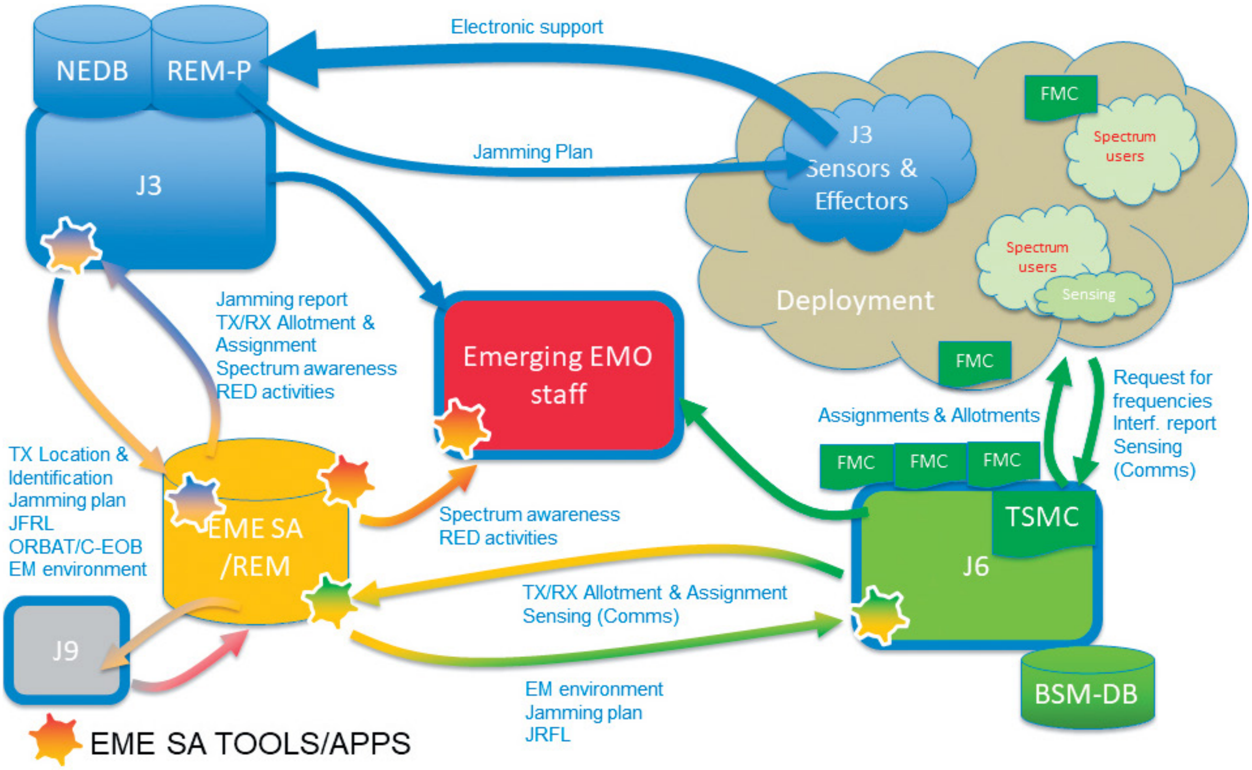

Figure 15: EME-SA/REM recommended integration into the joint command structures.

was delivered during a military session of the Civ/Mil Spectrum Capability Panel 3 (CAP3) meeting and to the NATO Electronic Warfare Working Group (NEWWG).

EXPLOITATION AND IMPACT

The outcomes of the IST-146 is a set of reference material that can be drawn on to mature a REM solution to provide EME-SA capability to support Spectrum operations and Spectrum C2. This capability has potential to provide situational awareness products in the tactical and operational battle space as well as helping streamline and improve the way we manage spectrum at a strategic level. Change in the way we manage spectrum to enable an increase in the tempo of military operations as well as improving the probability of success is essential in modern warfare, this work should make these changes easier to realize.

CONCLUSION(S)

The project establishes the importance of Electromagnetic Spectrum Command and Control integrated with other C2 processes. The description of the data sources, models, and representation have been established. Key user benefits were highlighted and a proposal for possible evolution of electromagnetic operations and spectrum management within NATO were made. A reference architecture based on the Internet of Things (IoT) has been elaborated and the relationships between the REM elements have been validated through the project scenario and vignettes. Tests and simulations, carried out for the construction of measurement-based REMs and transmitter localization were conducted. A proposal for a demonstration, which enables understanding through visualization of an interference situation and de-confliction by dynamically re-assigning frequencies, has been made.

ANALYSIS OF IDENTIFICATION AND NEUTRALIZATION METHODS AND TECHNOLOGIES FOR COUNTERING IMPROVISED EXPLOSIVE DEVICES (C-IED) (SCI-298)

Countering threat of Improvised Explosive Devices is a high priority issue for NATO forces in order to minimize casualties and maintain freedom of movement, since improvised explosive devices and other explosive hazards are and will be deployed by terrorists and insurgents in NATO areas of operation. SCI-289 investigated the performance and efficacy of technologies for IED identification and neutralization. RTG group members characterized performance, discerned trends, and identified areas for future research and investment. The group's efforts resulted in eight recommendations for increased investment and further development, while highlighting the need for increased interoperability, durability, affordability of Counter IED technologies.

Mr. Mark CUMO, USA, Army Combat Capabilities Development Command (DEVCOM)

BACKGROUND

Improvised Explosive Devices (IEDs), conventional landmines, and other explosive hazards pose a danger to NATO, allied forces, and civilian populations. Countering these threats remains a priority issue for NATO forces with objectives to enhance safety and survivability, maintain mobility, and ensure freedom of manoeuvre. Previous NATO Research Task Groups have explored IED detection technology performance with a focus on standoff detection of IEDs in Route Clearance and other operational scenarios. Technologies to identify and neutralize IED threats after a detection were largely considered outside of their respective scope. The SCI-298 RTG was formed in order analyse the performance of technology to increase operational effectiveness during these essential parts of the Counter IED mission. As IED identification and neutralization have been topics of national and international R&D for many years, a current assessment of the state-of-the-art and future foreseen capability of identification and neutralization technology performance was necessary. In addition, recent technological advances makes some technologies, which previously did not perform well enough to be viable, worth another look.

MILITARY RELEVANCE

Improvised Explosive Devices (IEDs) continue to be one of the most dangerous threats to NATO, allied forces, and local populations. As such, countering IEDs remains a priority issue for NATO forces. Previous RTGs have focused on standoff detection of IEDs in Route Clearance and other operational scenarios, whereas SCI-298 RTG investigated the steps that occur after an IED is detected for identification and neutralization.

OBJECTIVE(S)

The objects of this RTG were to analyze the performance and efficacy of technologies for IED identification and neutralization. To accomplish this analysis, SCI-298 group members created an inventory of all conceivable technologies and methods for the identification and neutralization of IEDs, defined of a representative set of threat items, and created a description of relevant scenarios. The members then assessed of the suitability and current and future performance of these technologies and methods for the defined threats and scenarios.

> “*A comprehensive inventory and analysis of IED identification and neutralization technologies will be an essential contribution to NATO and Allied Nations' Counter IED research and development programs. These technologies facilitate the exploitation of IED components that identify key aspects of IED networks and enable follow-on Attack the Network, targeting, and C-IED operations.*
>
> ***COL Juan Gómez Martín (ESP Army)***
> ***Director, NATO Counter IED Centre of Excellence.***

S&T ACHIEVEMENTS

SCI-298 group members used the results from their analysis, in conjunction with their technical expertise and operational experiences, in order to characterize technology performance, discern trends, and identify areas for future research and investment in Counter IED technologies. This resulted in recommendations for increased investment in the following areas: 1) Teleoperation and Tele-Manipulation, 2) Sensor Fusion and Algorithm Development, 3) Smart tools, use of Machine Learning for real-time information and analysis, 4) Nuclear Quadrupole Resonance (NQR), 5) Laser System for Separating IED Components, 6) Identification and Neutralization of Unmanned Aerial Systems and Unmanned Underwater Vehicles, 7) High Power Microwave / Directed Energy and 8) Chemical Neutralization of Explosives and Precursors. NATO and Allied

Nations can use the analysis, results, and recommendations from the SCI-298 RTG when deciding on investments, avoiding technology surprise, and avoiding duplication of effort. Nations will benefit by saving the time and investment required to learn the historical, current, and future anticipated performance of these technologies.

SYNERGIES AND COMPLEMENTARITIES

This task group built on the previous work done by the NATO SCI-233 RTG "Route Clearance Concepts." The SCI-298 RTG had strong participation with 15 people from nine nations. Of those, four members were uniformed military; seven were Ministry of Defense civilian personnel, one from industry, and two from academia. Three NATO Centres of Excellence (CoE) also provided significant support and participation: the Counter IED CoE, Military Engineering CoE, and the Explosive Ordinance Disposal CoE. Each participant added valuable information pertaining to the IED identification and neutralization technologies that are known and/or used in their respective nation. The RTG greatly benefited from civilian and uninformed military members' combined decades of technical and operational experience in Counter IED, assuring that the analysis of IED identification and neutralization technologies and recommendations for future research are relevant and have a strong tie to real-world operations.

EXPLOITATION AND IMPACT

The comprehensive inventory and assessment of current and anticipated technologies can be used by NATO and Partner Nations to identify capability gaps requiring future S&T investment in material, and/or updates to training and doctrine. Nations will be better able to understand and integrate current and future identification and neutralization technologies into route clearance and Explosive Ordinance Disposal (EOD) missions. After additional time and investment, nations will ultimately benefit by having better and more capable IED identification and neutralization technologies for war fighters, developed more quickly and at a reduced cost. These technologies have the potential to reduce the workload for military personnel, while increasing safety and operational effectiveness of countering IEDs

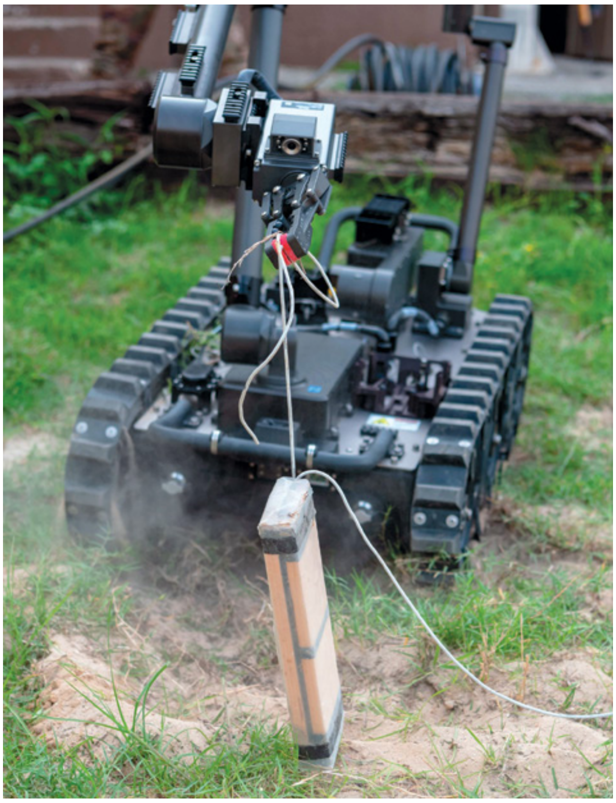

Figure 16: The Man Transportable Robotic System-Increment II, or MTSR II, removes a simulated pressure plate during training at Joint Base San Antonio-Lackland 14 April 2021 (Photo By: Jason Wilkinson).

CONCLUSION(S)

The final technical report addresses, in part, the "C-IED" Long Term Aspect of the Minimum Capability Requirements (LTA MCR), "C-IED technology must make safe/dispose detected IEDs and, where necessary, reduce the impact of detonated IEDs." In this era of great power competition, discussions regarding the threat from IEDs and the development of countermeasures are not as prominent. Nonetheless, countering these threats remains a priority issue for NATO forces. We in the research and development community must keep in mind that IEDs are a global threat and therefore interoperability, cost, and affordability must be considered when developing future technologies for IED identification and neutralization. The EOD community should also become more proactive in specifying requirements and criteria for development of new technical solutions, and at the same time, the research community should strive to reduce costs to ensure that solutions can be used worldwide. In addition, resources should be dedicated to prolong life cycles and reduce maintenance of existing equipment. Finally, information sharing and interoperability should be key policy considerations.

ASSESSING AND MODELLING THE PERFORMANCE OF DIGITAL NIGHT VISION IMAGE FUSION (SET-217)

NVG optically fused to thermal imagers are currently fielded. Future development will see the NVG replaced by focal plane arrays. This allows digital fusion including advanced signal processing and fusion algorithms. Performance assessment of such devices is mandatory but still lacking. SET-217 did such performance assessment and tried to derive general rules and methods from the results.

Mr. Uwe ADOMEIT, DEU, Fraunhofer Institute of Optronics, System Technologies and Image Exploitation (IOSB); Dr. David BERGSTRÖM , SWE, Swedish Defence Research Agency (FOI); Mr. Christopher Brook JACKSON, GBR, 4Sight Imaging; Mr. Stéphane LANDEAU, FRA, Direction Générale de l'armement (DGA); Dr. Ian PEDLAR, GBR, Defence Science and Technology Laboratory (DSTL); Dr. Vladimir PETROVIC, GBR, 4Sight Imaging; Dr. Joe REYNOLDS, USA, Army Combat Capabilities Development Command (CCDC); Dr. Simon ROY, CAN, Defence Research and Development Canada (DRDC); Mr. Greggory SWIATHY, FRA, Direction Générale de l'armement (DGA)

BACKGROUND

Thermal and low light imagers are essential for military operations at night. Both technologies possess complementing advantages and disadvantages. Combining them is obvious. Current state-of-the-art is optical fusion. Expected replacement of image intensifiers by focal plane technologies has improvement potential, e.g., by using sophisticated fusion algorithms and image enhancement.

OBJECTIVE(S)

SET-217 intended to develop and provide common tools, methods and metrics for assessment of image fusion systems. As image fusion for military applications is a large area, the focus lay on fusing reflective and emissive bands, night vision applications, rural and urban scenarios and a limited number of algorithms.

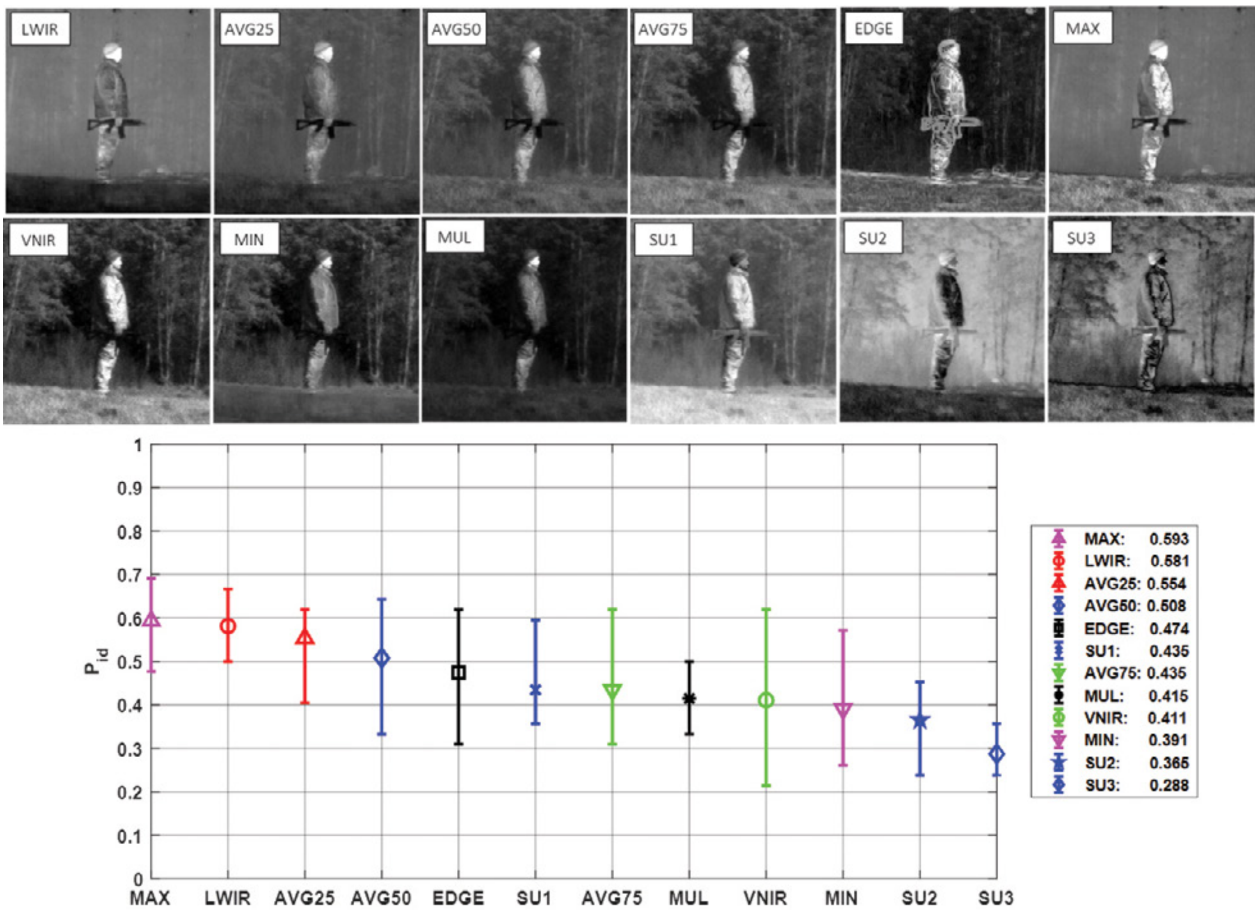

Figure 17: Imagery and results of a perception experiment for identification of weapons.

S&T ACHIEVEMENTS

Analyzing visual/thermal image fusion performance for detection and identification tasks proofed the advantage of the thermal for the detection task. This advantage transfers in the fused imagery when using a suitable algorithm. Unexpectedly, the same showed up for the identification task. Finally, the fusion can decrease, but not improve the performance over that of the single band.

Concepts for laboratory assessment and performance modelling achieved concept demonstration but not yet an optimum implementation. Work on video quality assessment showed a much better correlation between the introduced enhanced Video Quality Assessment scores and task probability than the ones found for classic methods.

SYNERGIES AND COMPLEMENTARITIES

Assessing image fusion is a large topic. Combining capabilities and knowledge of different agencies allows larger coverage within the same time span, giving a broader picture then possible for a single nation.

EXPLOITATION AND IMPACT

For the first time, the group proved the added thermal detection possibility scientifically. Beyond this, it showed that the thermal could add more than just detection performance. The assessments also gave today's red/green colour overlay as one of the best fusion methods and that simple fusion algorithms up to pyramid fusion are not necessarily an improvement. Development of next generation fusion devices will benefit from these findings.

CONCLUSION(S)

The strong scene and task dependency of image fusion prevented deriving a general valid assessment procedure. Including the results of former groups, it seems questionable if this will be possible at all. Further research is necessary.

The need of the visual band for situational awareness is obvious, but impossible to prove using classical approaches. Procedures and quality parameters to assess imaging systems against situational awareness should be developed.

ENHANCED AND ENRICHED RADAR IMAGING VIA MULTI-DIMENSIONAL RADAR SYSTEMS (SET-250)

Multi-dimensional radar imaging aims at exploiting all possible degrees of freedom that are offered by radar systems in order to provide radar images that can more accurately and robustly support automatic target recognition and, therefore, to enhance Intelligence, Surveillance and Reconnaissance (ISR) systems.

Prof. Marco MARTORELLA, ITA, University of Pisa and National Interuniversity Consortium for Telecommunications, National Radar and Surveillance Systems Laboratory

BACKGROUND

Synthetic-aperture radar (SAR), Inverse synthetic aperture radar (ISAR) images have been largely used for target recognition/identification. Nevertheless, limitations produced by traditional radar imaging systems reflect on limited performances in terms of target recognition. Multi-dimensional radar imaging systems offer the path to enriching the image information content and consequently make aided target recognition (ATR) systems more accurate and robust.

