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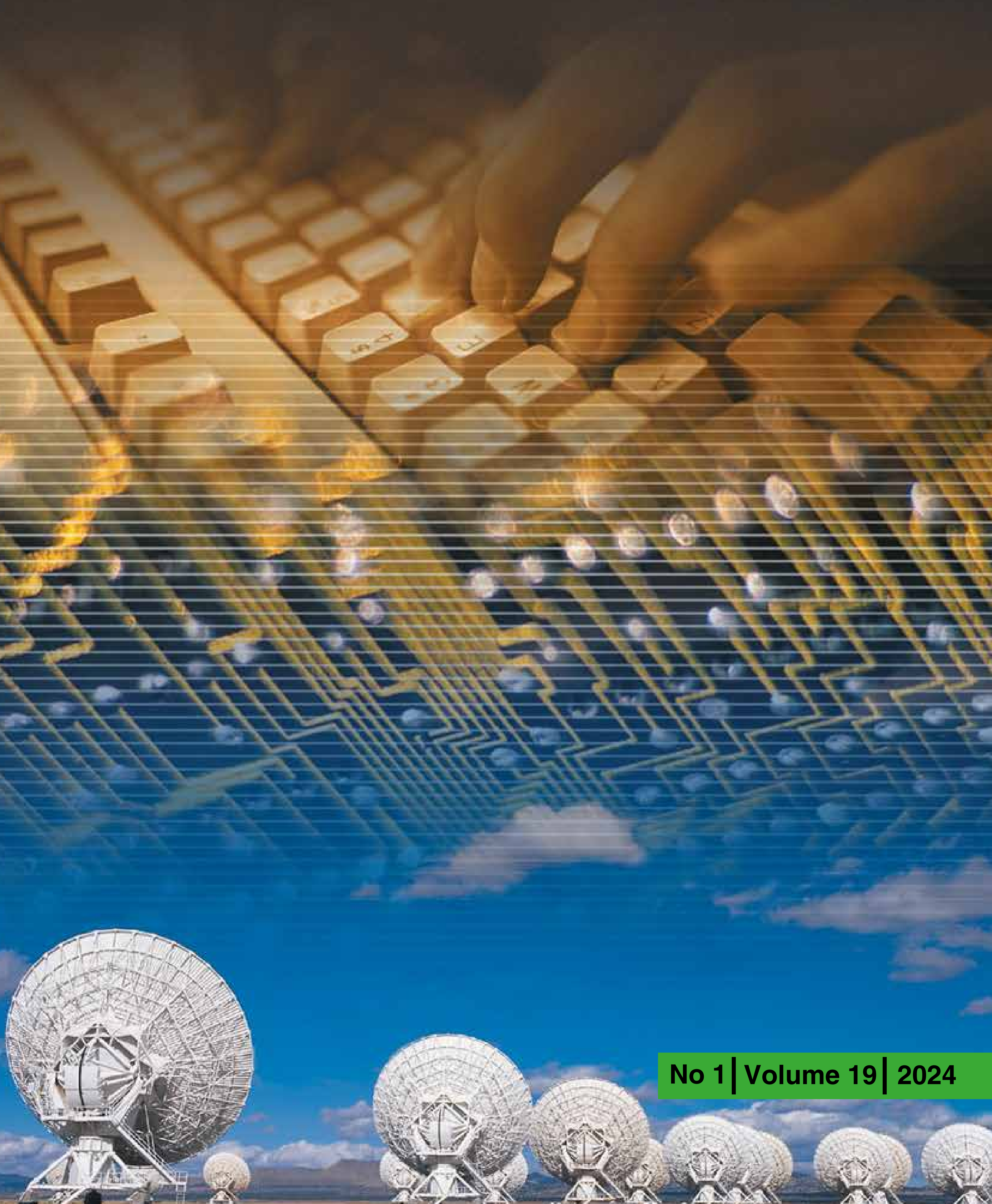
SCIENCE & MILITARY



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SCIENCE & MILITARY

The rationale for publishing this periodical by the Armed Forces Academy of General Milan Rastislav Štefánik is to enable the authors to publish their articles focused on particular scientific issues in the following areas: Military science, Natural Sciences, Engineering and Technology. Original scientific articles will be published twice a year.

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Dear Readers,

Science & Military is a significant platform for sharing knowledge in the field of military science. It also provides a forum for discussion about current trends and future perspectives in military research, which is important not only in terms of strengthening the country's defence, but also in terms of promoting technological advancement and innovation in both the military and civilian sectors. Linking scientific research with military practice brings the necessary perspective to education and the development of new technologies, while stimulating cooperation between different disciplines and sectors.

Publishing scientific papers Open Access (OA) is an important mechanism for promoting dynamic and transparent research. The Editorial Board of Science & Military is proud to publish scientific articles in Science & Military as "Open Access" under "Creative Commons" public licenses as part of Open Science. In doing so, it facilitates interaction among scientists, increases the dissemination of scientific information, and promotes the growth of the scientific community as a whole. In the context of military research, open science is even more important, given that security and defence are key aspects of national and international interest.

Dear readers, the editors of Science & Military continue to strive for the inclusion of the journal in the Scopus and Web of Science databases. For this reason, the Editorial Board of Science & Military places an emphasis on maintaining the high quality of published outputs as well as on adhering to professional and ethical standards throughout the process of evaluation and subsequent publication of submitted manuscripts in the journal.

The conditions of the rigorous peer review process were met by four articles that make up the contents of this edition. Let me briefly introduce each of them.

The first among the peer-reviewed papers in this issue is the paper titled ***„Use of Information Technology by the Army of the Czech Republic for Command and Control in Operations"*** *written by Petr Hrůza, Ivo Dumišinec, Jiří Černý and Petr Gallus. This paper deals with the application of content analysis to specify the capabilities of combat sets and their abilities when employed in operations. The goal of the paper is to focus on the capabilities of the C4ISTAR combat sets implemented in the Army of the Czech Republic (ACR) units and to examine the application of these technologies in an attempt to increase the efficiency of commanders in the implementation of command and control.*

Among the papers in this issue, you can find the paper written by Jana Ľoncová and Ján Ochodnický titled ***„Adaptive Algorithms in Radar Signal Processing".*** *This paper deals with some of the advanced technologies employed in radar signal and data processing and their impact on adaptability of radar systems. It highlights the benefits of adaptive radar signal processing. The most significant results presented in the paper are utilization of adaptive radar signal processing, solid state technology and other modern techniques that empowered radar systems to operate effectively in complex and dynamic environments.*

The authors Radovan Stephany, Vladimír Kadlub and Miroslav Marko wrote the paper titled ***„Tribotechnical Diagnostics – Degradation of Engine Oil Properties SAE 10W- 40 Iveco Crossway During Long Journeys"****. This paper deals with tribotechnical diagnostics, specifically by examining the properties of the engine oil (MO) type i-Sigma top MS; SAE 10W-40 used in the IVECO CROSSWAY bus with higher mileage compared to the inter-vehicle standard. All measurements were carried out in the tribodiagnostic laboratory of the Department of Mechanical Engineering of the Armed Forces Academy of General M. R. Štefánik (hereinafter referred to as „AOS") in Liptovský Mikuláš.*

The series of articles is closed with the paper titled ***"Object Recognition System for the Spinbotics Robotic Arm"*** *written by Patrik Štefka, Peter Pásztó, Marian Kľúčik, Martin Smoľák, Matej Vargovčík and Jakub Lenner. The paper presents a proposal for object recognition and grasping using relatively new deep neural networks - specifically the Spinbotics arm. This topic is highly relevant today.*

Dear readers, these are the articles, which have been selected for the first issue in 2024. We hope that you will find them interesting and that they will motivate and inspire you to create new opinions, conduct research, or react by writing new papers.

Enjoy to reading!

Brig. Gen. (ret.) Assoc. Prof. Eng. Boris ĎURKECH, CSc.
Chairman of the Editorial Board

Reviewers

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USE OF INFORMATION TECHNOLOGY BY THE ARMY OF THE CZECH REPUBLIC FOR COMMAND AND CONTROL IN OPERATIONS

Petr HRŮZA, Ivo DUMIŠINEC, Jiří ČERNÝ, Petr GALLUS

Abstract: The aim of the article is to apply content analysis to specify the capabilities of combat sets and their abilities when employed in operations. The purpose of the article is focus on the capabilities of the C4ISTAR combat sets implemented in the Army of the Czech Republic (ACR) units. Next purpose is to examine the application of these technologies in an attempt to increase the efficiency of commanders in the implementation of command and control. Main result of the article is to describe current situation of ACR in the area of modern information technologies (IT) to support the planning and decision-making process at the tactical level. In the context of modernization, we must not forget about security - specifically cyber security. In the military environment, this is a very topical topic recently. Penetration testing can be used to verify well-set cyber security.