MILITARY RELEVANCE

Radar is the go-to sensor for all weather, day/night long range imaging and, therefore, to enable ATR. By improving the ability to make rapid and correct target identification, military resources can be more effectively allocated and best courses of action taken. Enhanced aided target recognition will be achieved by making use of multi-dimensional radar observations.

OBJECTIVE(S)

The broad objective of this team has been to investigate the use of multi-dimensional radar to form multi-perspective, multi-frequency, polarimetric, high-resolution 2D and 3D radar images of targets, with the scope of enhancing target classification and recognition.

S&T ACHIEVEMENTS

SET-250 has reached the following goals: 1) Development of new radar imaging algorithms based on multi-dimensional radar data that improve the system performances and introduce new imaging modes; 2) Planning and execution of large trials (Spadeadam) to collect unique multi-dimensional radar data of military targets; 3) Demonstration of the superiority of multi-dimensional radar images in terms of target detectability and recognition

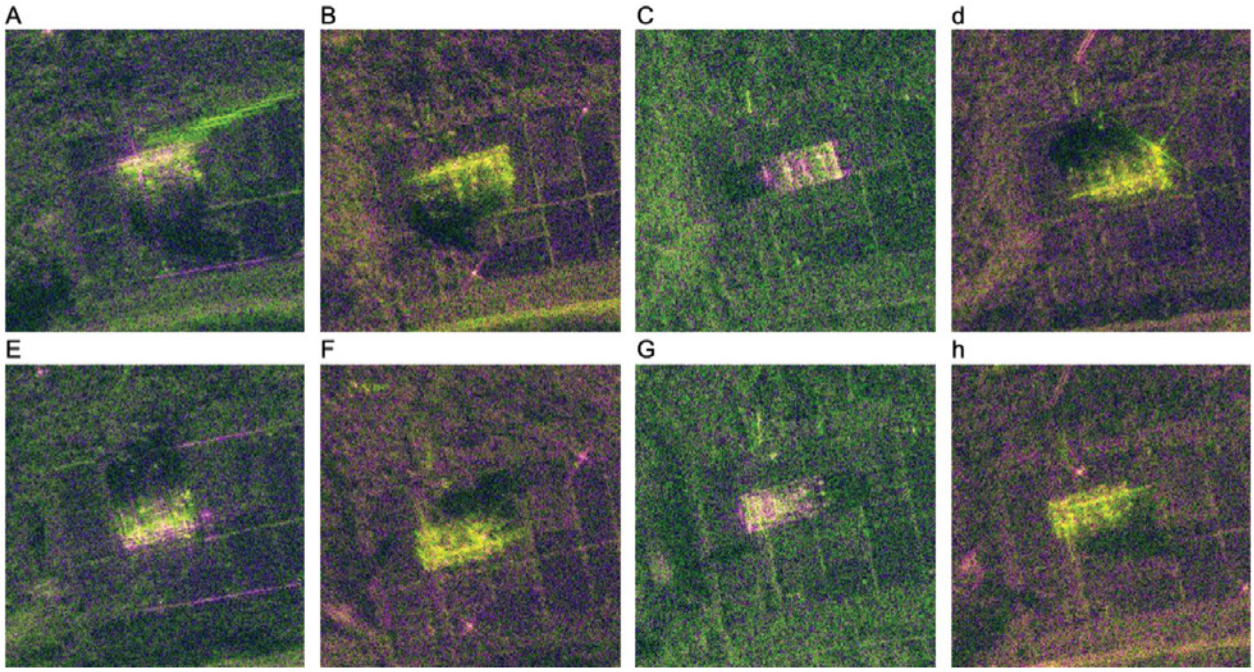

Figure 18: Multi-aspect and polarimetric radar images of a target – the information content is enriched greatly with respect to a single-pol, single-aspect radar image.

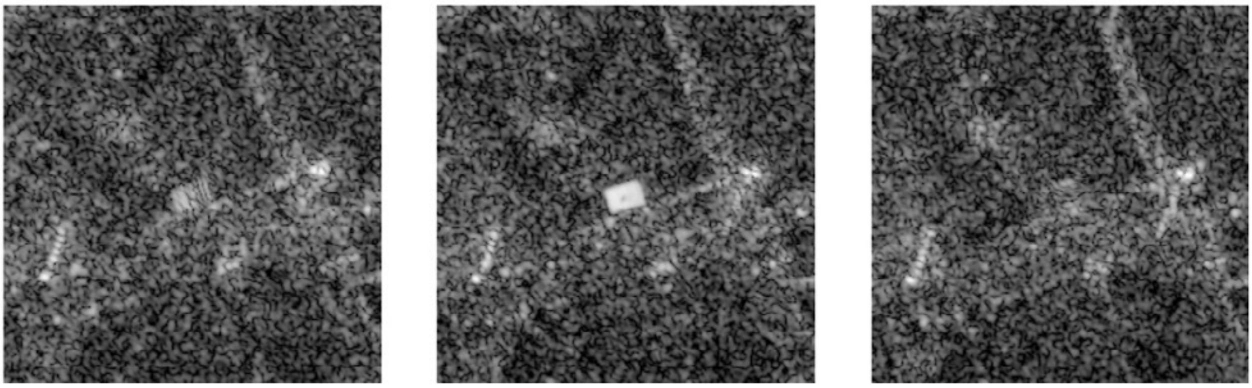

Figure 19: Importance of multi-frequency radar imaging — Single aspect, multi-frequency radar image — a target is visible at the central frequency but almost invisible at adjacent frequencies.Interoperability & Networking of Disparate Sensors and Platforms for Tactical ISR Applications (SET-256) conducts Successful Live Experiment.

SYNERGIES AND COMPLEMENTARITIES

SET-250 successfully exploited the sinergies and complementarities offered by its participants. The Spadeadam trials are the strongest evidence as four airborne radar imaging systems were deployed at the same time. Four different radar systems were simultaneously used that combined multi-polarization, multi-channel, and multi-aspect and multi-frequency characteristics to collect a unique dataset to prove the superiority of multi-dimensional radar images with respect to traditional ones.

EXPLOITATION AND IMPACT

The outcome of SET-250 is twofold. On one hand, multiple algorithms have been devised; implemented and tested that have enriched the know-how of the participants and, to some extent, the scientific literature in the field of radar imaging and target classification. On the other hand, the Spadeadam data collection has produced a very large and unique database, which will be used for many years to come to further develop radar imaging and ATR algorithms and will serve NATO CSO follow-on activities.

How far can we push the performance of ATR? Multi-dimensional radar imaging systems indicate that a significant leap forward can be achieved with respect to traditional ones.

Current results are already showing the superiority in terms of accuracy and information content of multi-dimensional radar images when compared to traditional ones.

CONCLUSION(S)

SET-250 has significantly advanced knowledge in matters of radar imaging and its relevance in terms of expected ATR performances. The knowledge generated, which has been shared within the NATO STO community through the Final Report, will be used to further push the development of multi-dimensional radar imaging system and its use in operational scenarios.

INTEROPERABILITY & NETWORKING OF DISPARATE SENSORS AND PLATFORMS FOR TACTICAL ISR APPLICATIONS (SET-256)

The SET-256 Research Task Group (RTG) conducted a live experiment in Portsmouth, United Kingdom, September 20-28, 2021. This multi-national exercise was conducted on a single network. SET-256 achieved interoperability of tactical edge Intelligence, Surveillance, and Reconnaissance (ISR) sensors from multiple nations.

Further, SET-256 successfully tested draft STANAG 4789 and were able to publish MASINT Reps (STANAG 4716).

Ms. Susan TOTH, USA, Army Research Laboratory

BACKGROUND

NATO forces currently cannot effectively take advantage of available disparate mobile and fixed ISR assets (e.g., sensors, cameras, unattended ground sensors, etc.) from coalition partners during coalition ground operations. Coalition partners must provide all of the ISR assets they need respectively, which creates significantly increased costs in logistics and sustainment and required personnel.

MILITARY RELEVANCE

The objective of SET-256 is to support the tactical commander's decision-making process by increasing information availability from multinational ISR capabilities and systems. Currently coalition forces do not share sensor data effectively, resulting in incomplete situational awareness, which unnecessarily exposes NATO personnel to threats.

SET-256 conducted a live experiment in Portsmouth UK, September 20-28, 2021. SET-256 achieved interoperability of tactical edge ISR sensors from multiple nations.

OBJECTIVE(S)

SET-256 identified four hypothesis for the experiment: (1) Relevant information can flow from any sensor integrated into the PED system to decision makers through a single processing, exploitation and dissemination command and control (PED/C2) node regardless of the nation owning the sensors or the PED systems; (2) A single PED/C2 node can control sensors within the system regardless of the nation owning the sensors or the PED systems; (3) Information can be filtered and fused such that the decision makers only receive relevant information vs. raw unfiltered, non-fused data, thus reducing cognitive burden, improving time to decision and more efficiently using network

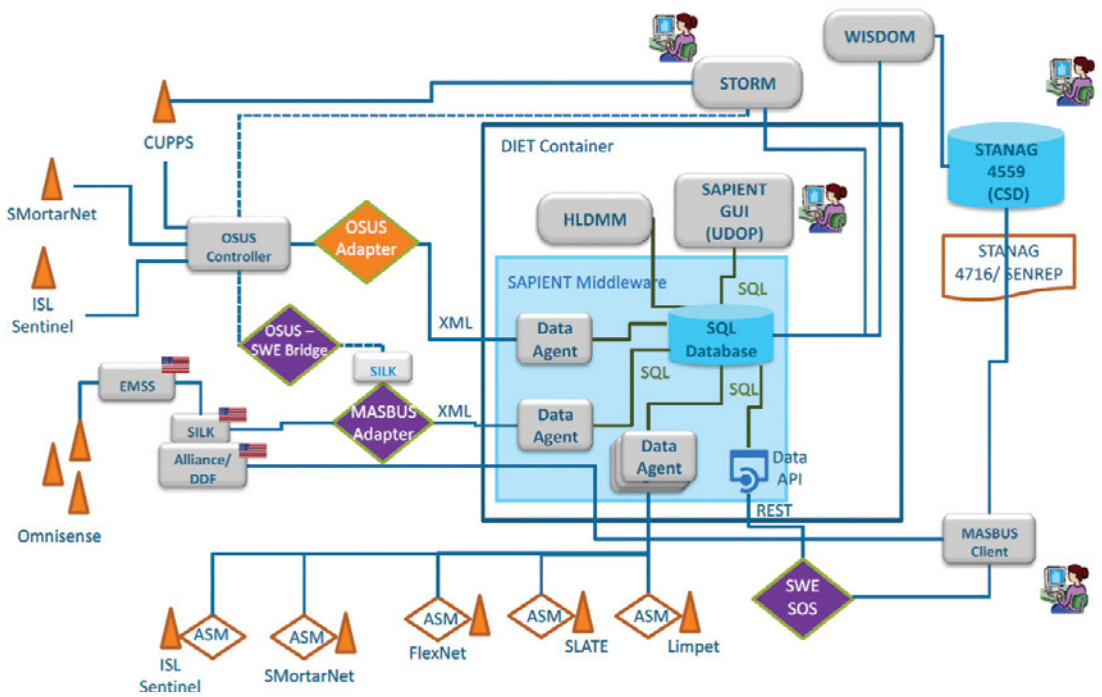

Figure 20: Network diagram.

bandwidth by transferring only relevant “sufficient information” for each information consumer; and (4) Reporting can be done in NATO standard formats regardless of native format to make information available to coalition partners.

S&T ACHIEVEMENTS

SET-256 proved each hypothesis during the event. During the experiment, the team conducted the successful integration of sensors using three separate middleware running simultaneously on sensors. Specifically, communication to Canada via Open Standards for Unattended Sensors (OSUS), the United Kingdom via their SAPIENT protocol and NATO via draft STANAG 4789. SET-256 also successfully tested draft STANAG 4789 and were able to publish MASINT Reps (STANAG 4716).

SYNERGIES AND COMPLEMENTARITIES

Four countries participated in the actual event. France, United States and United Kingdom participated in person. Canada participated virtually. Germany had to withdraw due to COVID concerns. Each Nation brought sensors to the experiment, with the United Kingdom providing the network architecture, facilities, personnel, and trials management.

EXPLOITATION AND IMPACT

This event provided the framework for SET-256 to develop a set of business rules that will allow sensor data sharing. SET-256 drafted a documented mechanism to integrate disparate systems at the edge, with curated data flowing into the NATO architecture. The ultimate result is improved decision-making resulting in increased operational effectiveness and survivability. Finally, nations will reduce costs through asset sharing, and the forces will be able to use the best tools available.

CONCLUSION(S)

NATO forces currently cannot effectively take advantage of available disparate mobile and fixed ISR assets (e.g., sensors, cameras, unattended ground sensors, etc.) from coalition partners during coalition ground operations. The SET-256 Final Report will provide recommendations on how to over come this obstacle, so that commanders can have the best information available regardless of sensor national provenance.

DATA-ENVIRONMENTAL KNOWLEDEGE AND OPERATIONAL EFFECTIVENESS (D-EKOE) (CMRE)

The CMRE D-EKOE programme contributes to NATO maritime information superiority and enhanced decision-making for NATO naval forces through the observation, comprehension and near future forecasting within physical and cognitive dimensions, with the overarching aim of effectively supporting integrated multi-domain operations.

Dr. Alberto ALVAREZ, ESP, NATO Centre for Maritime Research and Experimentation (CMRE)

BACKGROUND

Since its foundation in 1959, the NATO STO CMRE has had a long history of developing the sensors, tools and numerical models—both oceanographic and acoustic—to support the provision of environmental knowledge 'nowcasts' and forecasts with the goal of optimizing the operational effectiveness of NATO naval underwater warfare operations in physical domains. More recently, CMRE staff have applied advanced artificial intelligence, machine learning and information fusion techniques to extract knowledge from data and information in order to support improved decision-making for naval operations. In 2021, these strands of work were combined into a single D-EKOE programme under the Allied Command Transformation (ACT) Maritime Science and Technology Programme funded by NATO's Supreme Allied Commander Transformation (SACT).

MILITARY RELEVANCE

The D-EKOE programme supports NATO's Maritime Joint Intelligence, Surveillance and Reconnaissance (M-ISR) requirements. It aims to improve the Alliance's ability to operate in the maritime domain (i.e.,on surface and underwater), through greater understanding of the operating environment for decision-making.

OBJECTIVES

The objective of the D-EKOE programme is to assess emerging and disruptive technologies for implementation within distributed intelligence solutions for the near-real time surveillance and prediction of marine environments, and to bring forward information processing techniques to enable Information Superiority and improved decision-making in the maritime domain.

S&T ACHIEVEMENTS

During 2021, environmental knowledge researchers within the CMRE D-EKOE programme successfully developed algorithms for the real-time characterization of the anisotropy of the underwater ambient noise by using a compact volumetric sensor (cVAS) installed on a Slocum G3 autonomous glider, and similar capabilities are currently being implemented for other oceanographic data collection platforms such as drifters and floats. The implementation of high-resolution ocean models in the Arctic region continued during 2021, in order to assess the acoustic sensitivity to the ocean high frequency variability and to the small-scale ocean structures. Additionally, autonomous platforms for environmental monitoring have been successfully integrated into autonomous Anti-Submarine Warfare (ASW) networks, with the ASW platforms being able to exploit the observed environmental information to optimize their performance.

Figure 21: NRV Alliance in navigation near the sea ice in the Arctic Ocean, in June 2021, during the NREP-21 Sea Trial.

The Nordic Recognized Environmental Picture (NREP) 21 sea trial was conducted onboard the NRV Alliance during the period 11 June to 10 July 2021 in the Greenland Sea/Svalbard region. A total of 33 Conductivity-Temperature-Depth (CTD) casts, 68 Expendable Bathy-Thermographs (XBTs), 90 nautical miles of Underway CTD and 80 minutes of acoustic transmissions were collected at selected locations during the sea trial. In addition, two permanent moorings were deployed near the Molloy Hole and in the Svalbard continental slope. The data collection was designed to accomplish the following objectives: to support future studies about the impact on acoustic transmissions of vertical variations in the underwater sound speed profile; to monitor the ambient noise level in the Arctic soundscape; and, to determine the impact on acoustic transmissions of a random distribution of ice floes at the sea surface.

Data knowledge work within the CMRE D-EKOE programme focused on further refinement of deep-learning methods for maritime traffic

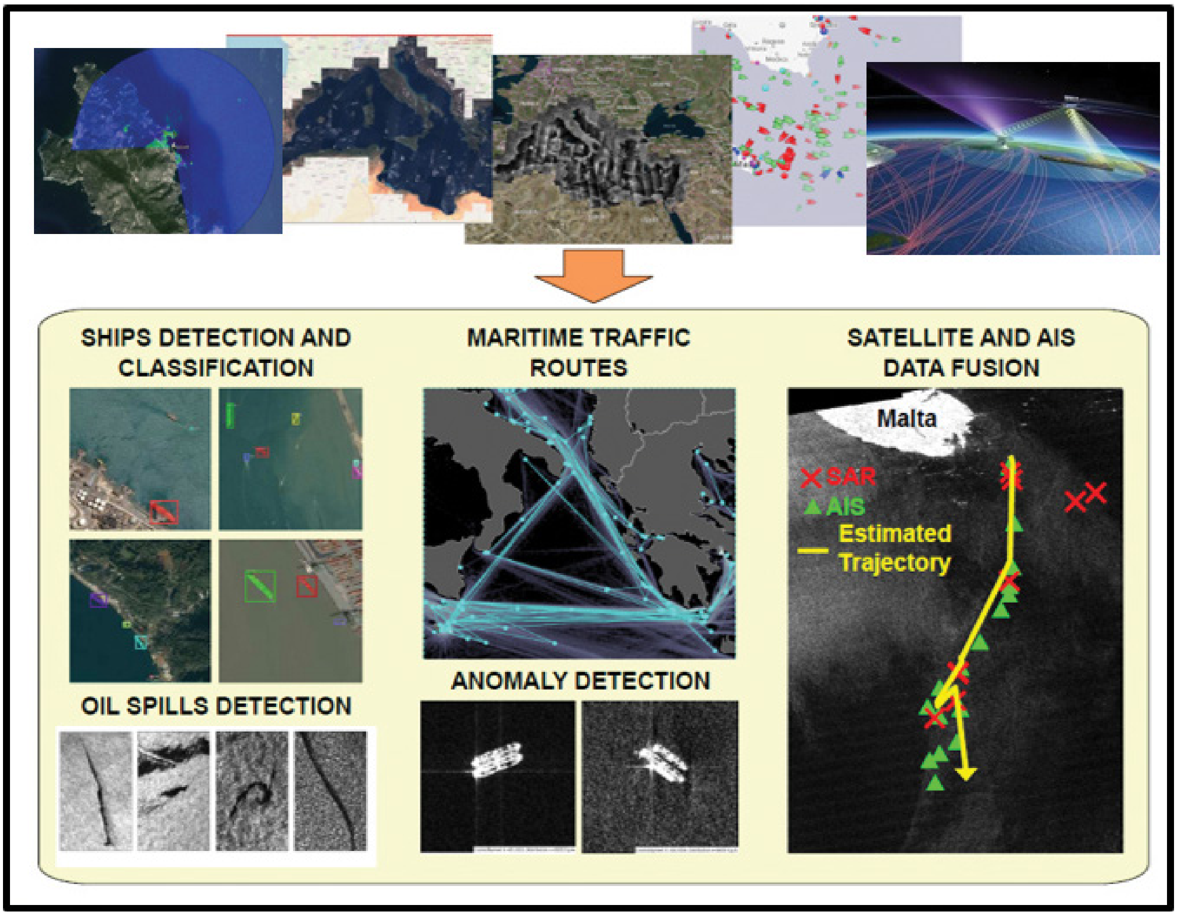

Figure 22: The processing of data acquired by heterogeneous sensors, e.g., space-based sensors, with state-of-the-art artificial intelligence and data fusion techniques allows extraction of information on the current maritime situation, such as detected ships and their category, maritime traffic routes, oil spills, anomalies (e.g., dark route deviations), and ship trajectories.

pattern learning and prediction from large sets of Automatic Identification System (AIS) data. Specific activity during 2021 included, inter alia: the extension of a belief-propagation data fusion algorithm to address the problem of multi-target tracking; the application of multi-source reasoning under uncertainty to decision-making in a coalition context; and, the development of an explanation model to provide meta-information about information content and to enable automatic generation of explanations.

SYNERGIES AND COMPLEMENTARITIES

ACT, the US Office of Naval Research (ONR) and STO Office of the Chief Scientist (OCS) funded the NREP21 sea trial. External collaborators included the Istituto Idrografico della Marina (IIM) Italy, Defence Research and Development Canada (DRDC), Forsvarets Forskningsinstitutt (FFI) Norway, and Woods Hole Oceanographic Institution (WHOI) USA.

Additionally, CMRE D-EKOE programme staff participated in a successful Passing Exercise (PASSEX) Technical Demonstration together with the Standing NATO Maritime Group 2 (SNMG2). Fusion of disparate and independent data sources was demonstrated, where AIS tracks from surface vessels were fused with acoustic returns captured by sonar sensors, to reduce the incidence of false underwater contacts.

EXPLOITATION AND IMPACT

NATO forces to optimize the operational employment of underwater warfare platforms and sensors to counter submarine and mine threats use environmental data and the forecasts from numerical models. The techniques developed under the programme for maritime traffic pattern learning will be implemented in future increments of TRITON, the new NATO maritime operational command and control system.

CONCLUSIONS

The CMRE's D-EKOE programme research and development activities focus on disruptive environmental monitoring technologies, numerical modelling, advanced artificial intelligence, and information fusion techniques, applied to data of different volume, velocity, variety and veracity. Such tools and techniques convert collected data and information to actionable knowledge to enable Maritime Information Dominance and improved decision-making for NATO forces.

THE MARITIME UNMANNED SYSTEMS ENABLERS (MUSE) PROGRAMME

The MUSE programme at the NATO STO Centre for Maritime Research and Experimentation (CMRE) seeks to design the architectural framework in which future autonomous underwater systems and missions will be cast, establishing standards for control, data flow, information security, performance and interfaces, to provide future NATO forces with secure, interoperable and scalable systems that increase effectiveness while reducing risk and cost.

Col. Eng. João ALVES, PRT, NATO Centre for Maritime Research and Experimentation (CMRE)

BACKGROUND

As presented in NATO Allied Command Transformation (ACT) Strategic Foresight Analysis and Framework for Future Alliance Operations, *"NATO should invest in the ability to use automated processes to collect data. It should also improve the ability to use cost-effective technology including autonomous and disposable assets, remote sensors, and intelligence networks to enable early warning."* Based on this guidance, the CMRE MUSE programme enables the interoperability of heterogeneous autonomous assets including, inter alia, underwater communications, common tactical-level situational awareness, and modelling & simulation tools for concept development, testing and validation. The CMRE MUSE programme is carried out under the ACT Maritime Science and Technology Programme funded by NATO's Supreme Allied Commander Transformation (SACT).

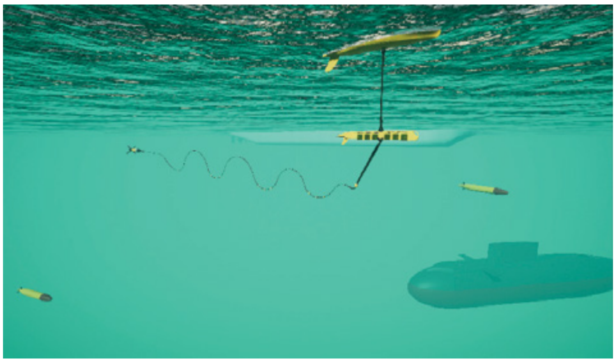

Figure 23: The Visualization of the synthetic world and models used to simulate CMRE's ASW missions.

MILITARY RELEVANCE

As recognized by NATO from its founding in 1949, interoperability and standardization are essential elements of effective multinational force integration, and fundamental enablers for the testing and rapid adoption of emerging technologies such as artificial intelligence-driven autonomous systems.

OBJECTIVE(S)

The main goals of the MUSE programme for 2021 were: to advance the understanding of data models and message sets to support multi-domain control stations for multinational autonomous systems; to establish a federation of simulators to support the testing, validation and concept development of maritime unmanned systems (MUS); to advance the scientific state-of-the-art in secure and adaptive underwater communications; to promote NATO interoperability in underwater communications; and, to support new operational concepts based on digital underwater communications.

The MUSE program at CMRE aims at enabling interoperability of autonomous assets from underwater communications to common picture aggregation at the tactical level, including modelling & simulation for concept development, testing and validation.

S&T ACHIEVEMENTS

During the Robotic Experimentation and Prototyping Augmented by Maritime Unmanned Systems—REP(MUS)—2021 exercise held in Portugal, the MUSE team deployed and demonstrated the initial version of a decentralized data architecture based on STO RTG SCI-288 / SCI-343 data sets, allowing the sharing of a common operational picture across different exercise participants and geographical locations. During the same exercise, a new concept of operations (CONOPS) was introduced for submarine rescue operations with the employment of NATO's digital underwater communications standard (JANUS) for automated transmission of vital data from a submarine in distress. Additionally, a new cognitive underwater communications system was employed at sea with the ability to change automatically the transmitted waveform in response to the underwater acoustic conditions, opening new possibilities for better exploring the limitations of the physical channel.

Finally, a proof-of-concept system for secure underwater communications based on Quantum-Key Distribution was developed in cooperation with Özyeğin University (TUR) researchers, which will be ready for experimentation and conceptual development from 2022.

Figure 24: CMRE Team on board NRV Alliance's RHIB, seen from a re-emerging CMRE's Ocean Explorer (OEX) AUV during REP-MUS 21 off the Coast of Lisbon - Portugal.

SYNERGIES AND COMPLEMENTARITIES

The work in MUSE programme is carried out in concert with STO Panel and RTG activities, and with the direct collaboration of academia and national laboratories from NATO Nations. Additionally, CMRE subject matter experts actively interact with industry and end-users to facilitate the adoption of new interoperability solutions for digital underwater communications based on NATO standards.

EXPLOITATION AND IMPACT

The outcomes of the MUSE programme include data sets, contributions to NATO standards, models and simulators, and research and development at the cutting edge of digital underwater communications. The near-term impact includes changes to CONOPS for certain operations—such as those to assist a submarine in distress—to support the transition to the era of autonomous systems.

CONCLUSIONS

The CMRE MUSE programme addresses the enablers for a new era of intelligent, autonomous maritime systems. Modular, scalable modelling and simulation tools facilitate concept development and the rapid adoption of such systems. New standards for secure underwater data flows among heterogeneous assets will eventually provide the much needed tactical-level connectivity for effective multinational operations.

AUTONOMY FOR ANTI-SUBMARINE WARFARE (AASW)

The AASW programme is one of the core activities of the NATO STO Centre for Maritime Research and Experimentation (CMRE). CMRE is in a unique position within NATO to undertake scientific research and experimentation to validate and de-risk advanced concepts for operational solutions that support the NATO Command Structure and NATO Nations in maintaining maritime underwater situational awareness and tracking submarine threats.

Mr. Robert BEEN, NLD, NATO Centre for Maritime Research and Experimentation (CMRE)

BACKGROUND

Advanced sensing technology and artificial intelligence (AI) hold promising potential for application to maritime autonomous systems, complementing the conventional ASW assets of NATO Nations. Accurate evaluation of emerging computational and platform technologies is required to establish their performance and suitability. The majority of the activities within the CMRE's AASW Programme are carried out under the Allied Command Transformation (ACT) Maritime Science and Technology Programme funded by NATO's Supreme Allied Commander Transformation (SACT), with additional funding being received from NATO's Maritime Command (MARCOM), NATO Nations, and industrial partners.

MILITARY RELEVANCE

Addressing the submarine threat is critical for the safety of maritime operations and the security of NATO Nations. Research and experimentation validating advanced sensing, algorithmic, and autonomous platform concepts in operationally relevant scenarios will help identify the most effective technologies for NATO to counter submarine threats.

OBJECTIVE(S)

Develop, test and validate advanced concepts for autonomous ASW.

S&T ACHIEVEMENTS

The two main projects of the Programme of Work for ACT are Maritime Unmanned Systems (MUS) for ASW and ASW Decision Support.

In the MUS for ASW project, scientists have been working to test a number of new sensors and algorithms for the detection of submarines. Two low power, long-endurance bottom nodes equipped with a heterogeneous sensor suite comprising acoustic vector sensors, quantum magnetic sensors and geophones have been developed for passive detection of submarines. These systems were deployed in concert—as a network—with two autonomous underwater vehicles (AUVs) towing advanced hydrophone arrays during the *Robotic Experimentation and Prototyping augmented by Maritime Unmanned Systems* - REP(MUS)21 - exercise in Portugal in September 2021. During the same exercise, an experiment was carried out with the two AUVs assisting in the localization of a submarine in distress.

ASW Decision Support project activity developed advanced concepts for the performance assessment of heterogeneous manned-unmanned ASW through operations research, with an emphasis on improving planning algorithms for active sensing networks. Additionally, a Table-Top Exercise was conducted with ASW operators and subject matter experts (SMEs) to evaluate the perceived utility of unmanned ASW networks for naval operations.

> *Unmanned platforms play a vital role in our future fleet," U.S. Chief of Naval Operations, Admiral Gilday wrote. "Successfully integrating unmanned platforms—under, on, and above the sea—gives our commanders better options to fight and win in contested spaces.*
>
> ***[from 2021 NAVPLAN]***

In the first week of October 2021, CMRE—funded by ACT's Innovation Branch—conducted a successful Passing Exercise (PASSEX) together with the Standing NATO Maritime Group 2 (SNMG2). The objectives included familiarization of naval operators with MUS technology in the field of Anti-Submarine Warfare (ASW); multistatic submarine detection using conventional ship-based platforms in concert with autonomous unmanned vehicles using multiple sources and multiple receivers; and, data collection for Machine Learning.

Additionally, work on quantum magnetometry was continued in 2021 to evaluate novel quantum effect magnetometers for their suitability to add a magnetic anomaly detection capability to MUS for ASW.

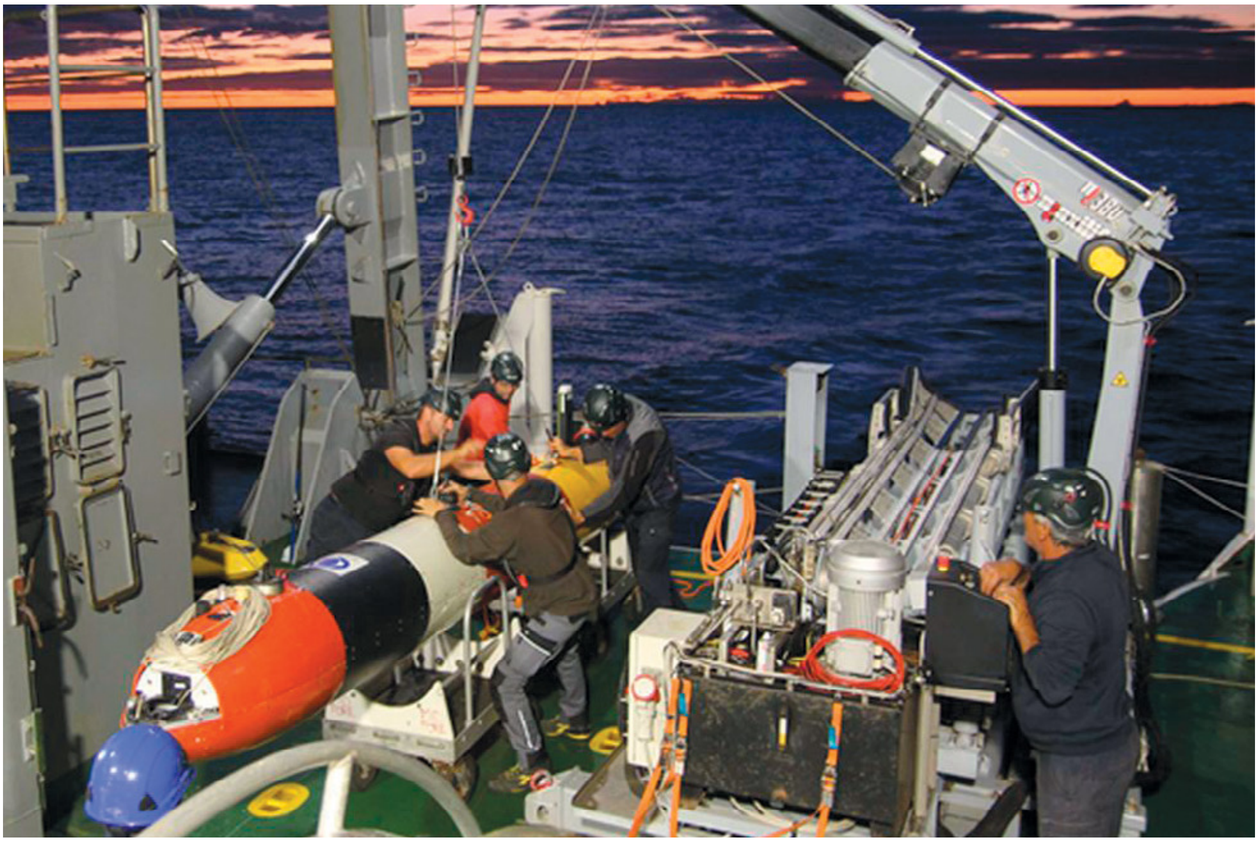

Figure 25: Deployment of a CMRE's Ocean Explorer AUV from the deck of NRV Alliance during the PASSEX 21 with SNMG2 in Ligurian Sea.

SYNERGIES AND COMPLEMENTARITIES

The sea-going element of the programme includes participation in multinational projects for the development and testing of advanced ASW concepts in a collaborative environment—such as REP(MUS)21—as well as participation in NATO ASW exercises and PASSEXs. The AASW Decision Support team provided acoustic performance predictions in support of NATO exercises, and collaborated with MARCOM's In-stride Debrief Team (IDT) to test advanced methods for exercise analysis based on generating an acoustic reconstruction of select ASW serials conducted during the exercise.

EXPLOITATION AND IMPACT

The outcomes of the AASW programme complement and enhance the ASW research and development activities of NATO Nations. De-risking advanced sensing technology, algorithms and maritime unmanned systems supports future procurement programmes.

CONCLUSION(S)

With its experience spanning over two decades of conducting unmanned system research and experimentation to improve the ASW capabilities of the Alliance, CMRE is at the forefront of both blue water and littoral ASW. The Centre is leading the way in advanced sensing, algorithmic, and autonomous platform concepts for ASW applications, demonstrating the potential of MUS for long-endurance, standoff operations.

AUTONOMOUS NAVAL MINE COUNTERMEASURES (ANMCM)

The CMRE's ANMCM programme work is shaped by the need to develop and test autonomous naval MCM autonomous systems—equipped with state-of-the-art sensors, securely communicating, and persistently operating with collaborative behaviours—for the detection, localization, classification and reporting of underwater mines. During 2021, work has been carried out on the continuing development of artificial intelligence techniques for automatic target recognition, enabling single and multiple vehicle collaborative autonomy, further developing the Centre's High Resolution Low Frequency Synthetic Aperture Sonar (HRLFSAS), and enhancing NATO's naval MCM Planning and Evaluation (P&E) algorithms.

Dr. Yan PAILHAS, FRA, NATO Centre for Maritime Research and Experimentation (CMRE)

BACKGROUND

The CMRE's ANMCM programme focuses on delivering technologies, methods, algorithms and data that will enable CMRE and Allied Navies to design develop and test a network of securely communicating autonomous vehicles under realistic operational conditions for the detection, localization, identification and neutralization of naval mines in all environmental conditions. CMRE's ANMCM programme carried out under the Allied Command Transformation (ACT) Maritime Science and Technology Programme funded by NATO's Supreme Allied Commander Transformation (SACT).

MILITARY RELEVANCE

Naval mine countermeasures (NMCM) operations in the past have been slow, have exposed human operators to significant risk from mines, and with performance significantly affected by environmental conditions. The ANMCM programme aims to exploit emerging technologies to improve the efficiency and effectiveness of NATO MCM operations while taking the human operator out of the minefield.

OBJECTIVE(S)

The objectives of the programme in 2021 were developing target localization and identification techniques using an autonomous vehicle; improving automatic target recognition (ATR) algorithms; developing novel processing techniques for High Resolution Low Frequency Synthetic Aperture Sonar (HRLFSAS) imaging; and, extending planning and evaluation (P&E) approaches to different sensors.

S&T ACHIEVEMENTS

The ANMCM Programme includes three projects: Collaborative Autonomous CA-MCM, HRLFSAS, and P&E for MCM.

CA-MCM project activities enhanced the convolutional neural network (CNN)-based ATR performance for synthetic aperture sonar (SAS) and side-scan sonar (SSS) images by extracting and exploiting seabed characterization features and auxiliary target information. Complementary effort was also directed towards the development of Generative Adversarial Networks (GANs) to augment the database of collected images with synthetic images. The BIONDo (Bi-modal Identification Or Neutralization DemOnstrator) autonomous underwater vehicle (AUV) fitted with an ARIS Explorer 3000 high-resolution acoustic camera has been upgraded to add the CA-MCM autonomy stack onboard, including single-vehicle behaviour management and multi-vehicle task arbitration of CMRE's D2CAF (Distributed Decoupled Collaborative Autonomy Framework) tool.

HRLFSAS project activities included the analysis of the data collected in 2020 at-sea trials with the system. Developments in the theory of low frequency systems led to novel data-driven micro navigation algorithm enabling coherent SAS processing without any navigation information. On the aspect, a 3D Finite Difference Time Domain (FDTD) numerical simulation implementing a multigrid component has been developed to solve the visco-elastic wave equation. 3D simulations of complex objects close to a random interface are now feasible.

Crucial advances were made in 2021 within the P&E-MCM project transposing the modern evaluation algorithms developed during 2020 for SAS to SSS, and on evaluating the performance of multiple vehicles performing different phases of an MCM mission in simulation. Python-based simulation software was further refined to enable Monte Carlo runs. Statistical performance analyses are now available for a large variety of parameters including probability of detection or false alarm, or navigation error.

SYNERGIES AND COMPLEMENTARITIES

Funded by ACT, the ANMCM team participated in the Turkish naval mine warfare exercise NUSRET21 embarked on the NATO Standing Naval MCM Group 2 flagship. The CMRE's MUSCLE AUV equipped with SAS technology and organic ATR capabilities together with the BIONDo AUV successfully demonstrated the capability to autonomously detect, classify, and identify exercise mine targets. Additionally, the ANMCM team participated in a demonstration exercise in the Baltic involving more than 40 partners and funded under the EU OCEAN2020 project with the BIONDo vehicle successfully localizing and identifying targets passed from independent heterogeneous detection assets promoting new standards for interoperability such as those being developed by the STO SCI-343 RTG.

Additionally, CMRE ANMCM staff co-chair the STO SCI-343 RTG ‘Enabling Collaborative, Federated Autonomy’—the follow-on from SCI-288 RTG on ‘Autonomy in Communications Limited Environments,’ participate in the NATO Naval Mine Warfare Working Group (NMWWG), and coordinate scientific groups on automated target detection and P&E with participation of scientists and operators from NATO Nations.

EXPLOITATION AND IMPACT

The outcomes of the ANMCM programme are designed to complement and enhance the MCM research and development activities of NATO Nations in advanced MCM sensors, artificial intelligence for signal processing, single and multiple autonomous vehicle behaviours, and improved NATO planning and evaluation procedures for the operational employment of MCM system and sensors. The exploitation of the P&E outputs includes the implementation of a dedicated P&E MVP (Minimal Viable Product) to bring this new technology closer to the operators.

CONCLUSION(S)

Since the introduction of MCM research and development into the Centre’s programme of work in the early 1990s, CMRE staff have had a leading role in NATO developing advanced sensors for mine detection, classification and identification and their employment on autonomous robotic systems. The Centre continues to act as a focal point within NATO for Allies to collaborate on potential innovative solutions to improve the effectiveness, efficiency and safety of naval mine countermeasure operations.