Keywords: Command and control; Information support; Information technology; Modular combat sets; C4ISTAR; Tactical radio communications; Cyber security.

1 INTRODUCTION

The current form and asymmetry of modern battlefields place high demands on factors that determine the nature of operations. Key factors include the availability of data and information that not only provide an up-to-date overview of the situation in the area of the operation, but are also conducive to make individual command decisions and to manage forces and assets in operations. No military expert today doubts the fact that the successful conduct of an operation means handling information effectively and purposefully. The ability to obtain, accept, process, and appraise obtained data and information as quickly as possible, and then to further distribute it along the horizontal and vertical levels of forces in an operation, is one of the most significant activities of commanders and military staff, having a substantial effect on the achievement of the objectives and the final status of a military operation. The ACR, as a fully-fledged Member State of the North Atlantic Treaty Organization (NATO), is constantly working to develop its capabilities in the field of information management. In the context of the contents of this article, this primarily concerns the implementation of C4ISTAR capability (Command, Control, Communications, Computers, Intelligence, Surveillance, Target Acquisition, Reconnaissance) in combat units and their interconnection with other types of troop units. In addition to having the necessary technical equipment (hardware), the basis for achieving this capability is software and of course the high-quality training of operators [1].

The purpose of using IT in military operations is to strive for a constant overview of the situation (situation awareness) to make the functioning of military processes more efficient. The effort to implement information management (IM) into the equipment of combat units of ACR is the attempt to accelerate the transfer of data and information. Information support enables the unit commander not only to make decisions and manage combat, but also to share these particulars, information, and decisions with other command and control bodies. The ACR actively implements combat sets into the structures of units in order to connect combat units with support units, command posts (CP), and ISR elements in the C4ISTAR system at the national and alliance level.

2 ANALYSIS OF THE PROBLEM

2.1 Application of Information Systems within the ACR

The current dynamic and rapid development of communication and information systems and technologies is enabled by the integration of new applications and programs into the environment of systems that further improve the decision-making process of the elements involved. By means of exponentially increasing computing power, these systems offer response and support in near real time to users and, according to interoperability rules, also possibilities for deployment in cooperation with alliance partners.

Information systems (IS) of command and control have been under constant development in the ACR over the last 30 years. Their development is motivated by the effort to support the information, management, and decision-making processes of the command bodies and to enable them to transform the decision of the commander (command) and their intention (operation control) towards subordinate soldiers. The crucial task is to create a common operational picture of the situation or a comprehensive overview of the deployment of units, and to display the development of the situation in the area of operation [2].

For IS, it is essential that the communication security, which is provided by means of mobile communication infrastructure, functions well. Communication systems (CS) and assets ensure the exchange of information between the sender and the recipient. Modern communication and information systems provide faster and better data transmission and processing. They serve, inter alia, to create a constant operational picture, to provide data and information in real time, and at the same time as a data database. The use of these systems reduces time and provides command authorities with the necessary information in real time. When used effectively, these systems make it possible to gain information superiority over the enemy [3,4].

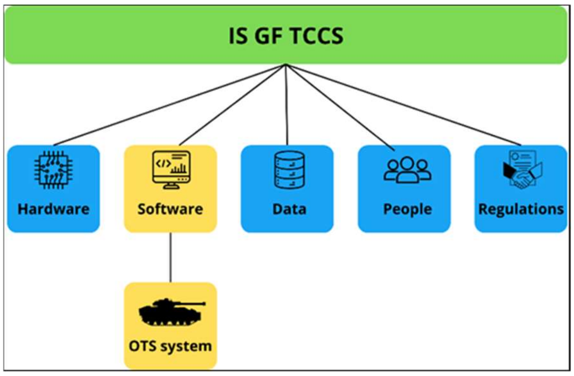

Fig. 1 IS GF TCCS Architecture
Source: [own].

In its Ground Forces, an „Ground Forces Tactical Command and Control Information System" (IS GF TCCS) has been introduced and used by the ACR to work with information and data.

It is a complex computer program with integrated application software (ASW); this system is divided into two components:

- the combat vehicle information system (BVIS) SAMET, which is intended for the transfer of unclassified information among battalion units and the battalion CP. This system is installed at the battalion in the assets of the wheeled combat vehicle Pandur II (WCVP), VRp, R5M1p, R6M1p, R7M1p and, after the acquisition and modernization of radio stations, a newly implemented wheeled armored vehicle command - staff (WACS),
- the operational tactical system is the system (OTS) DOLPHIN, which is designed to transfer information to the classified level „confidential" within the place of command (PC) of the battalion, brigade and superior levels. This system is installed at the battalion within the workplaces of the main command center [5].

The environment of these systems implicitly offers individual items (applications, editors) and at the same time allows you to choose and switch among individual ASW functions. The systems make it possible to create documents using editors or predefined forms, or to create them in an office package, to provide them with the appropriate level of classification, and to distribute them to the authorized users. Command authorities can create a variety of documents, formalized reports, reports, plans, and combat orders with minimal effort using created and predefined documents. The environment also makes it possible to notify and warn subordinate forces and assets (signals) [2].

The MIP Protocol (Multilateral Interoperability Programme) also enables not only the creation and distribution of documents, but also the exchange of data and information during joint operations in a multinational environment. Other editors used for command and control units are the task editor, the event editor, the status editor for one's own resources, and enemy event records. The editor for plans and orders allows users to completely create within a defined structure OPORD (Operation Order), FRAGO (Fragmentary Order), and WARNO (Warning Order) [3].

Other (supporting) applications can be used to support the decision-making process of commanders. These include, for example, the service of the operational tactical application, which is suitable for planning the deployment of reconnaissance elements (optical visibility), connecting retransmission nodes (radio visibility, RRL), and planning the movement of units (or enemy) within the operation (relief visualization). Additionally, it is possible to use applications displaying operating times, applications allowing users to calculate the sum of combat values of deployed elements (force ratio) when selecting variants, to determine the speed of vehicle flow (movement on roads), to perform an analysis of the quality and the connection strength (analyzing the RRL connection), and to compute other elements within the command of the operation, etc. [4,6]

The concisely analyzed systems used in the ACR are dependent on ensuring sufficient transmission speeds and the timely transfer of important information to the right place. In contrast to the irrefutable advantages, the disadvantages of these systems must also be mentioned, especially in the area of measures to protect information during its transmission. This mainly concerns the classified transmission of data, restricting access of the unauthorized persons to sensitive information, and cryptographic protection. All these measures must be constantly improved, updated, and constantly developed. It is also necessary to take into account the environment of the operation and the possibilities of one's adversaries, especially in areas where systems are susceptible to the interruption of information flow from individual sensors (for instance, a disintegration of information flow occurs when disabling a transit node), in the event of an attack with a nuclear electromagnetic pulse by the adversary, all electronic components operating on the basis of transistors that are in operation at the time of the explosion may be disabled. And the last example of a negative impact is electromagnetic interference by the adversary, performed by electronic combat (EC) units, which affects the data flow by disrupting it, altering it or influencing it with misleading information.

2.2 C4ISTAR Architecture

The basic multiplier of the forces of advanced armies is C4ISTAR architecture. Its main purpose is to ensure adequate situational awareness of all soldiers, and to enable the most effective command and control at all levels of command and control (C2). With its assistance it is possible to obtain data and information, especially seeing at night, conducting fire support, and carrying out reconnaissance without the need for any physical presence in the area. C4ISTAR architecture makes a vital contribution to the protection of forces and the precise deployment of weapons and ammunition. Therefore, it saves human lives and reduces the logistical complexity of units. Its principle lies in the effective use of the electromagnetic spectrum for command, control, communication, data processing, military intelligence, surveillance, target acquisition and reconnaissance. It enables the digital connection of sensors with assets for data processing, transmission, and analysis. The outcome is a system applicable across the organizational levels of troops. At the level of small units, it supports the decentralization of command and control as well as autonomy of action on the battlefield. From the perspective of current operations, C4ISTAR architecture is a key element for the asymmetric (non-linear) battlefield. Its individual parts provide [7]:

- command in a unified digitized map environment;
- control on the basis of compatible navigation, location – position and acquisition data;
- communication via standardized waveforms and protocols;
- data processing in a way that corresponds to the organizational level and needs of the unit;
- military intelligence across organizational levels with a unified datalink;
- surveillance according to the needs and reach of the unit, during both daytime and nighttime;
- acquisition of a target for military intelligence and fire support;
- reconnaissance with the possibility of direct and indirect action in the area of interest.

Appropriate components are available for each of these functionalities at individual organizational levels. Vertical integration of these components allows the appropriate use of interoperable technologies in a way that meets the requirements and logistical capabilities of individual units. The horizontal integration of these components supports the creation of complete sets for deployment at individual organizational levels [8].

2.3 Modular Combat Sets

In order to create s unified C4ISTAR environment (for the technological and operational interconnection of combat units at the platoon and company levels), the acquisition process (purchase and armament) of combat units was commenced in the ACR at the beginning of 2016. For the Rapid Deployment Brigade, modular combat sets (MCS) were gradually introduced into combat units (airborne, mechanized). The aim of this process was to systematically connect combat units with combat support units, CP, and the ISR units in the C4ISTAR system at the national and alliance level through the implementation of MCS. The aim of the project is to ensure the capabilities of combat units in obtaining and maintaining an up-to-date overview of a common picture of the situation [8].

MCS represent a multi-level combined system of command, control, communication, datalink, intelligence, surveillance, reconnaissance, and target setting to extend the existing command and control system. The purpose is primarily the collection and immediate appraisal of information in the operational area, but it also mediates the transfer of data from units of unmanned aerial assets, fire support of artillery, and the air force. The MCS ISTAR architecture is based on the effective and systematic application of the electromagnetic spectrum in order to achieve sensory and information dominance in the area of conducting combat operations.

2.4 Modular Combat Sets Technical Support

The Czech soldier system bears the designation SSR TA (Sensor Surveillance Reconnaissance, Target Acquisition) within the MCS and takes the form of three sets:

- a small set for a team (SS SSR TA (T));
- a small set for a platoon (SS SSR TA);
- a large set for a company (LS SSR TA) [9].

The common factor of all three versions is the MANET network (MOBITE AD HOC NETWORK) with the high-speed waveform WaveRelay and MIMO option (MULTIP1E-INPUT, MULTIPLE-OUTPUT), enabling the transmission of information at speeds up to 150 Mbps [9].

The Czech SSR TA system is operated in the frequency range 1,350 MHz to 1,390 MHz, i.e. in the band used within NATO for the most modern communication networks of small units. ACR units most often use a 5 MHz channel, systemically set up for thirty participants (the equivalent of a combat platoon). Communication security (COMSEC) is based on the application of the AES (Advanced Encryption Standard) key and complies with the requirements of Suite B of the US National Security Agency (NSA). Management of information transfer is provided by the situational firmware MyVector, built on the web server of the same name with a Linux operating system, enabling the mutual integration and connection of other components [9].

The system also includes the MyTS sensor interface (tactical sensors), the MyUI system interface (user interface), and the MyVector OL web client (open layers) for working with map data. The MySQL (structured query language) database system is used to store and manage the obtained information [9].

The sensor interface allows various types of ISTAR architecture components to be connected to the data terminal. For instance, optoelectronic elements such as digital cameras and laser rangefinders, or terminals of the ROVER type (Remotely Operated Video Enhanced Receiver), tactical radio stations and control stations of UAVs (Unmanned Aerial Vehicle), UGVs (Unmanned Ground Vehicle) and UGSs (Unmanned Ground System) such as sensors and radars.

The basis of the system interface is one of three digitized map materials (raster, vector, and orthophotomap), which can be enlarged or reduced while displaying the current scale. Furthermore, it is possible to use tools for drawing in a digitized map, including the measurement of lengths and areas or the conversion of obtained data among individual coordinate systems. Thus, it is possible to mark on the map dangerous areas, places of concentration, points of interest, etc. These tools also include a message-writing function (similar to SMS) and photo production (similar to MMS). All these objects can be further shared with other network participants equipped with data terminals [5, 9].

An analog image from optoelectronic sighting devices, observation devices, or output captured by digital cameras, camcorders and smartphones, can therefore be converted and distributed to the network. Personal, manual, portable and transportable acquisition units represent one of the greatest sensory benefits of the system, and enable not only surveillance of the target, but also measurement of its distance, direction, or even coordinate position. They are used not only for surveillance and reconnaissance, but also play a very important role in the acquisition of targets, in the use of combat support units (snipers, ATGM, mortars), and fire support for artillery and air force.

2.5 Modular Combat Sets Combat Support

Lethality and mobility are one of the most important characteristics of ground combat units. Within the form of current conflicts there is a growing need to deploy ground units in the form of separate infantry elements that depend on infantry redeployments and a high level of autonomous security. Thus, the ability to navigate and coordinate these dismounted elements on the battlefield, and to ensure cooperation with elements of combat support, such as fire support, comes to the fore.

The SSR TA system is based on audiovisual communication that is easier to understand and clearly displayed. For this reason, the SSR TA network cannot be understood as a replacement, but rather as a parallel system to the existing C2 command and control networks. The SSR TA system must therefore be seen as a tactical intranet, fully independent from fixed infrastructure. Its main goal is to obtain information and data to support the situational awareness of commanders and to promote sensory dominance over the adversary.

The basic tool of the SSR TA system, common to all versions, is the tactical hub MPU (Man Portable Unit) in the form of a personal terminal. The MPU-5 terminal looks like a personal radio, but it is actually a computer with an Android operating system with a built-in GPS receiver, video decoder, detachable radio module, three flat system connectors to allow you to connect peripherals via the interfaces Ethernet, USB, and a connector for connecting an analogue video source. The main task of each MPU-5 terminal is to actively participate in the creation of the MANET network, thereby contributing to its robustness, performance, and reach [9].

Another common component of MCS which connects all the levels of MCS, is the ruggedized MyVector 5 data terminal, which is attached to a special chest strap. It enables working with map data, the user monitors the positions and movement of other members of the unit and is able to command them effectively [9].

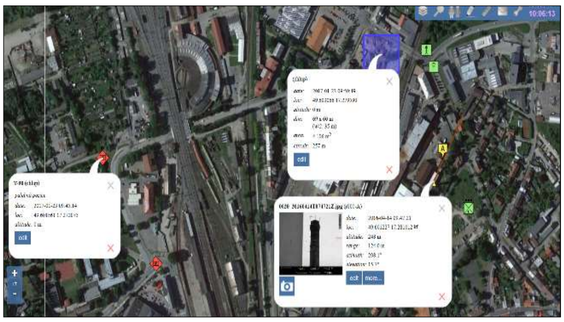

Fig. 2 Output example of the ortophoto map in MyVector 5
Source: [own].

The MyVector 5 terminal is connected to the hand-held radio AN/PRC-148C IMBITR (Improved Multiband Inter/Intra Team Radio) with the FMV-MM module (full-motion video mission module). The FMV-MM module, powered and controlled from the IMBITR radio, belongs to the ROVER group of terminals. This functionality allows you to share video outputs from unmanned aerial vehicles (all available types such as Wasp, Raven, Scan Eagle ad Predator) for all the members equipped with MCS [9,10].

Other very modern and efficient elements of MCS are the acquisition units MOSKITO IT and JIM COMPACT. The hand-held acquisition unit MOSKITO IT, with a weight of just 1.2 kg and the possibility to control it with only one hand, is the main sensory system of the platoon SS SSR TA, offering a daytime channel and an uncooled thermal imaging channel. It is also possible to use an optoelectronic channel, a laser rangefinder, a digital compass and inclinometer, and a GPS receiver. The MOSKITO IT allows users to monitor the area of combat activities beyond the effective range of hand-carried weapons (2,500 meters) during daytime and nighttime. This ensures the search for targets and possible threats well in advance and thus effectively supports the selected firing system of the unit on the battlefield. All captured videos and photos can of course be shared on the MANET network for the needs of other users. The technology for sharing the scanned image online or IN TIME through the MyVector 5 terminal is very advanced [11,12].

The 2 kg JIM COMPACT unit is a company-based surveillance platform that includes a cooled thermal imaging camera, a high-resolution color daytime camera, as well as a MOSKITO IT laser rangefinder, digital compass and inclinometer, and a GPS receiver. It does not possess a daytime surveillance branch, but it can still detect the movement of people at a distance of 6 km and combat equipment up to 10 km, regardless of the time of day. The maximum operating time of the battery is 4 hours [11,12].

As is apparent from the foregoing, SSR TA sets should not be a burden, but assets enabling small units to multiply their capabilities, not only in classic linear, but especially in increasingly frequent and confusing asymmetric operations. MCS can be considered as multipliers of the capabilities of ACR combat units.

2.6 Current Restrictions and Limits

Currently, the ability of the system is set communication-wise to the level of team–platoon–company connection, which positively affects the ability and support for timely information about the adversary, and the possibility for the tactical reconnaissance of areas of interest at the lowest tactical level. Adequate technical assets for the transmission path have not been created for the correct operation of the system containing security of the required information transfer towards the intelligence group of the staff.

In the event of identifying information, the intelligence group of the battalion staff is able to analyze, process, appraise, and further distribute the received data to other interested elements of the tactical infrastructure, with added value in the form of detailed data and the creation of inputs to unit warning systems.