Figure 26: CMRE’s MUSCLE AUV equipped with SAS onboard SPS Bam Rayo during the Naval Mine Warfare (NMW) Exercise NUSRET 21 in Turkey.

NATO STO Programme of Work

ADVICE TO LEADERSHIP

ROTORCRAFT FLIGHT SIMULATION MODEL FIDELITY IMPROVEMENT AND ASSESSMENT (AVT-296)

Rotorcraft flight dynamics simulation models require high levels of fidelity to be suitable as prime items in support of life cycle practices, particularly vehicle and control design and development, and system and trainer certification. A range of time- and frequency-domain methods to assess and improve flight simulation model fidelity is compared using a large set of flight-test based case studies. The case studies encompass eight different rotorcraft databases and use seven update methods, organized in terms of complexity and expertise required. Various metrics to evaluate model fidelity when compared to flight-test data are presented and evaluated.

Prof. Mark WHITE, GBR, The University of Liverpool

Membership included 31 participants from 20 organizations including researchers, academics, and industry experts from 9 NATO countries AUS, CAN, DEU, FRA, GBR, ITA, NLD, TUR, and USA.

BACKGROUND

The Task Group aimed to determine and achieve the 'good enough' state for rotorcraft flight simulation models that are used for control design and development, and system and trainer certification.

MILITARY RELEVANCE

During design phases, accurate mathematical models are critical to provide assessment of a future air asset's capability and utility. Simulation throughout the life cycle helps improve warfighter readiness by providing a high-fidelity training environment.

> *The report provides an excellent and comprehensive overview about the benefits of system identification and parameter optimization methods for model fidelity improvement that were developed over the past decades."*
>
> ***Dr. Wolfgang von Gruenhagen, DLR Research Associate, Germany***.

OBJECTIVE(S)

The goals of the activity were to 1) share learned 'best practices' in simulation model fidelity assessment and improvement, 2) develop harmonized recommendations, and 3) provide insights into model update strategies for various model end-uses.

S&T ACHIEVEMENTS

The final report serves as a lasting and comprehensive reference for the NATO community on a topic of major importance in the design and development of conventional helicopters, advanced high-speed rotorcraft, and the growing novel urban air mobility configurations. Seven update methods and four fidelity assessment methods (with associated fidelity metrics) were compared in case studies using eight flight-test databases. To further disseminate this work to the community, 16 papers were presented at international fora and three papers were published in a peer-reviewed journal with another accepted for publication.

SYNERGIES AND COMPLEMENTARITIES

The majority of the publications derived from the RTG include authors from several participating organizations. The teaming accomplished between industry, academia, and research laboratories during this research activity was highly effective for data sharing, analysis, and technology transfer between the various groups.

EXPLOITATION AND IMPACT

A follow-on three-day Research Lecture Series was presented twice, the first favouring European time zones and the second North American times zones. More than 260 registered participants attended it.

CONCLUSION(S)

The documentation of rotorcraft simulation fidelity assessment and model update strategies in the AVT-296 report will benefit NATO Nations by allowing for common, agreed-upon best practices and recommendations, ensuring each country's flight dynamics and simulation models are of the highest calibre possible.

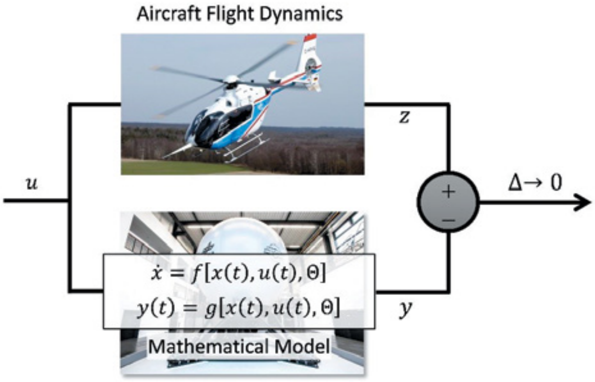

Figure 27: Documenting model error minimization and evaluation strategies was the goal of this research activity.

STANDARDIZATION RECOMMENDATION DEVELOPMENT FOR NEXT-GENERATION NATO REFERENCE MOBILITY MODEL (AVT-327)

The AVT and the NMSG panels have completed a new STANREC, 4813, covering the standard, AMSP-06, on the development of Next-Generation NATO Reference Mobility Models (NG-NRMM). This recommendation describes the latest mobility M&S tools needed to plan the NATO Nations' military vehicle operations, and to support vehicle acquisition and design.

Dr. Michael MCCULLOUGH, USA, BAE Systems; Dr. Jean DASCH, USA, Huntington Ingalls Industries

BACKGROUND

The NATO Reference Mobility Model (NRMM) is a recognized international standard for modelling the mobility of ground vehicles over specified terrains. NRMM has proven to be of great practical value to the NATO Nations since its development in the 1970s. However, it exhibits inherent limitations compared to modern modeling tools. Since 2014, four AVT groups have developed the requirements for a physics-based, state-of-the-art model to predict mobility of military vehicles over off-road terrains, culminating in this NG-NRMM STANREC.

Figure 28: AMSP-06 describes the data, methods, and attributes necessary for an NG-NRMM compliant model to predict the trafficability of a vehicle over specified terrains.

MILITARY RELEVANCE

NG-NRMM models provide the optimal path and speed for military vehicles to use to traverse off-road terrains in order to accomplish operational missions.

OBJECTIVE(S)

The main goal of AVT-327 was to describe the capabilities required by an NG-NRMM compliant model. An NG-NRMM model takes vehicle data and GIS-based inputs on the soil and terrain, as well as their uncertainties, and then produces probabilistic maps of traffic ability, speed, and efficiency.

S&T ACHIEVEMENTS

Starting in 2014, AVT-ET-148 and AVT-248 developed the requirements needed to upgrade NRMM to a state-of-the-art vehicle-terrain model. In 2018, simulations compliant with these requirements were compared to actual vehicle test results in a Cooperative Demonstration of Technology (AVT-CDT-308). Results from the CDT demonstrated that NG-NRMM compliant models were far more accurate than legacy NRMM models and addressed important gaps in standard metrics. In addition to four NATO Final Reports and many publications, the work earned the AVT Panel Excellence Awards in 2020 and 2021, and was promulgated as STANREC 4813 recommending AMSP-06 in July 2021.

> *This new NATO Standard Recommendation will allow better predictions of off-road mobility for operational planning as well as the acquisition of new ground systems."*
>
> ***Dr. David Gorsich, the U.S. Army DEVCOM Ground Vehicle Systems Center Chief Scientist and AVT Panel Mentor.***

SYNERGIES AND COMPLEMENTARITIES

Contributors to the AVT effort included representatives from 11 nations. AVT worked with NMSG in the writing of the final STANREC. In particular, the success of the first CDT covering wheeled vehicles has led to the plan for a second CDT in May 2022 in Trier, Germany with an emphasis on tracked vehicles.

EXPLOITATION AND IMPACT

NG-NRMM models, as described by this STANREC, will provide military planners with the tools needed to plan operations in difficult terrain situations, as well as supporting vehicle acquisition and design. The common agreed mobility metrics and prediction standards would promote interoperability for all joint operations.

CONCLUSION(S)

NG-NRMM models, as described by the AVT-327 STANREC, will provide the data required by military planners to operate rapidly and safely over any terrain. AMSP-06 describes the latest methods for mobility prediction, including geographic information systems (GIS) map-based input and output, fully 3D vehicle dynamics and terramechanics, uncertainty quantification and a suite of verification and validation benchmarks.

IMPROVING DEFENCE INVESTMENT PORTFOLIO DECISIONS: INSIGHTS FROM THE LITERATURE AND NATIONAL PRACTICE (SAS-134)

SAS-134 has surveyed and summarized contributions of capital investment-relevant literatures and surveyed and reported defence investment prioritization practice trends from 13 nations. We recommend Decision Quality as a mature, robust framework for managing portfolio decision complexity and two widely proven decision process models that generate strong follow-through commitment and documentation supporting adjustments as uncertainties resolve and new ones emerge.

Dr. John STEELE, CAN, Defence Research and Development Canada – Centre for Operational Research and Analysis; Mr. Alf-Christian HENNUM, NOR, Norwegian Defence Research Establishment; Prof. Juha-Matti LEHTONEN, FIN, Finnish National Defence University (Defence Procurement); Prof. Francois MELESE, USA, Naval Postgraduate School Defense Resource Management Institute; Col Zdenek PETRAS, CZE, Army of the Czech Republic - General Staff (Force Planning Division); Mr. Anthony WEEN, AUS, Australian Defence Force HQ (Acquisition & Sustainment Group)

BACKGROUND

Affordable, sustained national defence hinges on uncertain, decade-long capital investment processes to equip forces to defeat continually advancing and proliferating technologies in an unknowable future.

MILITARY RELEVANCE

Militaries fight and win according to how well needs were understood and investments prioritized and executed to meet them. Our guidance orients executives toward ensuring their defences have what will affordably secure their nation's future.

OBJECTIVE(S)

To survey literature and NATO community practices to capture the current state-of-the-art of defence investment prioritization and advance it, highlighting best practices.

S&T ACHIEVEMENTS

We show limited named OR method usage, unrealized analysis ambition and widely diverse practices, signaling more need for principles than procedures. We situate investment portfolio decisions within the six Decision Quality dimensions: appropriate decision frame, creative and feasible alternatives, clear values and trade-offs, relevant and reliable information, sound reasoning and commitment to act; providing questions and rating criteria for context-appropriate management of each dimension.

Figure 29: Sound and affordable defence capability development over time requires characterisation of costs, benefits and risks associated.

The Decision Quality (DQ) construct locates the natural seams between decision elements, letting them be clearly separated for deep scrutiny without doing violence to the problem.

SYNERGIES AND COMPLEMENTARITIES

Both surveys were impossible without SAS Panel support and the networks and literature expertise of 14 past and present members including defence executives, senior military officers, economists, quantitative analysts, academics and a member of industry, until posting or COVID burdens pulled several away.

EXPLOITATION AND IMPACT

Executives will see their national processes in a new light, understanding how to evolve portfolio decision dynamics for better national and alliance outcomes. Matériel and facility investment decision support will be tuned to recognize what affordably delivers more of what defence needs. Stakeholder communities will recognize the impact of their expertise on portfolio decisions, and managers will understand where there is and is not flexibility to mitigate portfolio risk.

CONCLUSION(S)

More than analysis technique, we provide perspective and structure to see and manage portfolio decision complexity, with executive tools to monitor progress toward "good enough" in each decision dimension.

LONG-TERM SCIENTIFIC STUDY ON CBRN DEFENCE (HFM-273)

HFM-273 explored current and future chemical, biological, radiological and nuclear (CBRN) threats and hazards through 2030 along with the impact and opportunities of existing and emerging scientific and technological (S&T) advances to strengthen CBRN defence and to improve existing and create future CBRN capabilities. The study provides knowledge and recommendations to policy and decision makers, capability developers and scientists within NATO Nations in the use of S&T resources to obtain the best CBRN defence effect within the Alliance.

Dr. Janet Martha BLATNY, NOR, Norwegian Defence Research Establishment (FFI)

BACKGROUND

Rapid advances in S&T combined with a deteriorating security environment broadens the CBRN threat and hazard spectrum. The controls and norms established by international treaties, e.g., the Biological and Toxin Weapons Convention and the Chemical Weapons Convention have eroded within the last decade. Globalization has increased access to otherwise restricted information and enabled actors to exploit information, notably progressive S&T hitherto unavailable. Advances in S&T impacts existing and future CBRN challenges and necessitates that current CBRN defence capabilities needs to be evaluated and further developed as integrated parts of the overall defence system. Since the previous LTSS on defensive aspects of biological and chemical warfare, published in 2006, extensive global scientific and technological advances have occurred, as well as the rise of various technological megatrends (Emerging Disruptive Technologies, EDT), as described in the STO S&T Trends 2020-2040 report. The CBRN threat and hazard is increasingly diverse, challenging the Alliance's detection systems, physical protection, hazard management and medical countermeasures. As the threats from CBRN capable states, as well as from non-state actors, cannot be ignored, NATO Nations must respond to the increased threat, and do so with an inter-agency perspective.

MILITARY RELEVANCE

The study assists in identifying the most effective technologies and other advances in S&T to prevent and prepare our Alliance against CBRN threats and hazards, as well as to strengthen NATO Nations' response and capabilities to defend us from the use of CBRN agents and materials.

OBJECTIVE(S)

The main goal of the HFM-273 activity was to identify technologies and means to support CBRN defence through 2030 by: a) reviewing S&T capabilities against the evolving CBRN threat; b) describing and applying S&T context to NATOs strategic-level policy of Prevent, Protect and Recover and; c) analyzing S&T gaps in current CBRN defence capabilities using the five enabling components: Knowledge Management; Hazard Management; Detection, Identification and Monitoring; Physical Protection; and Medical Countermeasures and Casualty Care; in order to identify future priority work streams.

Figure 30: A collection of images illustrating the broad range of activities involved in CBRN defence [Reference: Final LTSS CBRN Report].

S&T ACHIEVEMENTS

HFM-273 reviewed and evaluated the state-of-the-art, future advances and emerging S&T megatrends along with the deteriorated global security environment. The study identified relevant S&T areas within the CBRN field and paved the road for developing future CBRN defence capabilities. The results were presented, reviewed and evaluated at a multinational exercise at NATO Headquarters in January 2020. The final Report was published in June 2021. Due to the increasing concern over the threat from radiological materials, the current CBRN LTSS covers, for the first time, also radio local aspects.

SYNERGIES AND COMPLEMENTARITIES

Eleven nations and the Joint CBRN Defence Centre of Excellence (CoE) participated in this research task group. This diverse group contributed to the success of the activity and the high quality of the work. Other NATO bodies were also involved and took part in different ways to the activity, e.g., COMEDS CBRN Medical Working Group, NATO Arms Control, Disarmament and WMD Non-Proliferation Centre (ACDC), NATO Communications and Information Agency (NCIA), NATO Allied Command Transformation (ACT) and Joint CBRN Defence Capability Development Group (JCBRND-CDG). In total, more than 70 participants took part in the study.

EXPLOITATION AND IMPACT

Due to global changing demands, the outcomes of HFM-273 assists and supports NATO Nations' security, policy and decision makers, capability developers and scientists in improving the Alliance's prevent, protect and recovery pillars, in order to obtain the best future CBRN defence effect.

CONCLUSION(S)

The CBRN threat cannot be neglected. These agents may be used anytime, ranging from peacetime to crises and conflict or war. CBRN Defence therefore requires an "all hazards" and whole of government approach to keep the war fighters prepared for and safe against CBRN hazards in various environments and operations. Preparedness planning for missions must therefore include CBRN events as a part of hazard assessments and risk management. This will furthermore strengthen the resilience of NATO's defence and security. The technological development trends, e.g., digitalization, miniaturization, new materials and production technologies facilitate for improved education, training and CBRN capabilities. CBRN defence must be viewed as a system of linked and interacting components and within the overall defence system. In addition to employing advances in technology to counter the threat, arms control disarmament and non-proliferation measures as well as intelligence cooperation need to continuously adapt to new threat challenges posed by availability of advanced technology to threat actors.

NATO ANALYTICAL WAR GAMING - INNOVATIVE APPROACHES FOR DATA CAPTURE, ANALYSIS AND EXPLOITATION (SAS-139)

SAS-139 ran between 2018 and 2021, and conducted research to advance NATO's capability for Analytical War gaming – that is war games that are designed to rigorously address specific research questions. Members researched artificial intelligence and automation for war gaming, how to improve war-game rigor by using experimentation principles, mitigating for bias, and pairing established operations research and analytical methods to war-game design and analysis. The research group also investigated and demonstrated the use of technology for war gaming and established a NATO war gaming community of interest. Work was disrupted due to the COVID-19 pandemic, but SAS-139 found an opportunity to research and learn early lessons from the exponential rise in Distributed War gaming.

Ms. Sue COLLINS, GBR, NATO Headquarters Supreme Allied Commander Transformation (SACT); Dr. Margaret POLSKI, USA, Naval War College

BACKGROUND

There has been a resurgence in interest and application of war games across the NATO community in order to address strategic, operational, and tactical decision problems. War gaming experts identified a need to develop analysis capabilities in order to improve war-game design, data capture and reporting of results. There have been considerable advances in general analytical practices over the past fifteen years that could be fruitfully applied to war gaming. The team identified a need to investigate these advances, and to derive applications that could improve the usefulness of war games and associated products for NATO decision makers.

The COVID-19 pandemic led to an expansion of distributed war gaming which arose in NATO almost overnight.

MILITARY RELEVANCE

Efforts to synchronize military operations analysis, research, and planning are needed to improve decision-making with respect to the readiness and effectiveness of NATO member nations' warfighting forces. War gaming is a well-established method for assessing and rehearsing warfighting strategy, concepts of operations, operational plans, and tactics.

OBJECTIVE(S)

To advance NATO war gaming practices through improving analytical war gaming capabilities. It aims to provide guidelines for ensuring analytical rigour and meaningful data capture in analytical war games to support the decision-making process. It will identify and share analytical methods for war gaming, and demonstrate the practical application of those analytical capabilities

Figure 31: Application of war games across the NATO community.

S&T ACHIEVEMENTS

In its first year, the team surveyed analytical war gaming capabilities in order to identify areas of best practice and gaps, shortfalls, and challenges in data capture and analysis. The second year focused on identifying and demonstrating innovative approaches, solutions and technologies, identifying analytical techniques that could usefully be combined with war gaming, and methods to ensure analytical rigor in war gaming. The third year pivoted to focus on distributed war gaming, creating a war gaming community of interest, and extracting findings for a final technical report aimed at professional operations research analysts, war-game designers and military decision makers.

The final report contains a series of stand-alone chapters and includes; discussion on how automation and artificial intelligence can fruitfully be applied to war gaming; application of operations research techniques such as Bayesian Networks, Morphological Analysis and Game Theory to war-game design and analysis; application of experimentation principles to ensure rigor and bias mitigation; a distributed war-game framework to aid in designing distributed games.

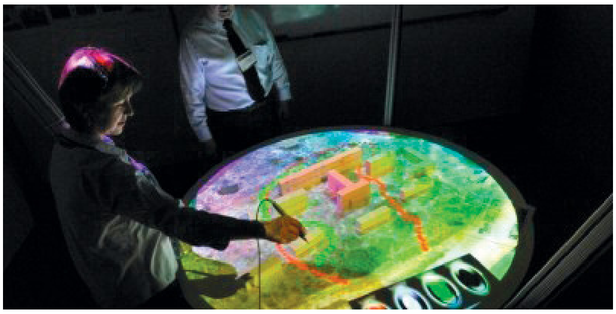

Figure 32: Analytical Wargaming as a distinct practice.

Figure 33: Conducting research to advance NATO's capability for Analytical Wargaming.

SYNERGIES AND COMPLEMENTARITIES

The team's work complements SAS-130 RTG on "Course of Action Analysis in the 21st Century and the Work on Distributed War Gaming" will feed SAS-170. SAS-139 also established a NATO War gaming community of interest and associated collaboration hub. Members expressed much interest in continuing the community beyond the end of the RTG, and serendipitously NATO established a NATO Audacious War gaming capability in 2021 that will continue the efforts of building NATO's War gaming capability and capacity, complementing the well-established series of Connections War gaming conferences.

EXPLOITATION AND IMPACT

This work will advance strategic and operational decision-making and synchronization in NATO by developing war gaming capabilities in many NATO Organizations and Nations, sharing best practices, identifying and encouraging the use of innovative methods for war-game design and analysis, and establishing a NATO analytical war gaming community of interest.

What are the future military and operational applications; think along DOTMLPFI (pick and choose, not necessary to address all). Why, how, where and to what degree are your findings militarily relevant to NATO, Allied and Partner Nations? How and where will they or have they been used in operationally relevant applications and/or tests/experiments in field trials and/or operational/exercise/policy decisions? Think along the lines of DOTMLPFI, factor in future military capability gaps including game changing effects for friendly and adversary forces, significant policy decisions informed by S&T results are especially relevant.