Adequate assets would be, as part of the process of modernization, the deployment of radios from the same manufacturer HARRIS, using the same type of data transmission (ANW2C) in the facilities at the command post of the battalion. At present, the facilities of the radio network for the command and control of reconnaissance (network containing embedded reconnaissance bodies and elements) are operated on the equipment of the wheeled combat vehicle Pandur II (WCV-Pz, WCVP-PzLok) and R7M1p, where the RF and R-150MX series radios have been implemented; these radios do not have data compatibility with the technical assets of the MCS system.

3 DISCUSSION

3.1 Functionality of the System by Means of Complex Organization and Architecture

Finding a solution to the above-mentioned shortcomings is the ultimate goal, thereby achieving a functional and fully interconnected system of tactical radio communication (STRC). And this with the help of modern MCS technologies and the unification of C4ISTAR technologies with the effective integration of new communication systems to meet the current requirements for a modern command and control system.

The ACR tactical radio communications system provides a continuous secure radio connection in order to deliver C4ISTAR capabilities from the individual to the brigade task force commander. To this end, we need to define several fundamental requirements of the contemporary battlefield for the ability of communication and information support of deployed units:

1. The STRC architecture must be open, but managed across the operating environment, without additional technological and security constraints. It must allow the integration of new elements of the battlefield without the need for major intervention in existing systems.
2. The architecture must support an agile approach, not only in the deployment of units, effectors, weapon systems, sensors, but also for alterations in the configuration and organization of connections forced by the situation on the battlefield.
3. One of the fundamental requirements of the contemporary battlefield is to ensure information and cyber security, and a unified approach to cryptographic protection at all the levels of C2.

4. The architecture must be designed so robustly that it is prepared to withstand the explosion of data coming from current assets of the battlefield so that there is no overload of individual parts of the infrastructure during their transmission and processing.
5. Deployed assets of communication and information support must create the conditions for increasing the resilience of the entire STRC to the effects of the adversary's electronic warfare assets.
6. Given the dynamics of the contemporary battlefield, it is essential that a solution is used to integrate the basic functions of C4ISTAR that supports interoperability, mutual cooperation, and acceleration of the decision-making process.
7. In order to secure the connection system within the STRC ACR architecture, it is necessary to achieve comprehensive organization in the connection of units in the form of P. A. C. E. (primary, alternative, contingency, emergency).

Listed requirements were developed and made on the basis of conducting expert interviews. Expert interviews were conducted at the tactical level with members of battalions/brigades CP and users of MCS technologies. At the operational level, the proposals were formulated after discussion with members of the ACR Communications and Information Services Agency, which is the entity responsible for the development of IT technologies and complex management of the overall command and control architecture of the ACR.

Based on the above-mentioned requirements, the architecture must be divided into the following basic building blocks, i.e. datalinks (channels):

- Tactical datalink (national);
- Sensory datalink (alliance and national);
- Technological datalink (national).

3.2 Tactical datalink

The tactical datalink is primarily intended for the secure voice and data communication of individuals, teams, platoons, companies, combat platforms with a superior level, or command posts, and among units within the tactical communication C2 or C4ISTAR ACR. The tactical datalink is realized by multi-band radio stations, in vehicle, portable, hand-held or personal configurations.

To get the required capabilities of the tactical datalink, it is necessary to choose multi-band radios with a TYPE-1 fully-fledged encryption algorithm, which is compatible within NATO. These radios are obligatory in terms of building architecture, especially in terms of the compatibility of waveforms, including connection to vehicle intercoms and other integration platforms. In terms of the use of the tactical datalink in the air force for the capability of air-to-ground communication, aircraft radios must be fully compatible in the operating modes and at least in the waveforms VULOS, HAVEQUICK I/II, SINCGARS and ANW2C [14].

At present, the radios of several manufacturers are used in the ACR, some of which do not allow for full integration into the tactical datalink. Their current configuration only allows integration based on unclassified voice transmission, or they operate on a fixed frequency basis and are not capable of full integration into a managed and open, federated architecture.

L3HARRIS radios in the AN/PRC model series are technologically suitable for creating the above-mentioned tactical datalink. Like for instance the AN/PRC-150 FALCON II, AN/PRC-152 FALCON III, AN/PRC-160 FALCON IV, AN/PRC-163 FALCON IV and AN/PRC-117G. Or personal radios RF-9820S, RF-7850S PR, RF-330M DL (SSDL) and RF-335A DL (SSDL), and the hand-held or vehicle terminal BGAN of the RF-7800B radio [10].

3.3 Sensory datalink

The sensory datalink is especially used to ensure the data communication of sensor elements applied in units for the transmission of sensory data (video, metadata, audio). Thus, in the context of sensory datalink, the data is transferred between the sensor and the sensor control element or the receiver outputs from the sensor. A typical example of a sensory datalink is the transmission of metadata (video, data, position) from an unmanned aerial vehicle or an unmanned ground vehicle. In the case of electronic warfare, such as interference of the sensory datalink, the C2 and C4ISTAR systems are not affected in any way.

It is necessary to divide the sensory datalink into a) alliance (NATO), which is represented by ROVER type receivers and complies with STANAG 7085, and b) national, which is represented by the WaveRelay waveform and is for securing sensory data within the ACR [13].

To get the required capabilities of the sensory datalink, it is essential to choose radios and receivers with the AES-256 encryption algorithm, a unique frequency for vehicle platforms, and the possibility to have the same bandwidth for all the units. Assets providing adequate capabilities for sensory datalink are, for instance, Rover 6i and TNR (Tactical Network Rover) receivers, or GVR-5 and MPU-5 devices [10].

3.4 Technological datalink

The technological datalink is used to ensure solely data communication of the vehicle and technological units of combat and reconnaissance platforms. The technological datalink is therefore used mainly for transmitting technical and configuration data.

In the context of technological datalink, data is therefore transferred between the combat platform and the control element, or the service or configuration element. A typical example of the technological datalink is the transmission of control and configuration data (control, position) from an unmanned aerial vehicle (miniVTOL) or an unmanned ground vehicle (UGV). At the same time, this datalink can be used to retransmit the MANET technological network in the required band. In the event of interference with the technological datalink, the C2 and C4ISTAR systems are not affected in any way.

From the perspective of the activity of the architecture, this datalink plays an irreplaceable role in the diagnostics of combat platforms in relation to service and maintenance activities. The basic advantage of the technological datalink is the ability to transfer large volumes of data from one configuration location, or the application of uniform settings for all combat platforms without the need to build a remote network infrastructure [14].

As part of increasing the ability of diagnostics and service activities, this datalink can be used to fulfill the ability of the “Technological BFT”. The designation BFT (Blue Force Tracker) allows support units to search for combat platforms on a map base, without the need to enter the channel C2 with situation awareness support [14].

In order to get the required capabilities of the technological datalink, it is necessary to choose assets that enable the overall compatibility of waveforms, including the connection to integration platforms. Assets that provide corresponding capabilities for the technological datalink are, for instance, the GVR-5 and MPU-5 [10].

3.5 Cyber security

The previous text dealt with connections and means of connection. A secure connection was also mentioned. The development of communication and information systems brings, in addition to unquestionable benefits, also new threats and risks. Recently, there is a need to address security as a whole, especially with a focus on cyber security.

Cyber security deals with the security of all information throughout its existence and is closely related to cyberspace. Future wars will not take place on the battlefield, but mainly in cyberspace.

The 2016 NATO Summit in Warsaw recognized cyberspace as the fifth operational domain. Cyberspace is the fifth domain of war, and therefore this issue needs to be addressed. The technical/technological security of all systems has been addressed for several years and is at a very good level. It is just necessary to follow the rules. The biggest threat to cyber security is an insufficiently trained or insufficiently knowing soldier. Penetration into any military information or communication system is not so simple. The main goal of the enemy will be to obtain valuable data about the arms industry. Another goal may be to infiltrate an information system or an opponent's server and replace its contents with data created by an attacker. Information operations conducted in cyberspace also gain in importance, with the aim of influencing the thinking and possibilities of the enemy. It is the use of cyber capabilities and capabilities of individual armies or states to achieve goals in cyberspace that can be understood as a cyber operation. Cyber attacks make it possible to strike and endanger the functioning of public administration, critical infrastructure (such as electricity or water supply), the financial sector, they can endanger the security of important objects, and they are means of espionage and disinformation campaigns. Therefore, the issue of cyber security must be addressed not only by individual states, but also by armies and also by the soldiers themselves. It is a person or a soldier in case of military environment that is the weakest link in the whole system.

3.6 Penetration testing of military IT systems

Penetration testing of military Information Technology (IT) systems plays a crucial role in maintaining national security and operational readiness. Given the increasing sophistication of cyber threats, regular and comprehensive penetration tests are indispensable for identifying vulnerabilities and ensuring the resilience of these critical systems.

Unlike conventional IT environments, military networks host highly sensitive data and control mission-critical operations, making them prime targets for adversaries. The objective of penetration testing in this context is not only to detect exploitable weaknesses but also to assess the potential impact of such vulnerabilities on national security and military operations. By simulating real-world cyber attacks under controlled conditions, military organizations can evaluate their defensive mechanisms, improve incident response strategies, and enhance the overall security posture of their IT infrastructure. This proactive approach is vital for preventing data breaches, maintaining the integrity of military operations, and safeguarding national interests against the backdrop of an evolving cyber threat landscape.

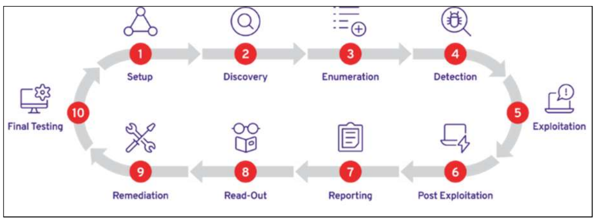

Fig. 3 Penetration testing process in steps
Source: [19].

Historically, military intelligence was the gestor, responsible subject and executor of penetration tests of IT systems of the Czech Armed Forces. In 2024, this role will be partially transferred to the Cyber Regiment, or its newly established department, which will be dedicated to penetration testing not only of field IT systems used in operations. This department is currently being set up administratively and in terms of personnel, the technical and legal boundaries of penetration testing processes are being defined and its operation is planned for the second half of this year.

3.7 General comparison

Comparing the IT used by the forces and assets of the ACR at the CP with other armies of NATO member states is always problematic in similar studies (articles), as they are usually subject to the "SECRET" level of secrecy. However, for ACR units operating in foreign operations (in NATO and EU BG operations), the ACR Communications and Information Services Agency ensures connection with stationary communication and information systems via the Automated Command and Control System (ACMS). The operation of information systems to support the department's administrative activities, such as operational-tactical system (OTS), SIS (staff information system), internet of the Ministry of Defense (IMO) and also functional services such as FIS (financial information system), ISL (information system of logistics), ISSP (integrated service and personnel subsystem) and others. In this way, the management of units from the level of the permanent operations centre (SOC), logistics and personnel support is also ensured. All alliance units have a similar IT structure and related systems. To date, the ACR has not deployed and approved a security mechanism enabling the seamless exchange of data between alliance and national stationary command and control systems (Static Network). A security mechanism enabling the seamless exchange of data between the stationary (Static Network) and deployable (Deployable Network) information systems of ACR is not deployed and approved due to their different degree of secrecy. Interoperability of CIS units of land and air forces at the national level is not fully ensured.

4 CONCLUSION

From the foregoing it follows that the architecture of tactical radio communications provides for the comprehensive treatment of radio communications on a modern battlefield in the context of national and international relations. It is therefore necessary for this concept of architecture to be adopted by all types of units on the battlefield, not only by ground units, but also by airborne and special units. In addition, in the context of ground forces, the acquisition process of the modernization of the ACR must be uniform for all types of troops. This is the only way to achieve comprehensive compatibility among the different troop types.

For the future successful development and implementation of new technology in the ACR, it is crucial to ensure the harmonization of all previously developed concepts for the development of the ACR in individual functional areas. The newly prepared concept of ACR command posts can be given as an example. This will result in the functional interconnection of all elements and increase the effectiveness of conducting combat operations within a modern battlefield, a successful confrontation with the tools of hybrid conflicts and information operations, as well as the reduction of secondary impacts on the civilian population [15].

Effective deployment of military forces in diverse operations requires the widest possible support of modern information technologies. Mathematical algorithmic models, using a raster representation of geographic and tactical data described in [16,17], represent one of them. Utilization of such software will provide commanders with substantive independence and speed of decision-making in the course of military operations [18,19]. Sharing designed maneuver routes or observation posts with all adjacent units and higher headquarters also enables to coordinate the activity of all superior task forces.

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ADAPTIVE ALGORITHMS IN RADAR SIGNAL PROCESSING

Jana ĽONCOVÁ, Ján OCHODNICKÝ

Abstract: The development of modern technologies has fundamentally transformed the field of radar signal and data processing. With the use of advanced algorithms and computational power, radars are now capable of extracting crucial information from received signals, facilitating improved target identification and tracking. This article presents some of the advanced technologies employed in radar signal and data processing and their impact on adaptability of radar systems. It traces the evolution of radar technology from old systems to the present, emphasizing the benefits of adaptive radar signal processing, which includes algorithms such as adaptive beamforming, Space-Time Adaptive Processing, and the integration of Machine Learning and Artificial Intelligence. In conclusion, challenges, and future prospects in the field of radar systems are discussed, with a focus on the potential integration of Artificial Intelligence methods, Cognitive radars, and Multiple Input Multiple Output technologies. Despite technical obstacles, opportunities emerge to enhance the performance of radar systems and achieve new levels of efficiency.

Keywords: Radar signal processing; Radar data processing; Adaptive radar; Adaptive algorithm.

1 INTRODUCTION

The development of modern technologies has the field of evolved signal and data processing in radars. These advancements have allowed for more efficient and precise detection, low probability of intercept (LPI), and electronic counter measurements. With the use of advanced algorithms and computational power, radars are now capable of extracting valuable information from the received signals, enabling better target identification and tracking. This paper presents some of the latest technologies used in radar signal and data processing and their radar performance impact.

M. I. Skolnik wrote in 1985: "Digital technology has allowed significant new capabilities in signal and data processing, and Very High-Speed Integrated Circuit (VHSIC) offers the promise of even greater performance. Most of the proposed radar applications of VHSIC seem to be describable as doing more of what is already being done. This is usually the case for any new technology, but it would not be surprising if, a decade hence, VHSIC is being used to achieve some new radar capability not now being pursued." 1] The following development proved him fully right, and high-performance integrated circuits, such as Field Programmable Gate Arrays (FPGAs), deeply affected the development of radars. [2],[3],[4]

The construction of modern radar systems, besides their specific features ensuring adaptability, also includes FPGAs. These fields, along with the corresponding adaptive algorithm, represent a comprehensive solution for processing the received signal. The choice of FPGA type and adaptive algorithm depends on the type of radar system, the environment in which the radar system is placed, and the type of transmitted and received signal. Radar systems that integrate FPGAs can provide a high degree of adaptability and flexibility in radar signal processing. [2],[3],[4],[5],[6],[7]

Nowadays, radar signal processing represents a complex set of digital techniques not only for receiving, but also for transmission and further manipulation of radar signals with the aim of obtaining high-quality information about the area of interest. It includes a wide range of advanced algorithms and computational methods, such as waveform design, modulation, demodulation, adaptive filtering, etc. which are applied to radar signals to enhance their quality and extract vital target information. These techniques enable radars to achieve high-resolution imaging, accurate target detection, improved signal-to-noise ratio, and other advanced functionalities, thereby playing a crucial role in the modernization and effectiveness of radar systems. [8],[9],[10]

In radar signal processing, the focal points lie in efficiency, speed, accuracy, and adaptability. The adaptability of radar systems is achieved through the incorporation of adaptive elements. These distinct components leverage their inherent properties and parameters to facilitate adaptive signal transmission, reception, filtering, and processing. [9],[10],[11],[12]

These modern technologies have innovated the field of radar signal processing, enabling more accurate and reliable information for various applications, including military surveillance, weather forecasting, and air traffic control. [10],[11]

The primary objective of this paper is to represents a fundamental principles of adaptive radar signa processing. The inception of this paper delves into the intricacies of comparing technologies employes in old radar systems with contemporary advancements, primarily focusing on radar signal processing. A crucial aspect of radar signal processing, discussed in this article, is adaptability. This is achieved through the utilization of a digital signal processor with FPGA, where adaptive algorithms such as adaptive beamforming or Space-Time Adaptive Processing (STAP) can be programmed. In modern radars, ensuring adaptivity also involves the incorporation of Machine Learning (ML) or Artificial Intelligence (AI). By constructing a comparative model, these technologies can optimally identify a target in clutter and noise. The future integration of these algorithms may achieve faster processing, leading to real-time radar signal processing in big interferences.