CONCLUSION(S)

Over three years, SAS-139 defined Analytical War gaming as a distinct practice and identified the analytical challenges associated with war games at all stages of the design, execution and reporting process. They demonstrated new technology that can be applied to war gaming, explored the use of automation and artificial intelligence, combined operations research techniques with war-game design and analysis, developed methods to improve analytical rigor, learned early lessons from the rise of distributed war games, and created a NATO War gaming community of interest.

THE MILITARY IMPACTS OF COVID-19 ON THE ALLIANCE: CHALLENGES AND OPPORTUNITIES (SAS-169)

The SAS-169 study details potential strategic and operational military impacts of the pandemic in the context of possible short-term (one to six years) futures of the COVID-19 environment, and in so doing provides planners, and decision makers within NATO and its member nations with high-level recommendations to address these potential impacts.

Mr. (General (rtd)) Sverre DIESEN, NOR, Norwegian Defence Research Establishment (FFI)

BACKGROUND

In recognition of the current and future impacts of the current global pandemic, on 22 April 2020, 15 representatives from NATO Nations and Organizations participated in a SAS Programme Development Team focus session to discuss options to support the NATO COVID-19 response. The session aimed to identify what research the SAS Panel in response to the COVID-19 crisis should undertake.

MILITARY RELEVANCE

NATO forces must accomplish a delicate balancing act: continuing essential missions, preparing for new missions, supporting national civil efforts to deal with COVID-19, all while keeping forces healthy enough that those missions are not adversely affected. Besides operational impacts, this creates significant challenges for military leaders in the areas of training; recruiting, procurement and many other areas where the impacts will vary based on the future environment and by country based on national governments responses.

> *The enduring COVID-19 pandemic continues to be a generational test of Allies' resilience, challenging national authorities and societies in unprecedented ways. The World Health Organization (WHO) Director-General noted, "This is the sixth time a global health emergency has been declared [...] but it is easily the most severe."*

OBJECTIVE(S)

The main objective was to examine possible short-term (one to six years) futures for the post-COVID-19 environment and analyse the potential military strategic and operational impacts, in order to provide national and NATO planners and decision makers with high-level recommendations to address the impacts.

S&T ACHIEVEMENTS

The team produced a report describing the multiple futures and potential military impacts, making high-level recommendations to NATO, National planners and decision makers on how to address the impacts. The report highlights strategic and operational opportunities, which when actioned become enablers for the greater NATO enterprise to address challenges such as the current pandemic or other non-military crises. It also contributes to strengthening business continuity policies and galvanizing research activities to demonstrably influence and lead militaries across its member nations.

Figure 34: The French President, Emmanuel Macron, launched a special military operation to help fight the coronavirus pandemic in France (Photo by Mathieu CUGNOT / POOL / AFP).

SYNERGIES AND COMPLEMENTARITIES

The report is directly relevant to the NATO Science and Technology Organization, the NATO Secretary-General's Policy Planning Unit, and NATO's Strategic Commands (Allied Command Transformation (ACT) and Allied Command Operations (ACO)) plus other NATO and national bodies.

EXPLOITATION AND IMPACT

The specific recommendations for each functional area have been developed to assist national and NATO defence planners in designing their future programs to advance the ten fundamental requirements highlighted above. The value of this report will not be diminished should the after-effects of COVID-19 prove to be less challenging than first anticipated or feared. Global distribution of the vaccine will take considerable time, while the economic effects affecting military affairs will be more enduring than the pandemic itself.

CONCLUSION(S)

The key impacts and recommendations contained in the report are based on a Futures Framework spanning a wide range of possible courses for the evolution of the pandemic, in accordance with expert medical opinion available in the public domain. The inherent uncertainty stemming from the breadth of possible outcomes is increased by an order of magnitude when the indirect political, social, economic, etc. implications of the pandemic are estimated to ascertain the military impacts of COVID-19, with each of these estimates in themselves spanning a range of possible outcomes. A statistically complete space of hypothetical effects of the pandemic, from a combination of best case medical, economic, etc. outcomes to one of worst case, therefore, extends from the insignificant all the way to the disastrous in terms of their military impacts – hence the report's continued relevance.

NATO 2030

MEANINGFUL HUMAN CONTROL OF AI-BASED SYSTEMS: KEY CHARACTERISTICS, INFLUENCING FACTORS AND DESIGN CONSIDERATIONS (HFM-322)

Dr. Jurriaan van DIGGELEN, NLD, Toegepast Natuurwetenschappelijk Onderzoek (TNO);
Dr. Mark DRAPER, USA, Air Force Research Laboratory (AFRL)

BACKGROUND

This activity addresses an important issue identified in the SCI-296 Specialists Meeting (ST) on “Autonomy from a System Perspective,” held in May 2017 as part of the STO theme devoted to that topic. As noted in the SCI-296 TER, “in many or most cases, it is foreseen that ‘meaningful human control’ (MHC) will be mandated, necessitating the human to maintain awareness and ‘drill down’ on demand.” Responding to this need, the HFM Panel commissioned an exploratory team (HFM-178) to rapidly assess the area from a human-centric perspective. This team came to a consensus as to a working description of MHC, which is “Humans have the ability to make informed choices in sufficient time to influence AI-based systems in order to enable a desired effect or to prevent an undesired immediate or future effect on the environment.” This team also canvased MHC from several dimensions and settled on the need for a dedicated expert-heavy workshop to unpack the most pressing influencing factors. The current proposed activity integrates several research issues emerging from SCI-296, especially those combining humans, (technical) systems, organization and behaviour. Since meaningful human control is deemed to be important for many kinds of automated and (semi) autonomous systems, the term “AI-based systems” is used to encompass all AI-based forms of automation and autonomy, for tasks that are either physical (e.g., unmanned platforms) or informational (e.g., Big Data Analytics, decision support). Given the implications of MHC for the latter application domain, this TAP is also relevant for the STO theme “Big data and AI for military decision-making.”

MILITARY RELEVANCE

Given the current exponential developments in the field of AI and in civil applications such as drones, autonomous driving, personal assistants and game players, and given the almost unbridled proliferation of AI technology, there is an urgent need to develop AI-based military capabilities. On the one hand, there are significant lessons that can be learned from civil applications. On the other hand, there are significant differences between military and civil applications and requirements. Intelligent systems operating in a military context must, for example, withstand adverse conditions and deliberate adversarial actions, and remain within bounds set by international law and rules of engagement. Moreover, systems should be adaptive: while requirements are relatively constant in the civil domain, they must follow the dynamics of pre-war, war and battlefield in the military domain, where in the course of escalation and de-escalation, rules of engagement have to be dynamically adjusted.

> *There is no silver bullet for achieving meaningful human control. It requires a continuous effort of banning certain types of systems, developing the right types of human-machine teams, and developing computational moral models.*
>
> ***The HFM-322 Team.***

OBJECTIVE(S)

The core objective of this Workshop is not to duplicate the ongoing efforts at the national and international level in the legalities and ethics of MHC. Rather, it is to learn from these ongoing discussions, apply a perspective to the problem squarely rooted in human factors and cognitive science understanding, and thus distill a set of practical human-centred guidelines to inform future NATO actions in this increasingly important area. Given the multi-faceted nature of MHC, six Themes were chosen for deep-dive investigation during this Workshop. Each Participant was assigned to explore one of these Themes via small Theme-focused breakout sessions. In addition, there was also a lot of cross-Theme discussion throughout the Workshop. The Themes were:

1. HSI, Organizational, & Operational Considerations of MHC
2. Human Factors Inspired Design Guidelines to Achieve MHC
3. Systems Engineering Methods & Metrics to Validate MHC
4. Adversary Exploitation of MHC
5. Complex Socio-Technical Systems
6. Moral Responsibility in Human-AI Teams

The results of this Workshop will directly inform recommendation of highly focused follow-on activities that inform NATO on how to identify, achieve, maintain, and regain MHC across a wide range of AI applications. The symposium was also essential to reactivate the network of collaboration and study within NATO during the Covid lockdown period.

S&T ACHIEVEMENTS

The NATO symposium on "Meaningful Human Control of AI-based Systems: Key Characteristics, Influencing Factors and Design Considerations" was conducted in Germany, Berlin on 25-27 October 2021 in a novel hybrid format. The hybrid format included six power sessions, i.e., the HFM-322 group in Berlin interviewing an expert panel of three or four experts participating online. The power sessions focused on each of the themes described above and resulted in a synopsis for each theme highlighting key challenges, possible controversy, and state-of-the-art within that theme. A professional cartoonist was present at the meetings to represent the results visually. Furthermore, three keynote presentations were given:

- Missy Cummings, who focused on recent developments in AI, how they relate to the use of AI on the battlefield, and how we need to shift the focus from debating bans to a discussion of meaningful certification.

- General Gäbelein who focused on a chain of trust for the effective accomplishment of their defence mission. The chain of trust includes society, policymakers, the armed forces and the system of deployed military personnel and their weapon systems.

- Daniele Amoroso who focused on the issue of filling the "meaningful human control" (MHC) placeholder with more precise content is primarily a normative problem rather than a technical one.

SYNERGIES AND COMPLEMENTARITIES

The workshop brought together perspectives from a wide range of NATO countries (USA, UK, Germany, the Netherlands, France, Italy, Sweden, and Australia). There was also an important and productive synergy with HFM-330, as productions from this workshop will be followed up upon in HFM-330. In particular, theme 1, 2 and 3 will be a focus point for HFM-330.

EXPLOITATION AND IMPACT

The workshop was evaluated by the TER as very successful, given the amount of experts interviewed within such a short timeframe, the wide range of topics that were addressed, and the way these topics were synthesized in sketches, and understandable synopses. In addition, the successes of the novel hybrid workshop format were recognized.

Figure 36: Workshop in Berlin during COVID period.

CONCLUSION(S)

Meaningful human control is about ensuring moral responsibility and agency of the human in military use of AI-based and autonomous systems. It is a multi-dimensional problem, which is highly dependent on context, stakeholders involved, and types of AI systems used. On 25-27 October 2021, we organized a hybrid workshop in Berlin, focusing on a range of interrelated themes regarding MHC. This workshop has provided crucial insights in the landscape of MHC research. These insights will be reported in a synopsis for each theme, and directly inform current and future activities of NATO STO.

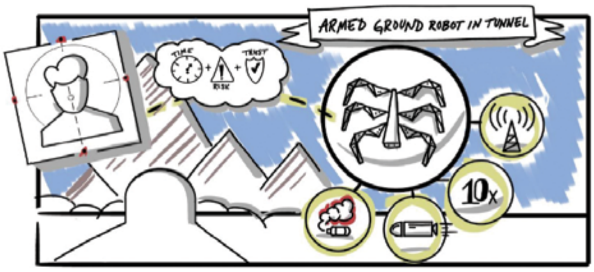

Figure 35: MHC across a wide range of AI applications.

MILITARY APPLICATIONS OF THE INTERNET OF THINGS (IST-147)

IST-147 conducted extensive research and experimental work that addressed a number of the critical issues identified for applications of Internet of Things (IoT) in the military domain. The team produced three demonstrators for scientific analysis and experimentation of IoT with innovative developments of new architectures, data models, and middleware to enable military C2 systems to interact with IoT technology and capabilities. These developments were successfully exploited to evaluate a comprehensive set of NATO operational scenarios to determine the impact of IoT and exploitation opportunities for future NATO operations in urban environments.

Dr. Niranjan SURI, USA, Army Research Laboratory (ARL); Prof. Zbigniew ZIELIŃSKI, POL, Military University of Technology (MUT)

BACKGROUND

The Internet of Things (IoT) is extensively developed worldwide with a focus on civilian applications. However, the applicability and implications of IoT within the military environment have been immature and not well researched or examined. This group focused on the intersection of IoT in military environments. The challenge undertaken by this group was to understand the fundamental nature of IoT concerning military operations and its impact on NATO operations; research and demonstrate how aspects could be adopted, adapted, and leveraged by both NATO forces as well as by adversaries against NATO forces.

MILITARY RELEVANCE

Internet of Things (IoT) is a disruptive and pervasive technology that affects all elements of the military domain. It has the potential to change the nature of military operations imminently.

The pervasive nature of IoT, especially in urban operations of strategic importance to NATO in the future, implies that significantly more information from multiple modalities covering wider areas can be made available to military commanders, thereby reducing the time to acquire Situation Awareness and shortening the decision-making process and command timelines. The economies of scale introduced by civilian IoT devices and communication technologies can also reduce costs for military systems.

OBJECTIVE(S)

The main goals of the IST-147 activity were: a) demonstrate through proof of concept trials the value of the application of the Internet of Things (IoT) in militarily significant situations; b) define an IoT architecture or architectures that might be used in military situations; c) identify the risks associated with the use of commercial IoT technology in the military domain; and identify possible mitigations or open challenges.

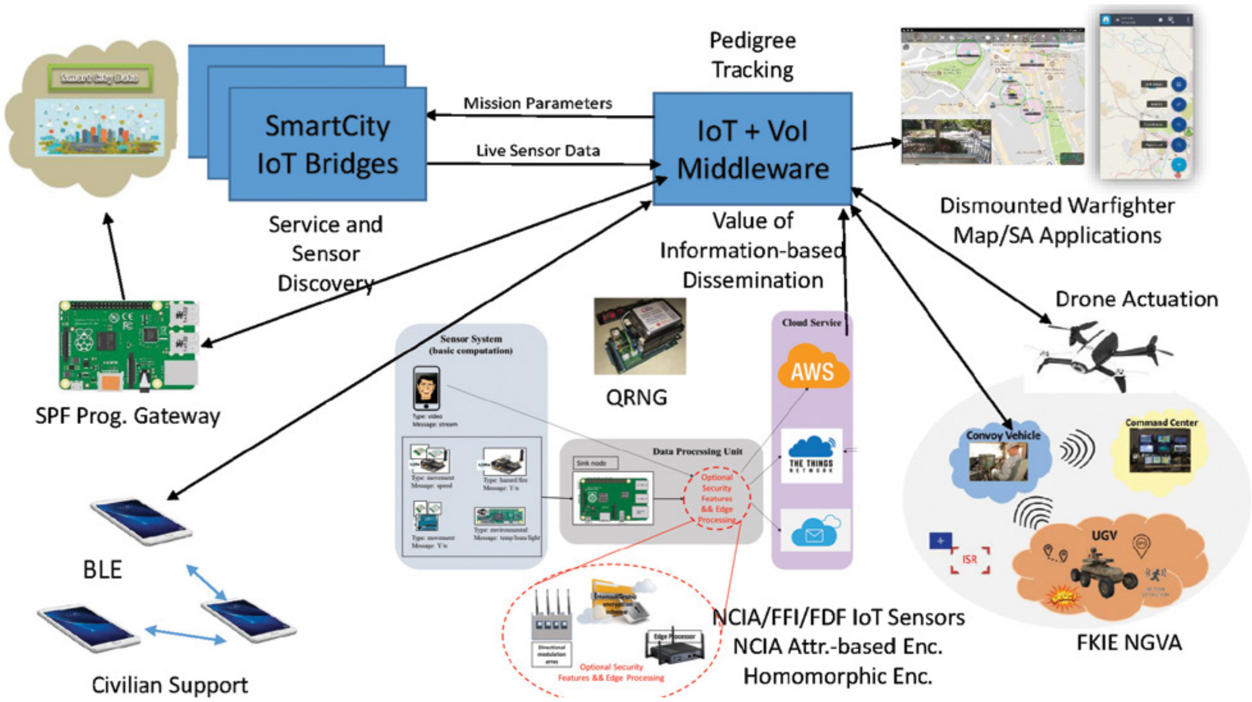

Figure 37: IoT architecture for demo and experimental verification of proposed solutions (at ICMCIS 2018).

S&T ACHIEVEMENTS

IST-147 demonstrated through proof of concept trials the challenges and benefits of applying the Internet of Things (IoT) in the military domain. Three technically advanced demonstrators of Joint Military / Civil Operations in Smart City Environments were built as examples of Humanitarian Assistance and Disaster Relief (HADR) operations. For these demos, appropriate prototype software was developed by many of the members of the RTG and then integrated into joint demonstrations. Apart from the successful technology demonstrations, the group published 24 papers in peer-reviewed conferences and journals, primarily sponsored by IEEE.

SYNERGIES AND COMPLEMENTARITIES

The group's work is an example of extensive research collaboration between industry, academia, NATO, and its allies' research organizations. The synergy of knowledge of teams from NCIA, NIAG, and ten allied countries was leveraged.

EXPLOITATION AND IMPACT

The IST-147 group's work outcomes are critical to advancing the thought and application of IoT in the military. They will help improve existing architecture, data integration, and security and trust solutions for IoT applications and provide interoperability with military C2 systems.

CONCLUSION(S)

The significant work results obtained by the group facilitated a change in perspectives within the NATO S&T regarding military applications of IoT. Through scientific analysis and experiments, the group evaluated critical operational scenarios and the impact of applying IoT technology in these operations. It examined and proposed security and trust management measures for military IoT applications. Finally, it demonstrated how military IoT adaptation and deployments in Smart city environments could significantly improve the speed and accuracy of commanders' acquisition of situational awareness.

HUMAN CONSIDERATIONS IN ARTIFICIAL INTELLIGENCE FOR COMMAND AND CONTROL (IST-157)

Over recent years, a growing recognition of the role for humans in the use of Artificial Intelligence has led to major developments supporting human-machine teaming. IST-157 has leveraged the work of other research groups to apply and update previous findings to C2 and decision-making processes. The work of IST-157 directly benefits three functional concepts of the ACT Command & Control focus area: Cognitive Computing & Advance Analytics, AI to support human sense making, and AI at the effector edge. IST-157 addresses two converging objectives:

• A comprehensive desk study/paper.

• The development and experimentation of a tool during a major NATO exercise.

Dr. Candace ESHELMAN-HAYNES, Allied Command Transformation (ACT); Mr. Hervé LE GUYADER, FRA, École Nationale Supérieure de Cognitique (ENSC)

BACKGROUND

IST-157 stems from the work conducted by the Multinational Capability Development Campaign (MCDC, 2013-2014). Its report "Focus Area Role of Autonomous Systems in Gaining Operational Access" concluded that "*The prevalence of systems employing... [Artificial Intelligence (AI)]... is growing in the military sphere; such systems will likely become a permanent feature of military operations. The implications military operations and capabilities are broad and significant. The role of [AI] in military systems is one of the most important considerations for defense policy makers in the near future. An important consideration for the design and operation of systems with autonomous capability is the level of human control in the system.*"

MILITARY RELEVANCE

In the military context, it is important that systems that employ AI remain under appropriate human control. As the implementation of AI will differ between Nations, such systems potentially deployed in parallel during a coalition environment operation will require that NATO commanders understand the subsequent effect on planning and C2. Creating a common standard for describing the role of the human operator and the role of the machine in systems that use AI will help commanders incorporate such systems in their planning processes.

OBJECTIVE(S)

The main goals of the IST-157 activity were: a) The production of an exhaustive technical report, b) the development of a prototype – ANTICIPE – and c) its experimentation in STJUA-JA20, a major NATO exercise.

> *Human considerations are a constant and crucial requirement for any artificial Intelligence based system, especially when it is used in a command and control environment.*
>
> ***The IST-157 Team.***

S&T ACHIEVEMENTS

IST-157 has produced the expected exhaustive technical report, addressing novel considerations like the importance of Human Factor in Cyber issues and in any AI code and architecture development. It has also delivered the expected capacitity demonstrator, ANTICIPE (Augmented Near real Time Instrument for Critical Information Processing and Evaluation). Because of the cancellation of STJU-JA20, because of the pandemic, IST-157 also created a follow up activity, IST-192, which will focus on the experimentation of ANTICIPE in STJU-22.

SYNERGIES AND COMPLEMENTARITIES

Seven nations and two NATO bodies participated in this research task group. This diverse group contributed to the success of the activity and the high quality of the work. Synergies with works conducted by the HFM panel were optimized.

EXPLOITATION AND IMPACT

The outcomes of IST-157 will help improve the design of future AI-based C2 systems, as already evidenced by the growing demand for live demonstrations of ANTICIPE and for presentations at high-level events.

CONCLUSION(S)

The very specific issue addressed by IST-157 epitomizes today's on of NATO's main challenge, i.e.,the importance of the human dimension in any conflict situation. Technology, as leading edge it can be, never solves problems by itself. Human factor must be firmly built-in from the start, not as an afterthought.

Figure 38: Mock-up of ANTICIPE (Augmented Near real Time Instrument for Critical Information Processing and Evaluation) Prototype.

ARTIFICIAL INTELLIGENCE, MACHINE LEARNING AND BIG DATA FOR HYBRID MILITARY OPERATIONS (IST-190)

The RSY underlined on one hand the relevance of hybrid military operations for NATO operations and how the capabilities of Artificial Intelligence (AI), in particular Machine Learning (ML) and Big Data (BD) should be applied in this context and on the other hand carved out the needs for further research activities. The combination of specialists from various technical and non-technical domains as well as military experts allowed various insights and the discussion of new aspects and challenges.

MajGen Dr. Michael FÄRBER, DEU, Bundeswehr Communication and Information Systems Command; Dr. Michael WUNDER, DEU, Fraunhofer Institute for Communication, Information Processing and Ergonomics (FKIE)

BACKGROUND

NATO Nations face the challenge of hybrid threats[1] in military scenarios that are increasingly dominated by AI-based technology. In hybrid scenarios, such as hybrid warfare there are three distinct battlefields – conventional, indigenous population, international community.

MILITARY RELEVANCE

In the context of hybrid operations, the use of AI, ML and BD has to be treated holistically and particularly involves the domains of Architectures, Intelligence Information Systems, Communication Systems, and Information Warfare. Traditional vectors like the electromagnetic spectrum are complemented by components from cyber warfare and information warfare domains. Particularly, the last two open up a wide range of opportunities for both defensive and offensive actors to exploit modern Artificial Intelligence and Big Data technologies in order to gain superiority in a given scenario for a real or virtual battlefield.

S&T OBJECTIVES AND ACHIEVEMENTS

IST-190 reviewed, evaluated and established the state-of-the-art of exiting and emerging AI technologies. It also identified research challenges in the field of human-machine collaboration and the limitations of AI technologies in general. The outcomes of the IST-190 will help researchers to better identify the significant areas of research and – thanks to the clear statements of participants from the military branch – to focusing on operational relevant challenges.

SYNERGIES AND COMPLEMENTARITIES

200 technicians, researchers, officers and militaries from more than 20 Nations participated in this research symposium. Three well-suited key notes span a thematic umbrella from a military perspective over STO's self-conception to fundamental scientific challenges. In 34 extended papers, mostly with excellent scientific quality, various aspects of hybrid operations were elaborated and discussed.

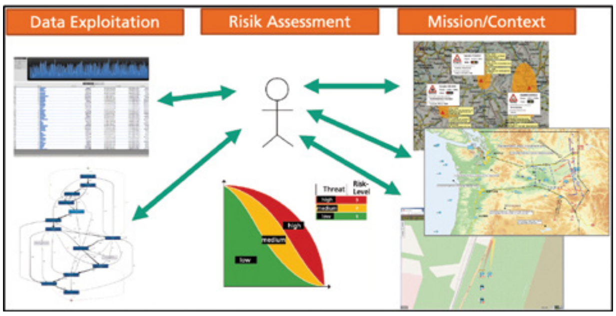

Figure 39: Detection of Hybrid Threats as prerequisite for adequate Hybrid Operations.

Several papers portrayed that the threat of combined hybrid technologies is real, and that AI/ML practitioners are gaining experience in applying them to military operations. The papers also show, collectively and in diverse ways, that defending against the threat requires the development of new and improved tools to deal with the technical challenges. The need for solutions is growing.

CONCLUSION(S)

High speed and precision are the decisive factors of future combats. A mixture of heterogeneous threats with different technical and temporal facets require a hybrid common operational picture and sophisticated AI-based means that find the needles in multiple haystacks and help operators to keep the overview and prepare appropriate operations.

1 NATO ACT: *"[…] Hybrid threats are those posed by adversaries, with the ability to simultaneously employ conventional and non-conventional means adaptively in pursuit of their objectives […]."*

AI AUGMENTED IMMERSIVE SIMULATION IN TRAINING AND DECISION-MAKING COURSE OF ACTIONS ANALYSIS (MSG-189)

MSG-189 Specialist Team activities focus was that of evaluating how to combine and integrate, into the evolution of M&S techniques and related Simulation systems, the new Emergent Disruptive Technologies. In particular, the study analyzed those that could potentially have a positive impact into this evolution aiming at providing a better and more efficient support to Training and Decision-Making.

Ing. Agatino MURSIA, ITA, Leonardo S.p.A, Investments & Technology Plan Governance

BACKGROUND

In recent years, new emerging technologies have had a remarkable development and have shown a good degree of maturity. The main enabling technologies (partial list) identified for MSG-189 study are:

- Artificial intelligence (AI)/Machine Learning (ML)
- Big Data and Advanced Analytics (BDAA)
- Augmented/Virtual/Mixed Reality
- Live-Virtual-Constructive simulation systems
- Cloud based technologies (MSaaS)
- Cyber Security Technologies
- New generation communications (5G)

The integration and proper use of these technologies into the evolution of current M&S systems could be realized through the specification of a new M&S Ecosystem based on a Reference Architecture enabling the requested support for the decision makers and the proper advanced training.

MILITARY RELEVANCE

Both tactical and strategic scenarios have shown an urgent need for an efficient and effective support in the decision-making process. A characteristic of these scenarios is the huge quantity, heterogeneity, speed and obsolescence of the information available to personnel (both civil and military) called to manage them and act rapidly at various levels of engagement. Advanced staff training through innovative Simulation Products/Services is the key factor that allows better facing and resolving these situations using a proper decision-making process.

> *Far from being the smartest possible biological species, we are probably better thought of as the stupidest possible biological species capable of starting a technological civilization — a niche we filled because we got there first, not because we are in any sense optimally adapted to it.*
>
> ***Nick Bostrom, Superintelligence: Paths, Dangers, Strategies.***

OBJECTIVE(S)

The objectives achieved by the MSG-189 working group are:

- An overview of the state-of-the-art of each of the enabling technologies (AI, BD, XR etc.) aimed at defining the qualifying aspects that each of them can play in the proposed future simulation framework for training and decision-making support

Figure 40: Volume of Interest for MSG-189.

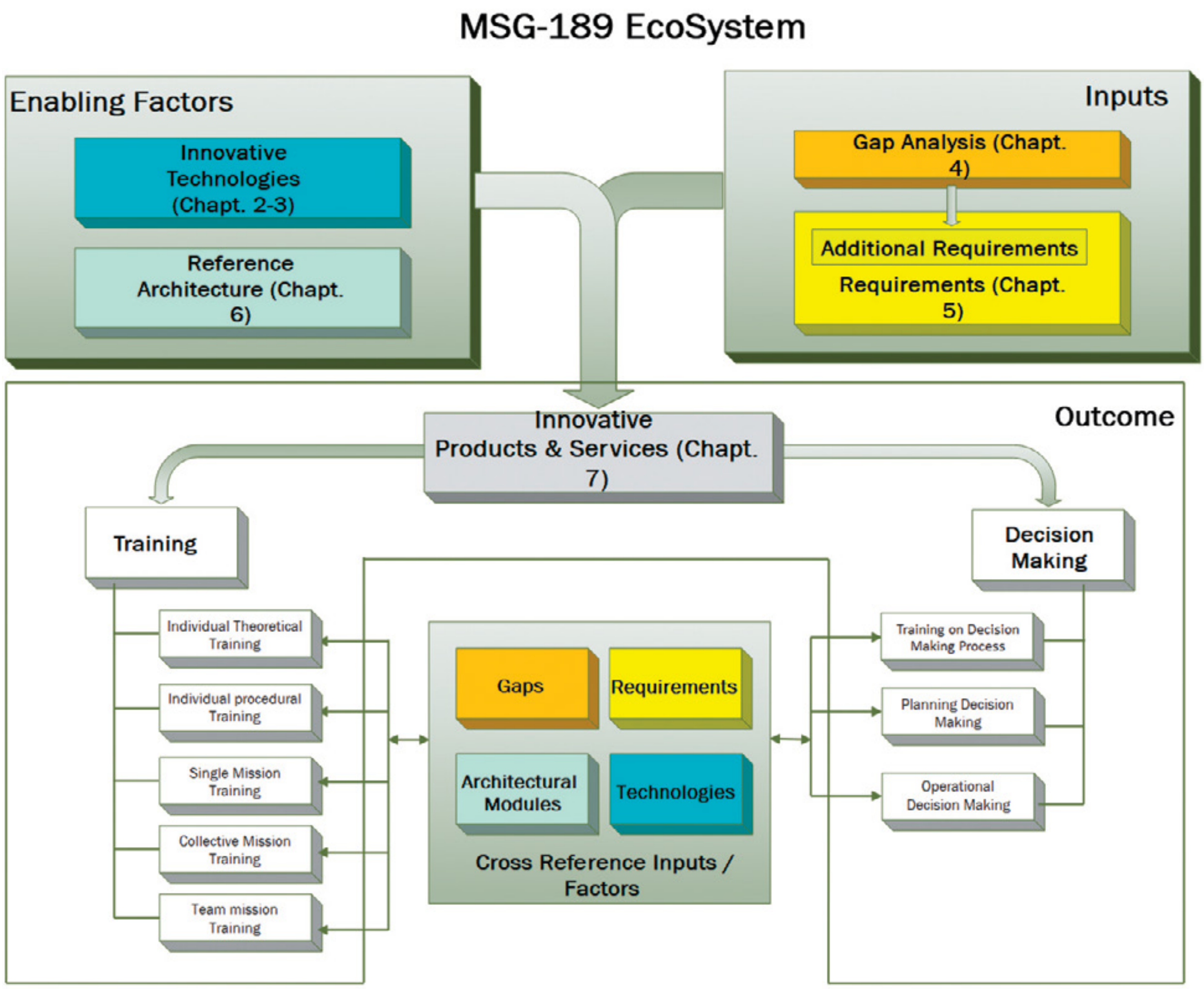

Figure 41: MSG-189 Ecosystem.

- The indication of the gaps, in the training and decision-making military fields, to which the proposed technologies can provide a valuable and viable solution
- The definition of the system requirements of the simulation framework
- The definition of a reference architecture on which an open, interoperable and extensible MSG-189 M&S Ecosystem can be built
- The specification of Simulation Products/ Services that the resulting MSG-189 Ecosystem could provide
- The dissemination of the resulting ST Technical Report

The MSG-189 defined an M&S Ecosystem described by a Reference Architecture. The produced Reference Architecture has its main foundation on long standing and very important NMSG activities such as MSaaS and MTDS. MSG-189 ST activities built on those references to find new and innovative solutions that can enhance the use of a critical technology such as M&S. A “secure” design concept with a high resilience of the infrastructure to cyber threats (Secure by Design) is also indicated as a specific requirement to be met.

Another point to highlight of the Reference Architecture is the relationships among its building blocks and the products/services provided. They constitute a set that can be composed and tailored to what the user needs to do regardless of the type of user (teacher, student, commander, front line soldier, etc.) and the type of activity (training or decisions making) they are doing.

S&T ACHIEVEMENTS

The possibility of introducing new technologies as enablers to improve what already exists or to provide new innovative solutions to solve problems that do not currently have one was debated. This is not so straightforward unless you have a modular structure where the relationships between modules are well defined.

The first step was that of identify a specific Volume of Interest for the MSG-189 in the M&S Space, then functionalities and uses of the resulting MSG-189 Ecosystem were described with regard to two specific areas: the Training of military personnel (including the Decision Makers) and the support for the Decision-Making Process of Commanders and their staff.

SYNERGIES AND COMPLEMENTARITIES

Below is a list (non-exhaustive) of NATO STO working groups that have addressed issues related to the study in question:

- MSG-155/MSG-186 Data Farming
- MSG-164 MSaaS
- IST-173 AI and BD for MDM
- IST-121 – Machine Learning Techniques for Autonomous Computer Generated Entities
- MSG-145 C2SIM
- MSG-ET-050 Standards for XR
- MSG-193 M&S Standards in FMN
- AMSP-01 - NATO MODELLING AND SIMULATION STANDARDS PROFILE

EXPLOITATION AND IMPACT

In summary, the ST MSG-189 started to define a new way of supporting Training and CoA Analysis for Decision-Making. This will also in time produce a very high impact into the definition and building of future C2 systems, armaments and information management systems. These new systems will have embedded a capability of providing to the decision makers a very broad range of products/ services to complete any type of mission in the best possible way minimizing risks, human casualties and maximizing probabilities of success.

AI, M&S and XR have their own well-established CoI that, thanks to this activity, have the possibility to better exchange state-of-the-art knowledge present in their respective area of competence. Interoperability and Standardization in NATO could also improve by having these three domains working together.

CONCLUSION(S)

The purpose of the ST was to quickly exploring a topic of interest to the stakeholders who have endorsed it and decide whether it is necessary to further investigating with follow-on activities certain areas and/or correlations/synergies identified during the development of the ST itself.

These principles inspired the work of the MSG-189 ST; the result of the activity carried out is presented in a final report that is a good starting point for successive Task Groups, as it provides a view of what the actual possibilities are and what are expected to become available in the near future.

As possible suggestion for a follow up working group is that related to the definition of a certain number of use cases in the FMN domain in order to validate the choices made and demonstrate the validity of the MSG-189 Ecosystem.

GAMIFICATION OF CYBER DEFENCE/RESILIENCE (SAS-129)

Gamification techniques can be useful in training and education regarding different cyber defense/resilience scenarios in a joint and high-pressure environment. Thus, gamification provides opportunities to understand the possibilities inherent in cyber defence and train or educate people while keeping the training interesting, contributing to ever increasing critical needs for cyber defence needed by the NATO nations.

Mr. Levent Berke ÇAPLI, TUR, Mecra Yazilim; Mr. Geert ARENDS, NLD, Cyber Warfare & Training Centre Ministry of Defence

BACKGROUND

Close bilateral and multinational cooperation plays a key role in enhancing the cyber defence capabilities of the Alliance. Technological innovations and expertise from the private sector are crucial to enable NATO and Allies to achieve the Enhanced Cyber Defence Policy´s objectives. Serious games are simulations of real-world events or processes designed for the purpose of understanding problems. Although serious games can be entertaining, their main purpose is to train or educate users. Gamification is the use of game thinking and game mechanics in non-game contexts to engage users in solving problems and increase users´ self-contributions.

Gamification will increase cyber security awareness in a more attractive format.

MILITARY RELEVANCE

Cyber threats and attacks will continue to increase in numbers, sophistication and potential damage and this activity will contribute to cyber defence resilience in modern NATO environments. Cyber security game/gamification solutions can be used to train or educate people. Conventional methods for raising the general awareness are often either costly or ineffective, therefore one of the possible solutions for training and education is developing serious game and gamification applications.

OBJECTIVE(S)

The research team aimed at producing a guide for cyber security serious game acquisition and utilization for smart buyers, serious game developers and training experts. The guide will also include common development problems in serious games and a catalogue of already available cyber security serious games.

S&T ACHIEVEMENTS

The team provided an analytical framework for the use of games in cyber defense/resilience training and education and to demonstrate the use of these concepts using one or more prototypes. The report contains key questions that needs to be answered before a serious game acquisition project to provide a guide for the smart buyers. Finally, the report includes a taxonomy based serious game examples that the SAS-129 team catalogued during their research to understand the wide spectrum of gamification and serious game applications for cyber security training/education.

Figure 42: Cyber Resilience Card Games.

SYNERGIES AND COMPLEMENTARITIES

The team leveraged the work of national team members, coordinated with the NATO Cooperative Cyber Defense Center of Excellence and national defense organizations. The team utilized the results of the SAS-116 team on Military Strategic Level Decision-Making within a (future) Framework of Cyber Resilience that identified a list of strategic/senior level decision makers and decision types and developed 15 Use Case of strategic/senior level decisions. Members from the team have already demonstrated and reviewed the use of one cyber defense game in German Staff Officers Course and NATO COE DAT Terrorist Use of Cyber Space Course. Further, another serious game on tactical use of cyber assets in conventional battlefield has been under development in US Air Force Institute of Technology.

EXPLOITATION AND IMPACT

This work will advance strategic and operational decision-making and synchronization in NATO by developing war gaming capabilities in many

NATO Organizations and Nations, sharing best practices, identifying and encouraging the use of innovative methods for war-game analysis, and establishing a NATO analytical war gaming community of interest.

CONCLUSION(S)

Gamification and serious game methodology guidelines for cyber defence and resilience will be developed. One or more prototype demonstrations implementing this methodology will be developed. As cyber security is leaving cyber space and moving into modern battlefield need for training is ever increasing for end-users, commanders and decision makers.

COLLABORATIVE SPACE DOMAIN AWARENESS (SDA) DATA COLLECTION AND FUSION EXPERIMENT (SCI-311)

The SCI-311 RTG effort involved 31 globally distributed ground sensors from six participating nations and nine processing, storage, and visualization capabilities from four participating nations. These resources were used to explore and assess experimental approaches to support collaborative space object tracking and orbit determination. Membership in the SCI-311 RTG comprised 46 individuals, representing 12 NATO nations and agencies.

Ms. Carolyn SHEAFF, USA, Air Force Research Lab (AFRL)

BACKGROUND

Comprehensive operational awareness of the space domain is essential to the achievement of the NATO Long Term Aspect requirement for NATO Space Capability Preservation.

MILITARY RELEVANCE

NATO must ensure that their forces maintain continuity of operations and availability of space-based infrastructure for communications, PNT, and surveillance. The diversity of space-related data and products, which includes variations in data protocols and sensor attributes, requires a common integrated environment within NATO planning and operations domains to ensure the timely exploitation of those data and products. Through more effective collaboration strategies, NATO will achieve more accurate solutions through greater geometric diversity, enhanced observability of space objects, and timeliness of reporting. This leads to improved interoperability and SSA, enhanced capability to predict and avert collisions, and improved resiliency against outages and malfunctions. In addition, NATO will benefit from more effective operations planning and support for communications, PNT, remote sensing, launch support, and weather effects analysis. Finally, this effort will facilitate the integration/interface between upcoming commercial global space traffic management and military SSA.

OBJECTIVE(S)

The main objective of the SCI-311 RTG was to conduct a collaborative experimental activity that involved the collection and exchange of SDA data and information to support collaborative space object tracking.

S&T ACHIEVEMENTS

The SCI-311 RTG demonstrated that significant tracking performance improvements can be obtained through collaborative tracking. In addition, the experiment produced real-world data and analysis to support the development of NATO's Overarching Space Policy (OSP) and laid out a clear path for future space developments.

SYNERGIES AND COMPLEMENTARITIES

Several NATO nations have developed a range of different sensors and processing approaches/techniques. Through collaboration, NATO benefits from a diversity of phenomenology and geographic coverage, which leads to improved capabilities. Also, see SCI-ET-036, SCI-238 RSM and SCI-279 RTG. This experiment achieves a very high level of synergy/complementaries between systems and resources among several Nations, including SCI-ET-036, SCI-238-RSM, and SCI-279 RTG. Then delete remaining sentence.

EXPLOITATION AND IMPACT

The primary impact of this effort is in the Interoperability and Standard arena. This effort will identify and evaluate the nature of common formats/standards that are needed to enable a basic SSA common exchange/storage capability across NATO. Several efforts underway to develop/implement such standards – we don't want to reinvent anything - this experiment will help validate them and/or analyze how they need to be extended to enable a basic SSA collaboration capability. In addition, this experiment will exercise new data collaboration procedures - provides an initial assessment of those procedures, results in lessons learned to inform future investments and developments.

CONCLUSION(S)

In general, collaborative tracking can significantly improve space object tracking accuracies. To achieve this improvement, complete and accurate sensor parametric information must be shared among participants.