2 RADAR TECHNOLOGY EVOLUTION

One of the key advancements in the radar technology evolution is the development of solid-state radar systems. Unlike traditional radar systems that utilize vacuum tubes, solid-state radars rely on transistors and integrated circuits, resulting in smaller and more efficient units. These modern radar systems offer higher reliability, increased flexibility, and improved radar signal processing capabilities, making them suitable for a wide range of applications, including weather monitoring, air traffic control, and military operations. Additionally, solid-state radars can generate highly accurate and detailed images, allowing for precise detection and tracking of targets in real-time. Overall, the evolution of radar technology has revolutionized radar signal processing capabilities and paved the way for more sophisticated and efficient radar systems. [13],[14],[15],[16]

Early radar systems, despite their innovative design and capabilities, were not without their limitations. One major drawback was their susceptibility to interference and jamming, which greatly impacted their effectiveness. Moreover, these systems had limited range and resolution, making it challenging to accurately detect and track fast-moving objects. The inability to identify and distinguish between multiple targets further hindered their utility in complex military operations. [13],[14]

In contrast, modern radar systems feature advancements in coherent optimization. State-of-the-art antennas, such as Active Electronically Scanned Array (AESA) or Passive Electronically Scanned Array (PESA), demonstrate the capability to sustain phase coherence even under dynamic beam characteristics. The utilization of a robust and stable Transmitter (Tx), such as a solid-state Tx, significantly enhances the level of phase coherence in transmitted signals. Integrating a digital Receiver (Rx) with a high dynamic range in modern systems facilitates the maintenance of phase coherence and enables precise Digital Signal Processing (DSP). Consequently, DSP can achieve high coherence even with non-coherent and unstable transmitters or fully synthesized ones. This capability is particularly effective in military applications, where full radar adaptivity serves as a powerful tool for enhancing radar capability. In military contexts, the adaptability of transmitted signals can reveal the actual state of radar or scenario from the enemy's Electronic Warfare (EW) or Electronic Intelligence (ELINT) perspective. Radar's inherent chattiness further underscores the significance of adaptivity, making it clear that in military applications, adaptivity on the receiving side alone is not only more effective but also serves as a key aspect of Electronic Counter-Countermeasures (ECCM). [15],[16]

Contemporary radar systems often incorporate advanced technologies that enable the synchronization of timing references, contributing to high time coherence. The design of new radar systems prioritizes coherence optimization throughout the entire system with fully adaptive components. Advanced antennas, Tx, Rx collectively contribute to a high degree of both phase and time coherence. [15],[16]

As shown in Tab.1, in older radar systems, antennas may exhibit limited capacity to maintain phase coherence, particularly during antenna rotation. Traditional Tx, such as klystrons or magnetrons, can suffer from restricted phase stability, thereby affecting the coherence of transmitted signals. Besides, older receiver, like superheterodyne or heterodyne Rx, may have coherence in received signals influenced by the construction and quality of amplifiers. [13],[14],[16]

Tab. 1 Difference between old and modern radar systems

SYSTEM	EARLY RADAR	MODERN RADAR
Antenna	Parabola	AESA, PESA
	Dipoles	Active components
	Passive components	
Transmitter	Microwave tubes	Solid-state
Receiver	Homodyne	Software-defined Receiver (SDR)
	Superheterodyne	
Radar Signal Processing	Analog-to-digital converter (ADC) with Analog Signal Processor, standard	DSP FPGA with various adaptive algorithms

Source: author.

Advancements in modern radar technology have greatly improved the detection capabilities of radars. Through the integration of sophisticated algorithms and processing techniques, radars demonstrate enhanced precision and accuracy in detecting and tracking targets. The development of cognitive radars further enhances adaptability and intelligence, allowing automatic adjustments and performance optimization based on the surrounding environment. [14],[15],[16] The simplified block diagram of an advanced technology radar is illustrated in Fig. 1. The Tx of this radar is composed of semiconductor technology, emitting a signal with frequency diversity. This diversity involves the radar transmitting short and long pulses to ensure discriminative capability and radar range. These radars employ an adaptive phased-array antenna system, PESA or AESA and a receiver of the software-defined radio type. Radar signal processing of the received signal is carried out through DSP, which includes an FPGA with a programmed adaptive algorithm. This algorithm is optimized to the type of radar system, as well as its usage and environmental conditions. [15], [16]

These advancements in modern radar technology highlight the continuous efforts in radar signal processing advancements for improved radar capabilities. In conclusion, modern technologies have greatly improved radar signal processing. The use of advanced algorithms and ML techniques allows for better target detection and tracking, as well as enhanced identification of clutter and interference. [16]

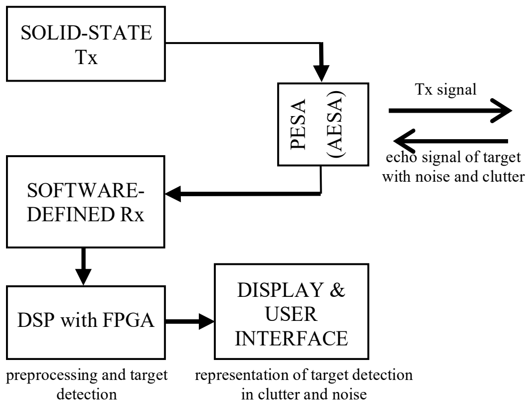

Fig. 1 Simplified block diagram of advanced technology radar
Source: author.

3 ADAPTIVE RADAR SIGNAL PROCESSING

How we were mentioned, adaptive radar signal processing has revolutionized the way we analyze and interpret received signal, particularly with the integration of DSP and FPGA. These advanced technologies have significantly enhanced the capabilities of radar systems, allowing for more efficient and adaptive processing of signals. [17],[18]

Firstly, the incorporation of DSP in radar systems has played a crucial role in the transition from analog to DSP. ADC allows for the conversion of analog signals collected by radar antennas into digital signals, facilitating more precise manipulation and analysis. This transformation enhances the radar's ability to filter, modulate, and analyze data, providing valuable insights into targets' positions, velocities, and characteristics. [17],[18],[19]

Secondly, FPGAs have become integral in radar signal processing, providing a versatile platform adaptable to diverse radar system needs. The programmable nature of FPGAs empowers radar engineers to deploy adaptive algorithms finely tuned to the radar's unique features and environmental conditions. This flexibility is crucial for optimizing radar performance across changing scenarios, ensuring efficient and accurate radar signal processing. [5],[6]

Implementation of DSP with FPGA in radar systems enables the use of advanced adaptive techniques. Adaptive filtering algorithms, for instance, can be applied to mitigate interference, improve signal-to-noise ratio, and enhance overall radar accuracy and resolution. This collaborative approach empowers radar systems to dynamically adjust and optimize their performance, making them more responsive to the challenges posed by complex and dynamic operational environments. [18],[19]

In conclusion, the integration of DSP with FPGA in radar systems represents a paradigm shift in radar signal processing. These technologies not only enhance the efficiency and precision of radar data analysis but also enable adaptive strategies that contribute to the overall effectiveness of radar systems in diverse scenarios. [17],[18],[19]

The principle of adaptive radar signal processing is illustrated in Figure 2. Adaptive radar signal processing provides the capability for the parameters of signal processing to dynamically adjust in real-time based on the characteristics of the input signal. In Figure 2, two radar systems are depicted, each composed of N adaptive, phase-linear systems that receive the reflected signal from the target. These received signals undergo processing in an adaptive processor, which, based on the parameters of the input signal, generates weighting coefficients or vectors. Subsequently, these coefficients undergo filtering, optimization, and processing. The results from both radar systems are then subjected to spatiotemporal decoding. Following this process, the output contains a signal that carries information about the target. [17],[18],[19],[20]

Most used DSP technique in radars is pulse compression. This technique allows for the separation of echoes from different targets that are closely spaced in time. By transmitting a long-coded pulse, the radar can distinguish echoes from closely spaced targets based on their unique codes. For pulse compression using nonlinear or linear frequency modulation (LFM) signals, the compressed signal *y(t)* can be given by: [20], [21]

$$y(t) = \int_{-\infty}^{\infty} x(\tau) s(t-\tau) e^{-j2\pi f_0 (t-\tau)(\tau-\tau)} d\tau, \qquad (1)$$

where $x(\tau)$ is the received signal, $s(t-\tau)$ represents a time-shifted version of the reference signal in waveform LFM $s(t)$ by a time value τ with a f_0 is the center frequency. [20],[21]

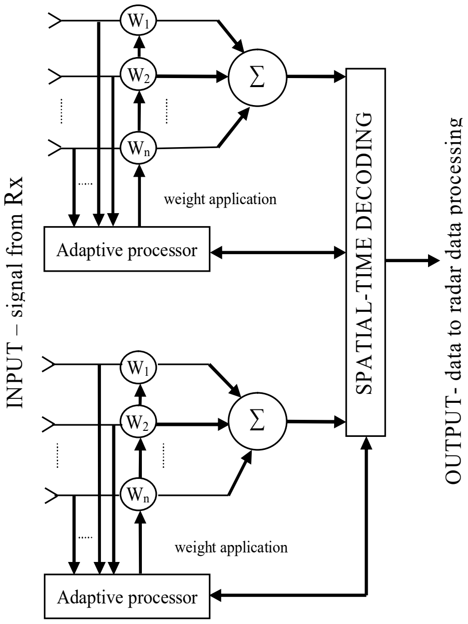

Fig. 2 Principle of adaptive radar signal processing
Source: author.