> *Collaborative tracking can significantly improve space object tracking accuracies.*
>
> ***The SCI-311 Authors.***

AUTONOMY FROM A SYSTEM PERSPECTIVE VERSION 2.0 (SCI-335)

The overarching objective of SCI-335 was to further refine the areas where NATO should increase scientific and technical focus in autonomy and autonomous systems (AS). Specific emphasis was added to increasing developments and focus in autonomy while preserving the values and norms of the Alliance. The Specialist Meeting included perspectives from all technical areas relevant to autonomy as well as ethical and philosophical discussions relating to the role of autonomy as it assumes greater human responsibilities.

Mr. Jean-Charles LEDÉ, USA, Air Force Research Laboratory (AFRL)

BACKGROUND

SCI-335 built on the work of at least four previous SCI activites related to autonomous systems. This Specialist Meeting was designed to build on the momentum of those prior efforts while investigating a few key topics previously identified. The meeting participants included representatives from operational and S&T communities in the nations of CAN, DEU, EST, FRA, GBR, NLD, NOR, USA. Their collective expertise included science, engineering, human factors, policy, ethics, operational analysis, academia, industry, program management, military operations, and more.

MILITARY RELEVANCE

Autonomy can be simply defined as the (bounded) freedom to select a course of action to achieve a superior's objective(s). With this broad definition, autonomy applies to a large range of systems and situations from simple decisions to highly complex ones. At the lowest levels, autonomy relates to Daniel Kaheman's fast system[2] (system 1) providing fast reactive decisions such as maintaining attitude, obstacle avoidance, moving in the environment, or other forms of "athletic intelligence," and extends to system 2 deliberative intelligence that, for example, leads to greater situational awareness, high-level command decomposition, task distribution, or adaptive behaviours. The benefits that AS offer operators include simplified and more precise operations, reduced crew interactions, expanded span of command over distributed systems, or decentralized decision processes. These in turn translate into military advantages such as: faster and more robust response to adversary actions, reduced dependency to high bandwidth communication, reduced human exposure to high risk environments, ability to perform in complex dynamic and uncertain multi-domain operations. New features being added to autonomy currently include the ability to reason and learn, and the ability to collaborate with other robots and systems either manned or unmanned. These new attributes will greatly expand AS flexibility and usefulness.

2 See *Thinking Fast and Slow* by Daniel Kahenan

OBJECTIVE(S)

Building on the findings of the 2017 SCI-296 Specialist Meeting on 'Autonomy from a System Perspective' which identified 17 topic areas and possible future activities related to AS, this "Version 2.0" was conducted to continue developing the AS thematic established by the previous events. The 2021 event focused on issues such as the optimization of human-machine resource allocation of the future force, enhancing trust in human-machine teaming for multi-domain operations, and conceptual approaches for evaluation, war gaming, and demonstration of AS in a relevant operational environments. In breakout sessions, the specialists considered how to appropriately pair mission capabilities and autonomy at various levels of human-machine interdependency allowing optimal use of the respective strength. Other breakouts reviewed the maturity level of high-payoff areas in autonomy, and formulated recommendations for areas of increased focus.

> *The Emerging Disruptive Technologies (EDT) implementation strategy calls for NATO to analyse autonomy in the context of potential military capabilities and to contribute to an autonomy implementation plan"*
>
> ***Dr Bryan WELLS, NATO Chief Scientist.***

S&T ACHIEVEMENTS

SCI-335 recommended a list of topics for which a program plan should be developed in which major lines of effort are elaborated. These topics address fostering progress and maintaining the technological edge of NATO with respect to AS technologies. In particular, the group drafted three topics for follow-on technical activities looking at emerging threats and opportunities:

- Counter Autonomy: understand the threat posed by the development and use of Autonomy/AI, and how can we use the Alliance S&T knowledge base to research and develop specific counter measures or interventions in the kill chain or the supply chain.

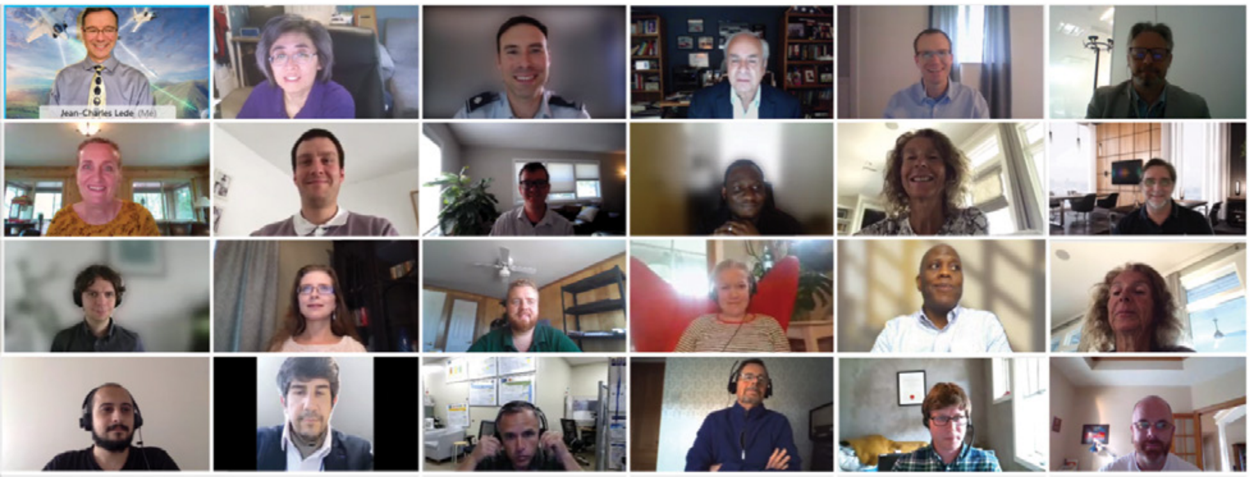

Figure 43: A few of the participants at the SCI-335 Specialist Meeting held virtually, May 2021.

- Accelerating AI: although there are numerous S&T efforts in autonomy and AI, development and adoption are slow. A new research group should review historical or ongoing examples of autonomous system development in the military and in the commercial sectors; identify best practices and common issues; and make recommendations on addressing these issues or generalizing best practices.

- Trustworthy AS: Trust in AS remains a significant barrier to the use of Autonomy. A research group should explore the human and system characteristics required to achieve the appropriate level of trust and the desired operational objectives.

SYNERGIES AND COMPLEMENTARITIES

SCI-296, SCI-299, SCI-331

EXPLOITATION AND IMPACT

Autonomy is a cutting-edge field with significant implications for military forces. Autonomy is poised to offer force multiplication effects, new combat strategies such as distributed systems and synchronized actions, increased speed of operations across multiple domains, logistics optimization, or dynamic system-of-system composability. It will be important for nations to stay at the forefront of this field to prevent technological surprises and to gain experience with the technology to guide the establishment of ethical use and standards. There are areas where autonomy and autonomous systems can prove useful today and have immediate military applications. For example, autonomy can be gradually inserted in current manned platforms to provide operator assistance, or unmanned platforms to improve resilience to communication outages. Autonomy can improve manual processes, leverage massive amounts of data, and develop candidate courses of action providing enhanced situational awareness and decision aids for commanders. Collaborative autonomy is becoming viable and will have the capability to coordinate actions of large groups of systems to overwhelm defenses or defeat large-scale attacks.

CONCLUSION

NATO has the unique opportunity and position to accelerate the adoption of autonomous systems and ensure their use is consistent with our shared values while providing significant military benefits in the near, mid, and far term as the technology matures. NATO can help establish autonomous systems standards in trustworthiness, interoperability, user interface, and other requisites. Autonomy is still new and requires exploration to reap its benefits. Coordinated exploration will accelerate the adoption of autonomous systems and allow NATO to maintain technological edge supporting the safety and security of the allied nations. This will also enable NATO to explore and establish the ethical use cases of this technology and lead by example.

NATO STO Programme of Work

EXCELLENCE IN NATO SCIENCE AND TECHNOLOGY

EXCELLENCE IN NATO SCIENCE AND TECHNOLOGY

Every year, the NATO Science & Technology Board (STB) recognizes outstanding achievements in the international collaboration on Science & Technology (S&T) within the NATO framework. In order to motivate individuals and teams alike to continue providing exceptional contributions to the benefit of the STO community and the Alliance writ large, the STB presents to types of awards: the Von Kármán Medal and the STO Excellence Awards.

VON KÁRMÁN MEDAL

The Von Kármán Medal is awarded to highly accomplished individuals with a lifetime dedication to international S&T collaboration in NATO. Through exemplary service, recipients repeatedly delivered significant contributions to STO activities over a long period. They combine an internationally recognized career in S&T with leadership and vision to advance the S&T collaboration among the Allied nations. Typically, the STB awards only one Von Kármán Medal per year.

Figure 44: Von Kármán Medal.

2021 VON KÁRMÁN MEDAL RECIPIENT – PROFESSOR AFZAL SULEMAN (PRT)

In spring 2021, the STB awarded the 2021 Von Kármán Medal to Professor Afzal Suleman (PRT). For over 20 years, Professor Suleman has delivered an exemplary service representing Portugal in the NATO Science & Technology Organization. He has made outstanding contributions to research and development in the fields of aeronautics, with a particular focus on unmanned air systems, aero-elasticity and morphing wing technologies.

Figure 45: Professor Afzal Suleman.

Throughout his career, he has championed the education of the next generation of aerospace engineers, designing courses at the University of Victoria and the University of Lisbon Instituto Superior Técnico to enable experiential learning for both undergraduate and graduate students. He has been critical in exposing young scientists to NATO S&T activities and over the course of his career, has supervised 35 PhD and 80 MSc theses.

Within the NATO community, Professor Suleman has represented Portugal at the Applied Vehicle Technology (AVT) Panel with exceptional dedication, including as a Panel Mentor and the Chair of a range of activities. His excellent work within the STO is demonstrated in his receipt of two AVT Panel Excellence Awards for his valuable scientific contributions to the Panel, and for his successful lecture series on the Structure Health Monitoring of Military Vehicles. Professor Suleman has exemplified the spirit of transatlantic collaboration, making significant contributions to the technological cooperation between Portugal and Canada through the AVT Panel Support Programme. He has developed synergies between the University of Lisbon Instituto Superior Técnico, University of Victoria, and the Portuguese Air Force and has fostered exchange student programmes between Portugal and Canada.

Professor Suleman has demonstrated a history of high quality and dedicated authorship. He has authored/co-authored over 120 scientific journal publications and over 350 conference papers in diverse areas such as the modelling of coupled fluid-structure problems and the application of smart structures concepts to active aeroelastic control of composite airframes. He has also published over 500 technical papers and several patents. Professor Suleman has served NATO S&T with excellence and professional integrity.

STO EXCELLENCE AWARDS

The STO Excellence Awards recognize exceptional accomplishments in recent STO activities, conducted and completed during the last four years. Recipients delivered high quality original work of considerable military relevance and benefit, while achieving a significant degree of international collaboration. The STO Excellence Awards can be granted to teams and to individuals. The STB typically presents several such awards every year.

The 2021 STO Excellence Awards were granted to the following two teams and one individual:

- Littoral Continuous Active Sonar Multinational – Joint Research Project" (CMRE-LCAS)
- Innovative Control Effectors for Maneuvering of Air Vehicles, and Demonstration (AVT-239/AVT-295)
- Mr. Bharatkumar Patel (MSG, GBR)

LITTORAL CONTINUOUS ACTIVE SONAR MULTINATIONAL – JOINT RESEARCH PROJECT (CMRE-LCAS)

Led by: Mr. Vince Rose, AUS; Mr. Stefan Murphy, CAN; Mr. Gary Wood, GBR; Cdr. Mirko Stifani ITA; Ms. Connie Solberg, NOR; Dr. Nathaniel de Lautour, NZL; Dr. Keith Davidson, USA; and Dr. Kevin LePage, USA

In the Littoral Continuous Active Sonar (LCAS) Multinational-Joint Research Project, five NATO and two partner nations joined together with NATO STO Centre for Maritime Research and Experimentation (CMRE) to study how continuous active sonars could be exploited for submarine target detection and tracking in littoral environments. Activities included the design and execution of four sea trials over a six-year period, including two with live submarine targets. The scientific approach was based on the simultaneous collection of data for both continuous active and traditional sonar waveforms under the constraints of equal energy and bandwidth, for identical environmental conditions and geometries, enabling the meaningful comparison of results. The collection of much supporting environmental information allowed for the validation of new theories generated within the project for explaining the sensitivities of the results observed to measurable parameters.

These theories and associated models enabled the project to generate guidance as to how existing CAS sonar sets should be used in the littorals and how these sonar sets may be further improved in future to maximize performance in confined, brown, and coastal waters. This effort directly informs both the operational and capability development communities within NATO and the LCAS partner nations.

INNOVATIVE CONTROL EFFECTORS FOR MANEUVERING OF AIR VEHICLES, AND DEMONSTRATION (AVT-239/AVT-295)

Led by: Dr. Douglas Smith, USA and Prof. Clyde Warsop GBR

The NATO STO AVT-239 Research Task Group (RTG) and the following NATO STO AVT-295 RTG for a Cooperative Demonstration of Technology (CDT) came together to investigate the application of novel flight control technologies for aircraft maneuvering.

Candidate technologies were identified, developed, and assessed against key vehicle performance and vehicle integration criteria (e.g., complexity, maintainability, reliability) in order to minimize the reliance on conventional control surfaces during portions of the vehicle mission profiles. Combined experimental and high-fidelity numerical simulations as part of the group achievements enhanced the assessment. The aerodynamic data was then incorporated into flight dynamics simulations where flow control technologies were used to provide flight control in lieu of conventional control surface deflections.

The group demonstrated two active flow control approaches, namely tangential blowing on the trailing edge and yaw fluidic thrust vectoring, that when applied in tandem yielded sufficient yaw and pitch control at acceptable levels of engine bleed to provide vehicle control during the ingress mission for two different configurations. This was an outstanding example of multidisciplinary teaming of academia, government, and industry collaborating to find solutions to complex problems to help the defense of NATO nations.

Figure 46: AVT 239-295.

MR. BHARATKUMAR PATEL (MSG, GBR)

Mr Bharatkumar Patel has actively led and conducted excellent collaborative and innovative research in the area of modelling, simulation and synthetic environments on behalf of the United Kingdom for over 25 years. As UK National Member in NATO's STO Modelling and Simulation Group, as well as in the Systems Concept and Integration (SCI) Panel, he has taken on many leadership roles in the STO including Chair, Panel mentor, program committee member, and technical team member in numerous NATO technical activities.

Over the last two decades, he has significantly contributed to the development of NATO's S&T capabilities, while maximizing the potential for exploitation into military capability through outreach and demonstrating benefit across the Alliance. He has championed the Command and Control to Simulation Interoperability (C2SIM) research in UK and NATO and has evaluated the underpinning technology and standard that are now ready for exploitation into military capabilities across the Alliance, including leading the transfer of C2SIM knowledge to stakeholders and the supplier base.

Mr Patel was part of the original NATO team that pioneered the original Modeling & Simulation as a Service (MSaaS) concept. He has been instrumental in moving the concept towards a sustainable and an affordable secure M&S ecosystem driven by a viable business model as well as leading the outreach programme to educate the Alliance on the benefits and challenges to changing to an ecosystem approach.

ANNEXES

70 YEARS OF COLLABORATIVE SCIENCE AND TECHNOLOGY

A rich history of scientific and technological advancement paved with important milestones

NATO OTAN

S&T organization

The strength to refine and employ new technologies has for decades provided countries in the NATO alliance with a multitude of cutting-edge capabilities to ensure military advantage, provide security to our societies, and protect the sovereignty of our democracies. Global technological leadership has been the foundation upon which NATO's ability to deter and defend against potential threats ultimately rests.

The NATO Science and Technology Organization (STO) has a rich history dating back to 1952, dedicated to ensuring that NATO maintains this technological and military edge over competitors and adversaries. Throughout these 70 years, STO and its predecessor organizations have fostered an international community of world class scientists, engineers, and military operators to meet the challenges and opportunities driven by rapidly evolving technologies through an exchange of knowledge, experiences and perspectives across NATO.

Our founder was driven by a wise philosophy:

Scientific results cannot be used efficiently by soldiers who have no understanding of them, and scientists cannot produce results useful for warfare without an understanding of the operations.

— Dr. Theodore von Kármán

AGARD

1952

Advisory Group for Aerospace Research and Development (AGARD)

Led by Professor Dr. Theodore von Kármán and his collaborative vision, AGARD is founded in April 1952 to foster the interchange of information relating to aerospace research and development between NATO nations and provide scientific and technical advice and assistance to the NATO Military Committee.

1958

NATO Science Committee

The desire of NATO Heads of Government to improve the coordination and effectiveness of the Alliance's scientific and technological resources leads to creation of the NATO Science Committee, along with the joint post of Science Advisor to the Secretary General and Assistant Secretary General for Scientific Affairs.

1963

Defence Research Director's Committee (DRDC)

The Defence Research Director's Committee (DRDC) becomes a permanent and independent committee of NATO. It attempts to bridge both the civil and military aspects of science at NATO. DRDC provides scientific and technical advice to NATO's Military Authorities on the formulation of operational requirements.

1967

Defence Research Group (DRG)

Major NATO reorganization in cooperative action for research and technology leads to abolishment of the DRDC. Its responsibilities are taken up by the Defence Research Group (DRG), which reports to the NATO military Authorities and the newly established Conference of Armaments Directors (CNAD)

DRG GRD

The end of the Cold War led to reductions in NATO member military budgets and the drive toward better coordination of pooled resources and avoidance of duplicated efforts.

RT ORGANIZATION

1998

NATO Research and Technology Organization (RTO)

The need for more cohesion and cost-effectiveness, and a single focus in NATO for air, land, sea and space research activities, results in AGARD and DRG merging to form the NATO Research and Technology Organization (RTO).

1999

Modelling & Simulation Group (NMSG) and Coordination Office (MSCO)

The NATO Modelling & Simulation Group and Modelling & Simulation Coordination Office (MSCO) are created to help improve the cost-effectiveness of Alliance operations (e.g., defence planning, training, exercises, support to operations, research, technology development and armaments acquisition).

S&T organization

2012

Science and Technology Organization (STO)

The current STO structure is established on 1 July 2012, bringing with it a renamed Centre for Maritime Research and Experimentation (CMRE) and Collaboration Support Office (CSO), and the new Office of the Chief Scientist (OCS) to combine 60 years of expertise and a legacy of achievements that continues today.

2021

Launch of NATO 2030

NATO 2030 is an ambitious agenda focused on making sure NATO remains ready, strong, and united for a new era of increased global competition and increased threats, including new disruptive technologies and climate change. STO has a critical role in delivering innovation, advice, and science and technology solutions to meet NATO's ever-changing needs and ensuring that NATO maintains its technological edge.

1959

SACLANT ASW RESEARCH CENTRE

The SACLANT ASW Research Centre was established in 1959 to provide scientific and technical advice to the Supreme Allied Commander Atlantic (SACLANT) in the field of antisubmarine warfare and to respond to the needs of NATO nations and maritime commands.

1987

In 1987 SACLANT ASW Research Centre changed its name to the SACLANT Undersea Research Centre. It reflected both changes within the NATO military organization (end of Cold War) and changing priorities in the research program.

SACLANT UNDERSEA RESEARCH CENTRE

2003

NURC

In 2003 the SACLANT Undersea Research Centre became NURC – NATO Undersea Research Centre. Finally, in 2012 the name was changed to the current CMRE – Centre for Maritime Research and Experimentation.

THE OFFICE OF THE CHIEF SCIENTIST

The Office of the Chief Scientist (OCS) is the STO executive body closest to the senior political and military leaders at NATO Headquarters. As the senior advisor to NATO leadership, the Chief Scientist has played a vital role in advising on the science and technology underpinning the next generations of military capability.

The OCS supports the Chief Scientist in two essential functions: as Chairman of the Science and Technology Board (STB), and as senior scientific advisor to the NATO leadership. In addition to providing executive support to the STB and its responsibilities, the OCS acts as the focal point for the STO work programmes (PoWs) and its users represented at NATO Headquarters. To this end, the OCS works with the S&T results generated through STO PoWs and promotes their use in the political and military context. Involving committees and staffs at NATO Headquarters and beyond, the OCS coordinates the generation of an overview of NATO S&T programmes across the Alliance to selectively highlight the most relevant and recent S&T results that are available to inform NATO decision-making.