Pulse compression helps identify targets in environments with high interference and enables the radar to distinguish between closely spaced targets. This technique is often implemented using specialized radar signals with frequency diversity, and digital processing techniques, including the use of algorithms for pulse compression. [21],[22],[23]

Pulse compression with frequency diversity is a key tool in many radar systems such as in the RL-2000 radar, which structure of signal consists of four pulses $P_{f1\text{-}f4}$ with different frequency and two short (P_{f1}, P_{f2}) and long (P_{f3}, P_{f4}) pulses is in Fig. 3. This radar is primary surveillance radar, which ensures enhanced system stability and robust clutter suppression, preventing false reports while maintaining exceptional target detection capabilities up to 150 kilometers. It includes improved performance for target accuracy and resolution. [21],[22],[23],[24]

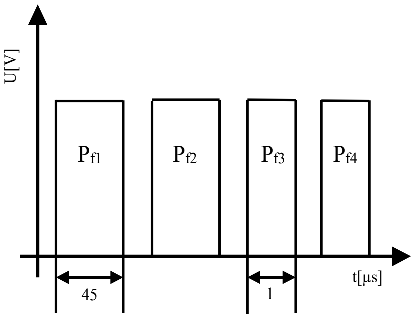

Fig. 3 Pulse signal with frequency diversity
Source: author.

4 ADAPTIVE ALGORITHMS FOR RADAR SIGNAL PROCESSING

One of the typical adaptive algorithms that significantly enhance radar signal processing capabilities in radars is adaptive beamforming. This technique uses a phased array antenna system to electronically steer the radar beam, allowing for improved target detection and tracking. Another innovation is the use of Space-Time Adaptive Processing which is used for filtration spatio-temporal data in time and frequency domain. This procedure ensures the mitigation of undesired interference and facilitates expedited processing of incoming signals. Lastly, the integration of ML algorithms into radar systems has facilitated the automatic detection and classification of targets, significantly reducing operator workload. [24], [25]

4.1 Adaptive beamforming

Adaptive beamforming is a crucial technique in modern radar systems, revolutionizing radar signal processing. This method allows real-time adjustment of the beam pattern, effectively mitigating unwanted noise and interference. By employing advanced algorithms, adaptive beamforming enhances target detection, tracking, and imaging capabilities, playing a pivotal role in improving overall radar system performance. [25],[26]

Through adaptive filtering, the algorithm dynamically adjusts the beam pattern by modifying the weights applied to individual antenna elements. The purpose of adaptive beamforming is to improve radar performance, specifically the signal-to-noise ratio, spatial resolution, and overall sensitivity, in the presence of interfering signals and noise. It involves adjusting the weights applied to individual antennas through adaptive filtering to optimize the received signal. The output signal $z(t)$ for an adaptive array with N antennas elements and $x(t)$ as the received signal can be expressed as: [25],[26]

$$z(t) = w(t+1)\frac{P(t)x(t)}{\sigma + x(t)^H P(t)x(t)}e(t), \qquad (2)$$

where the weight vector w is iteratively updated using the Recursive Least Squares (RLS) algorithm. Variable $P(t)$ is the inverse of the autocorrelation matrix, σ denotes forgetting factor, $x(t)^H$ is the complex conjugate of received signal and $e(t)$ is the error signal. [25],[26]

Adaptive beamforming in radar systems offers several advantages over traditional methods. Firstly, it enhances the radar's capability to detect and track multiple targets concurrently. Adaptive beamforming enables the system to reject interference, improving its overall sensitivity and accuracy. Moreover, this technique enhances the spatial resolution of the radar, allowing for better target discrimination. Lastly, adaptive beamforming facilitates the reduction of clutter and noise, resulting in improved detection performance in complex environments. [25],[26],[27]

In real-world scenarios, adaptive beamforming finds valuable use in radar systems for both military and civilian purposes. Its effectiveness in tracking moving targets, mitigating multi-path propagation and interference, and improving radar imaging capabilities highlights its significance in modern radar technologies. Technological advancements, including powerful computational tools and digital beamforming techniques, have further improved radar capabilities. Radars can now process complex waveforms and extract valuable information from cluttered environments. Digital beamforming enhances the radar's ability to steer and shape its beam pattern, significantly enhancing target detection and tracking capabilities. [26],[27]

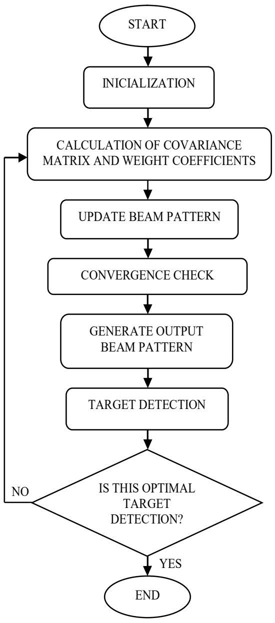

Fig. 4 Flowchart of adaptive beamforming
Source: author.

The adaptive beamforming process (flowchart is shown in Fig. 4, where received signals are processed through the correct initialization of algorithm parameters. Computations of the covariance matrix and weight coefficients are applied to update the beam pattern, allowing adaptation to changing conditions in the environment. The convergence process monitors whether the adaptive system has reached a stable state. This convergence process ensures stability, resulting in a final beam pattern used for effective target detection and localization in received signals. Detecting a target in a mixture of signal and noise can be a challenging process, and if it is not optimal, the process is repeated from the step calculation of covariance matrix and weight coefficients. [26], [27]

4.2 Space-Time Adaptive Processing

STAP is the optimized 2D filtration technique in modern radar systems that removes interference from received signal by radar. This algorithm involves using precision filtration of angle and Doppler frequency in spatial and time domain, which causes completely elimination noise and interference from received signal. [28],[29]

This method leverages knowledge about the spatial characteristics of interference and target signal to compute weight vectors, thereby minimizing interference and enhancing target detection. Its mathematical foundation is based on matrix algebra and estimation theory. [29]

The advancement of the STAP algorithms is closely intertwined with its diverse applications. Successful implementation necessitates an in-depth analysis of several aspects, including noise characteristics, performance and accuracy, computational capacity requirements, and other factors like interference immunity, calibration requirements, and dynamic range. [29],[30]

Each STAP algorithm is based on a flowchart applied to the specific radar system, external environment, and signal type in use. [31]

This flowchart is on Fig. 5 and illustrating the principles of individual steps, this demonstrates the correct configuration of the STAP algorithm. Its application allows for accurate target detection in received signals containing not only target information but also clutter and interference. [31]

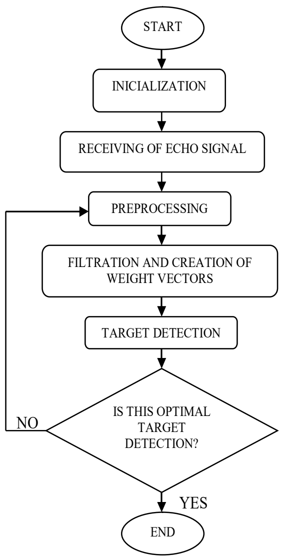

Fig. 5 Flowchart of STAP algorithm
Source: author.

The STAP typically operates on a matrix $\mathbf{X}(n,m)$, encompassing input signals received by the radar, where n represents pulse repetition frequency, and m represents number of antennas elements. The correlation operation is applied to this matrix, generating covariance matrix **R***(n,m)*, which is interpreted as: [31]

$$\mathbf{R}(n,m) = \left(\frac{1}{J}\right) * \mathbf{X}(n,m) * \mathbf{X}(n,m)^H, \quad (3)$$

where J is the total number of input signals and $\mathbf{X}(n,m)^H$ is the complex conjugate of the matrix $\mathbf{X}(n,m)$. [31]

Alternatively, correlation can be performed between input signals and noise, yielding the covariance matrix $\mathbf{U}(n,m)$, which is interpreted as: [31]

$$\mathbf{U}(n,m) = \left(\frac{1}{J}\right) * \sum_{m=1}^{M} \mathbf{S}(n,m)^H, \quad (4)$$

where M represents the number of antenna positions, $\mathbf{S}(n,m)$ represents the noise and $\mathbf{S}(n,m)^H$ is the complex conjugate transpose of $\mathbf{S}(n,m)$. Output signal after filtration and application of weight vectors $\mathbf{Y}(n)$ is characterized as: [31]

$$\mathbf{Y}(n) = \mathbf{w}(m)^H \mathbf{X}(n,m), \quad (5)$$

where $\mathbf{w}(m)^H$ denotes the complex-conjugate transpose of the weight vector, which is compute from covariance matrix $\mathbf{R}(n,m)$ and $\mathbf{U}(n,m)$ and $\mathbf{X}(n,m)$. [30],[31],[32]