In addition, OCS staff support the Chief Scientist in providing analysis of significant S&T trends and developments, while conveying an in-depth assessment of the potential impact of S&T and security EDTs on Alliance objectives.

Throughout 2021, the COVID-19 pandemic continued to influence STO work and networked communication, which are increasingly agile and virtual. The use of IT tools characterized most meetings and events. For example, the STB meetings (Spring and Fall) both the STO Plans & Programmes Workshop (PPW), the Disruptive Technologies Table-Top Exercise and the Programmatic Deep Dives were held virtually, as well as the communication event “Shaping the Future of S&T: Young Scientists in NATO” which attracted more than 200 participants from all over the world, and further increasing and spreading the STO network.

During the Fall there was a physical meeting of the SSG (Strategy Sub-Group) in Lerici (La Spezia) in October 2021, a Partnership Event at NATO HQ in Brussel in November, and with a DST (Distributed Synthetic Training) Workshop at NATO HQ in December. Responding to the NATO leadership’s increasing focus “on innovation and Emerging and Disruptive Technologies (EDTs) in particular, the Chief Scientist continued to steer the work of the STO to enhance the impact of S&T for nations and NATO and, under his leadership, the OCS strengthened strategic communication on that impact.

As a member of the Innovation Board, the Chief Scientist continued his work in advising senior leaders on how to address emerging and disruptive technologies, promote innovation and maintain the Alliance’s technological and knowledge advantage.

Due to the growing recognition of the importance and challenge of maintaining a technological advantage for the Alliance, there is a growing demand for evidence-based advice and scientific insights that the STO can bring to NATO Headquarters. The Chief Scientist and his staff are committed to meeting this demand.

THE COLLABORATIVE PROGRAMME OF WORK

Within the STO, NATO and Partner Nations benefit from a collaborative framework to address S&T issues and challenges of common interest.

The following six Panels and one Group address the total spectrum of this collaborative effort:

AVT	Applied Vehicle Technology Panel
HFM	Human Factors and Medicine Panel
IST	Information Systems Technology Panel
SAS	System Analysis and Studies Panel
SCI	Systems Concepts and Integration Panel
SET	Sensors and Electronics Technology Panel
NMSG	NATO Modelling and Simulation Group

These Panels and the Group are the powerhouse of the collaborative model and are made up of a network of approximately 5,000 national representatives, including recognized worldclass scientists, engineers, and information specialists. In addition to providing critical international S&T management and scientific oversight, they also provide coordination and cooperation opportunities with military users and other NATO bodies.

The scientific effort is carried out by Technical Teams, created inside one or across several of the Panels and Group, on specific research topics and have a defined duration (usually, from one to three years). These Technical Teams can take a variety of forms, including Task Groups, Workshops, Symposia, Specialist's Meetings, Lecture Series, and Technical Courses. All together, these activities represent the CPoW. In all cases, these activities result in the publication of highly valued scientific literature. The results of the research can also be found in some scientific peerreview journals.

With 301 activities conducted in 2021, the Collaborative Programme of Work (CPoW) has increased its efforts by 65% since 2011. In 2021, 44 % of the CPoW activities were related to at least one EDT.

Figure 47: NATO STO CPoW brochure.

All necessary information on the status of the CPoW can be found in the 2021 CPoW brochure at: **https://www.sto.nato.int/publications/Management%20Reports/NATO_STO_CPoW_2021.pdf**

THE COLLABORATION SUPPORT OFFICE

Directed by Mr. John-Mikal Størdal, the Collaboration Support Office (CSO) provides executive and administrative support to the STO Collaborative Programme of Work (CPoW), which materializes the collaborative business model whereby NATO and Partner Nations contribute their national resources to define, conduct and promote cooperative research and information exchange. The support provided by the CSO includes supporting the business of the six STO Panels and the NATO Modelling & Simulation Group, facilitating all collaborative activities, maintaining an active network of scientists, budget planning, managing activity reports publication, as well as a support service focused on disseminating the strong S&T findings from the CPoW. This includes a dedicated outreach and information and knowledge management staff and IT tools such as the STO website, the "Science Connect" SharePoint tool, and the CPoW database. All of these tasks performed by the CSO contribute to the high quality and associated recognition of the STO CPoW.

The CSO implemented a reorganization on 1 September 2021, following the NAC approval of its new Peacetime Establishment (PE). This reorganization will improve manpower resilience and will provide additional administrative support to the CPoW where needed, especially in the areas of network cyber security, cross-domain coordination, corporate communication, and exploitation of scientific findings as well as addressing strategic S&T topics such as Emerging and Disruptive Technologies.

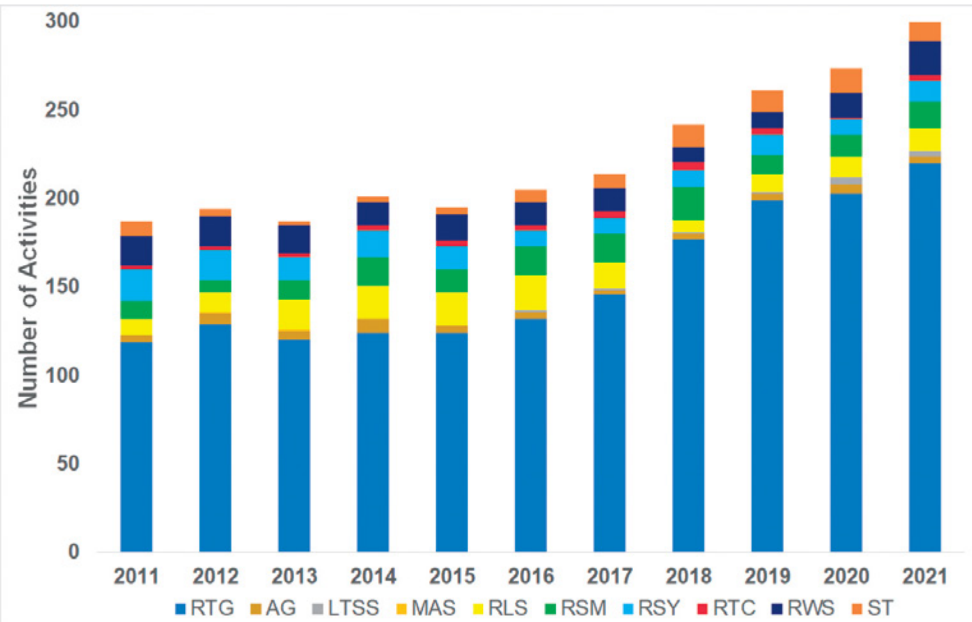

Figure 48: Trends in the NATO STO CPoW.

THE CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

ABOUT NATO STO CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

Directed by Dr Catherine Warner, the NATO STO Centre for Maritime Research and Experimentation (CMRE) is a world-class scientific research and experimentation facility focused on the maritime domain. The Centre delivers innovative and field-tested science and technology solutions to address defence and security needs of the Alliance.

Building on over 60 years of knowledge and experience, CMRE supports NATO's technological advantage in the maritime domain by strengthening the science and technology network, accelerating the development of critical capabilities within the Alliance and building science and technology capacity through partnerships. The Centre provides an outstanding at-sea research environment where internationally recognized scientists and engineers from all NATO Nations collaborate and deliver results more effectively than would be possible by individual nations.

RESEARCH VESSELS

Two NATO-owned research vessels enable CMRE experimentation ranging from concept development to prototype demonstration in an operational environment. Both ships, flagged and crewed by the Italian Navy, have modern facilities and are complementary, providing a flexible capability from the near shore to the deep ocean to the Arctic.

NATO RESEARCH VESSEL (NRV) ALLIANCE

One of the world's quietest ships, the NRV ALLIANCE is an ice-capable, global class vessel designed to minimize noise radiating from the ship into the water.

The ALLIANCE is an excellent platform for sonar testing and other types of research where a quiet platform is essential. The 93-metre, 3180 tonne, open ocean research vessel offers 400 square metres of laboratory space and state-of-the-art navigation and communication equipment.

COASTAL RESEARCH VESSEL (CRV) LEONARDO

Launched in 2002, the CRV LEONARDO is the smallest research vessel in the world that is fitted with dynamic positioning and substantial deck handling equipment. The CRV Leonardo is a 300-ton coastal vessel suitable for inshore operations, in particular research experiments with Autonomous Underwater Vehicles and port protection.

Interested in chartering a vessel? Please email **smo@cmre.nato.int**.

PROGRAMME OF WORK

CMRE conducts cutting-edge maritime scientific research and experimentation, ranging from concept development to prototype demonstration at sea. Today, the Centre's scope encompasses technological trends focused on Collaborative Autonomy, Big Data Analytics and Decision Support Tools, and Artificial Intelligence and Deep Learning. CMRE's main scientific programmes are funded by NATO Allied Command Transformation (ACT) and are designed to address future defence requirements of the Alliance in the maritime domain.

Autonomy for Anti-Submarine Warfare: Improving the Alliance's ability to counter submarine threats through networks of securely communicating autonomous systems.

Data- Environmental Knowledge and Operational Effectiveness: Using data science techniques to improve maritime situational awareness and information exchange between NATO Nations and enhancing the Alliance's ability to operate in the maritime domain through greater understanding of the operating environment.

Autonomous Naval Mine Countermeasures: Strengthening NATO's ability to counter naval mines through networks of securely communicating autonomous systems.

Maritime Unmanned Systems Enablers: Providing capabilities for the development of unmanned system of systems with a high level of interoperability, security and persistence.

The main ACT-funded programmes are supplemented by projects funded by the European Commission and the Nations.

LIST OF ACRONYMS AND ABBREVIATIONS

LIST OF ACRONYMS

3D	Three-dimensional
5G	Fifth Generation of Cellular Networks
AASW	Autonomy for Anti-Submarine Warfare
ACDC	Arms Control, Disarmament and WMD Non-Proliferation Centre
ACO	Allied Command Operations
ACT	Allied Command Operations
AFP	Agence France Presse
AFRL	Air Force Research Laboratory
AGARD	Advisory Group for Aerospace Research and Development
AI	Artificial intelligence
AIS	Automatic Identification System
AIS	Automatic Identification System
AMSP	Allied Modelling and Simulation Publication
ANMCM	Autonomous Naval Mine Countermeasures
ANTICIPE	Augmented Near real Time Instrument for Critical Information Processing and Evaluation
APL	Applied Physics Laboratory
ARIS	[Sonar]
ARL	Army Research Laboratory
AS	Autonomous Systems
ASW	Anti-Submarine Warfare
ATR	Automatic target recognition
AUS	Australia
AUV	Autonomous Underwater Vehicle
AVT	Applied Vehicle Technology Panel
BAE	British Aerospace
BARLAMARE	Bio-Acoustic Research to Learn About the Marine Environment
BD	Big Data
BDAA	Big Data and Advanced Analytics
C-EOB	Common Electronic Order of Battle
C-IED	Counter Improvised Explosive Devices
C2	Command and Control
C3	Consultation, Command and Control
C2SIM	Command and Control to Simulation Interoperability
C3B	Consultation, Command and Control Board
C3MRE	The Command, Control and Communications for Maritime Robotic Exploitation
C4ISR	Command, Control, Communications, Computers
CA	Collaborative Autonomous
CAN	Canada
CAP3	Civ/Mil Spectrum Capability Panel 3.
CAS	Continuous Active Sonar
CBRN	Chemical, Biological, Radiological, Nuclear
CCDC	Combat Capabilities Development Command
CDG	Capability Development Group
CDT	Cooperative Demonstration of Technology
CMRE	Centre for Maritime Research and Experimentation
CNAD	Conference of the National Armament Directors
CNN	Convolutional Neural Network
COE	Centres of Excellence
COL	Colonel
COMEDS	Committee of the Chiefs of Military Medical Services
CONOPS	Concept of Operations
COVID-19	Coronavirus Disease 2019
CPoW	Collaborative Programme of Work
CRV	Coastal Research Vessel
CSO	Collaboration Support Office
CTD	Conductivity-Temperature-Depth
cVAS	Compact Volumetric Sensor
CZE	Czech Republic
D2CAF	Distributed Decoupled Collaborative Autonomy Framework
D3TX	Disruptive Technologies Table-Top Exercise
DAT	Defence Against Terrorism
DEM	Data Exchange Model]
DEU	Germany [Deutschland]

DEVCOM	U.S. Army Combat Capabilities Development Command
DGA	Directorate General of Armaments [FRA]
DIANA	Defence Innovation Accelerator for the North Atlantic
DLR	German Aerospace Center
DOI	Digital Object Identifier
DOTMLPFI	Doctrine, Organization, Training, Materiel, Leadership (and Education), Personnel, Facilities, and Interoperability.
DPRC	Deputy Permanent Representatives Committee
DQ	Decision Quality
DKOE	Data Knowledge and Operational Effectiveness
Dr	doctor
DRDC	Defence Research and Development Canada
DRDC	Defence Research Director's Committee
DRG	Defence Research Group
DST	Distributed Synthetic Training
DSTL	Defence Science and Technology Laboratory
DTAG	Disruptive Technology Assessment Game
EC	European Council
EDA	European Defence Agency
EDT	Emerging and Disruptive Technologies
EKOE	Environmental Knowledge and Operational Effectiveness
EM	Electromagnetic
EME SA	Electromagnetic Environment Situational Awareness
EMS C2	Electromagnetic Spectrum Command And Control
ENSC	École Nationale Supérieure de Cognitique
EOD	Explosive Ordinance Disposal
EOP	Enhanced Opportunity Partner
ESP	Spain
EST	Estonia
ET	Exploratory Team
EU	European Union
EW	Electronic warfare
FDTD	Finite Difference Time Domain
FIN	Finland
FFI	Norwegian Defence Research Establishment
FMN	Federated Mission Networking
FOI	Swedish Defence Research Agency
FOM	Federation Object Model
FRA	France
GBR	United Kingdom of Great Britain and Northern Ireland
Gen.	General
GIS	Geographic Information System
GUI	Graphical User Interface
HADR	Humanitarian Assistance and Disaster Relief
HFM	Human Factors and Medicine Panel
HLA	High Level Architecture
HQ	Headquarters
HRLFSAS	High Resolution Low Frequency Synthetic Aperture Sonar
HIS	Human Systems Integration
ICI	Istanbul Cooperation Initiative
ICMCIS	International Conference on Military Communications and Information Systems
IDT	In-stride Debrief Team
IED	Improvised explosive device
IEEE	Institute of Electrical and Electronics Engineers
IIM	Istituto Idrografico della Marina
IMS	International Military Staff
IOSB	Fraunhofer Institute of Optronics, System Technologies and Image Exploitation
IPR	Intellectual Property Rights
IPB	Intelligence Preparation of the Battlespace
ISAR	Inverse Synthetic Aperture Radar
ISR	Intelligence, Surveillance and Reconnaissance
ISSN	International Standard Serial Number
IoT	Internet of Things
IST	Information Systems Technology Panel
IT	Information technology
ITA	Italia
JANUS	[NATO's digital underwater communications standard]

JCBRND	Joint CBRN Defence Capability Development Group
JEWCS	Joint Electronic Warfare Core Staff
JHU	Johns Hopkins University
LCAS	the Littoral Continuous Active Sonar
LEO	Low-Earth Orbit
Lt. Col	Lieutenant Colonel
LTA	Long Term Aspect
LTSS	Long-Term Scientific Study
M&S	Modelling and Simulation
MARCOM	[NATO] Maritime Command
MASINT	Measurement and Signature Intelligence
MC	Military Committee [NATO]
MCDC	Multinational Capability Development Campaign
MCM	Mine Countermeasures
MCR	Minimum Capability Requirements
MD	Mediterranean Dialogue
MDM	Military Decision Making
MHC	Meaningful Human Control'
ML	Machine Learning
Mr.	Mister
Ms.	Miss
MSaaS	Modelling & Simulation as a Service
MSCO	Modelling & Simulation Coordination Office
MSG	[NATO] Modelling and Simulation Group
MSIAC	Munitions Safety Information Analysis Center
MTDS	Mission Training through Distributed Simulation
MTSR	Man Transportable Robotic Systems
MUS	Maritime Unmanned Systems
MUSCLE	Minehunting UUV for Shallow Water Covert Littoral Expeditions
MUSE	Maritime Unmanned Systems Enablers
MUT	Military University of Technology [Poland]
MVP	Minimal Viable Product
NAC	North Atlantic Council
NATO	North Atlantic Treaty Organization
NCIA	NATO Communications and Information Agency
NCTR	NonCooperative Target Recognition
NERP 21	Nordic Recognized Environmental Picture 21
NEWWG	NATO Electronic Warfare Working Group
NG NRMM	Next-Generation NATO Reference Mobility Models
NIAG	NATO Industrial Advisory Group
NLD	The Netherlands
NLR	Netherlands Aerospace Centre
NMCM	Naval mine countermeasures
NMSG	NATO Modelling and Simulation Group
NMWWG	NATO Naval Mine Warfare Working Group
NOR	Norway
NQR	Nuclear Quadrupole Resonance
NREP	The Nordic Recognized Environmental Picture
NRV	NATO Research Vessel
NVG	Night Vision Goggles
NZL	New Zealand
OCS	Office of the Chief Scientist
OEX	Ocean Explorer [Unmanned Underwater Vehicle]
ONR	Office of Naval Research [USA]
OSP	Overarching Space Policy
OSUS	Open Standards for Unattended Sensors
P&E	Planning and Evaluation
PASSEX	Passaging Exercise
PBM	Panel Business Meeting
PE	Peacetime Establishment
PED	Processing, Exploitation, and Dissemination
PERMREP	Permanent Representative
PhD	Doctor of Philosophy [scientific degree]
PfP	Partnership for Peace
POL	Poland
PoW	Programme of Work
PPU	Policy Planning Unit
PPW	STO Plans & Programmes Workshop
Prof.	Professor
PRT	Portugal
PTSD	Post-Traumatic Stress Disorder

REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
REM	Radio Environmental Mapping
REP (MUS)	Robotic Experimentation and Prototyping Augmented by Maritime Unmanned Systems
RF	Radio Frequency
RHIB	Rigid-Hulled Inflatable Boat
RSM	Research Specialists' Meeting
RWS	Research Specialists' Workshop
RSY	Research Symposium
RTG	Research Task Group
RTO	[NATO] Research and Technology Organisation
S&T	Science and Technology
S-AIS	Satellite Automatic Identification System
SACT	Supreme Allied Commander Transformation
SAPIENT	Sensing for Asset Protection with Integrated Electronic Networked Technology
SAR	Synthetic Aperture Radar
SAS	System Analysis and Studies Panel
SAS	Synthetic Aperture Sonar
SC3IB	Spectrum & C3 Infrastructure Branch
SCI	Systems Concepts and Integration Panel
SDA	Space Domain Awareness
SET	Sensors and Electronics Technology Panel
SISO	Simulation Interoperability Standards Organization
SM	Spectrum Management
SNMG2	Standing NATO Maritime Group 2
SPS	Spanish Naval Ship
SSA	Space Situational Awareness
SSG	Strategy Sub-Group
SSS	Side-Scan Sonar
SST	Sea Surface Temperature
ST	Specialist Team
STANAG	[NATO] Standardization Agreement
STANREC	[NATO] Standardization Recommendation
STB	Science and Technology Board
STEM	Science, Technology, Engineering and Mathematics
STJUA-JA20	NATO Exercise STEADFAST JUPITER-JACKAL 2020
STO	Science and Technology Organization
SWE	Sweden
TAP	Technical Activity Proposal
TER	Technical Evaluation Report
TNO	Netherlands Organisation for Applied Scientific Research
TRMC	Test Resource Management Center
TUR	Turkey
UK	United Kingdom
US	United Stated [of America]
USA	United States of America
WHO	World Health Organization
WHOI	Woods Hole Oceanographic Institution
WMD	Weapons of Mass Destruction
XBTs	Expendable Bathy-Thermographs
XR	Extended Reality

LIST OF LINKS/CONTACT DETAILS

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