This formula represents the basic STAP method, from which have involved more contemporary, potent, and precise STAP methods. Their accurate implementation relies on comprehensive knowledge of application parameters, investigated signals, and the environment. [30],[31],[32]

4.3 Machine Learning and Artificial Intelligence in radar signal processing algorithms

ML and AI are emerging as valuable tools in radar signal processing. These techniques enable the extraction of meaningful information from effect radar signals. By leveraging advanced algorithms, ML algorithms can effectively detect and classify targets, track their movements, and even predict future behaviors. The application of AI in radar signal processing allows for more efficient and accurate detection and identification of targets, enhancing radar performance in various environments and scenarios. These advancements in ML and AI contribute to the continual improvement of radar systems and their capability to support critical tasks such as surveillance, object recognition, and threat detection. [30],[34]

The process of ML in radar systems is derived from the flowchart in Fig. 6, where received signals are processed based on the correct initial initialization of algorithm parameters. Data is collected from radar sensors, encompassing signals from targets, noise, and other influences. Following this, data undergo preprocessing, noise removal, and identification of relevant features for learning. The data is then divided into training and testing sets to verify the model. The selection of a suitable ML model, such as neural networks or decision trees, is followed by training the model on the training set. The model is subsequently validated on the testing set, and its parameters are optimized to improve performance. After successful validation, the model is implemented in real-time into the radar system for continuous monitoring and target detection. If needed, adaptation mechanisms are introduced for dynamic environments and changing radar conditions. The overall performance of the model is regularly monitored, and if it is not optimal, the process returns to the model selection stage. [33],[34]

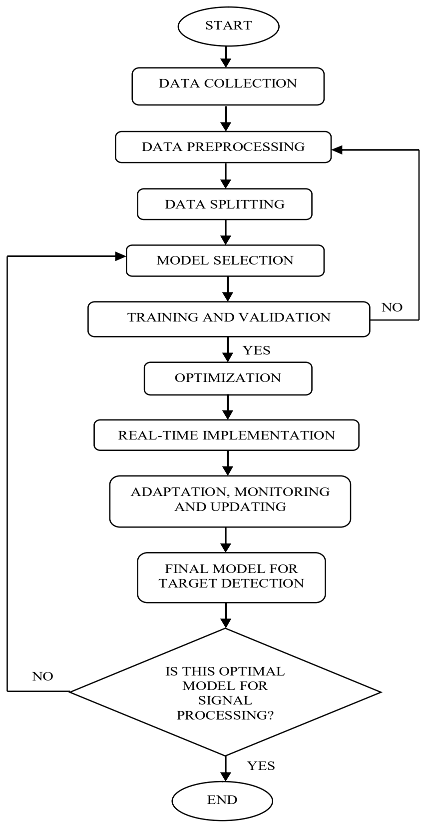

Fig. 6 Flowchart of ML
Source: author.

ML and AI have brought about a paradigm shift in radar systems, significantly enhancing their capabilities. These technologies play a pivotal role in enabling radars to autonomously learn and adapt in real-time, thereby enhancing the precision of target detection, tracking, and classification. By leveraging ML algorithms, radar systems can discern patterns in return signals, facilitating predictive analysis and informed decision-making.

AI algorithms contribute to the development of adaptive radar systems that possess the ability to self-optimize their parameters to effectively operate in diverse and changing conditions. This adaptability ensures optimal performance across various scenarios. In essence, the synergy between ML and AI has become indispensable in modern radar systems, equipping them to tackle the evolving challenges presented by complex and dynamic environments. [33],[34],[35]

These algorithms have greatly impacted radar signal processing. These algorithms can analyze and processing vast amounts of data to identify patterns and make predictions. They can effectively filter out noise and interference, improving signal quality. ML techniques also enable the detection and classification of targets, enhancing radar performance. Moreover, these algorithms can adapt to changing environments and learn from past experiences, making them highly efficient in real-time signal processing applications in radar systems.

For a nuanced ML model applied in radar, consider a simple logistic regression model for binary classification: [33],[34]

$$P(Q=1|A)=\frac{1}{e^{-(\beta_0+\beta_1 A_1+\beta_2 A_2+\cdots\beta_n A_n)}}, \qquad (6)$$

where P$(Q=1|A)$ denotes probability of class 1 given the input features A, β_0, β_1, ..., β_n, are the model parameters and A_1, A_2, ..., A_n are the input features.

For a more sophisticated ML model, let's consider a deep neural network (DNN) with multiple hidden layers. The output y can be expressed as: [33], [34]

$$c=\varsigma\left(\mathbf{W}_1*\varsigma\left(\mathbf{W}_2*\mathbf{T}+\mathbf{b}_1\right)+\mathbf{b}_2\right), \qquad (7)$$

where $\mathbf{T}$ is the input feature vector, $\mathbf{W}_1$, $\mathbf{W}_2$ are weight matrices, $\mathbf{b}_1$, $\mathbf{b}_2$ are bias vectors and ς is the activation function, such as the sigmoid or rectification linear unit (ReLU). [33],[34],[35]

These expressions provide intricate formulations for the corresponding radar signal processing techniques. It is essential to recognize that practical implementations may necessitate additional consideration and variations tailored to the specific requirements of the radar system. [34],[35],[36]

Another example of AI application in radar signal processing is target recognition. AI algorithms can be used to analyze radar signals and identify different types of targets, such as aircraft, ships, or automobiles. This is particularly useful in military applications, where quickly and accurately identifying targets is crucial for making strategic decisions. AI can also help in the classification of radar signals, enabling the detection of specific objects or anomalies in the environment. Overall, the use of AI in radar signal processing enhances the capabilities and effectiveness of radar systems in various domains. As we move further into the 21st century, the field of radar signal processing has experienced significant advancements, largely due to modern technologies. The integration of advanced algorithms and AI has allowed for improved target detection, clutter suppression, and overall system performance. Additionally, the utilization of high-speed digital signal processors and parallel computing techniques has enabled the processing of massive amounts of data in real-time, enhancing the radar's ability to track multiple targets simultaneously. [34],[35],[36]

5 CHALLENGES AND FUTURE PROSPECTS

In the realm of radar systems, we encounter several challenges that need to be successfully addressed in the coming years. One of the primary issues is the complexity of contemporary radar systems, requiring advanced algorithms and cutting-edge hardware architecture. The escalating demand for real-time processing poses challenges in terms of computational power and energy consumption. [37], [38]

The integration of multiple radar systems introduces challenges related to synchronization and interference, necessitating precise solutions to achieve effective coordination between systems. Despite these challenges, future prospects emerge. The application of AI methods, specifically deep learning, has the potential to significantly enhance the performance of radar systems, particularly in the areas of detection, tracking, and target classification. [37],[38]

New technologies, such as cognitive radars and Multiple Input Multiple Output (MIMO) radars show promising potential for enhancing the capabilities of radar systems. The development in the field of these advanced radar systems could bring new dimensions to the analysis and radar data processing. Despite technical challenges, opportunities are emerging to advance radar systems to a new level of performance and efficiency. [37],[38],[39]

Cognitive radars, leveraging their adaptability and intelligent decision-making capabilities, enable more efficient utilization of available resources and enhance target detection accuracy. [39],[40]

MIMO radars introduce an additional layer of complexity with multiple antennas at both the input and output, allowing for more precise localization and tracking of targets. These technologies provide us with tools to effectively address challenges associated with interferences and various environmental conditions. [41],[42]

The development in these systems is crucial for optimizing real-time signal processing. Utilizing advanced algorithms, adaptive approaches, and parallel processing allows for more efficient gathering and interpretation of radar data. What's even more significant, these technologies enable substantial improvements in performance, accuracy, and processing speed, creating new possibilities for the effective utilization of radar systems in various scenarios and conditions. [38],[39],[40],[41],[42]

6 CONCLUSION

The evolution of radar technology, coupled with advancements in radar signal and data processing, has significantly transformed the capabilities of radar systems. The integration of digital technologies, such as FPGAs and adaptive algorithms, has played a pivotal role in enhancing radar performance. The transition from early radar systems, with their limitations in interference susceptibility and range resolution, to modern solid-state radar systems highlights the strides made in achieving higher reliability, flexibility, and precision.

The utilization of adaptive radar signal processing, including techniques like pulse compression, adaptive beamforming, STAP, and the integration of ML and AI, has empowered radar systems to operate effectively in complex and dynamic environments. These technologies contribute to improved target detection, tracking, and classification, ensuring enhanced adaptability and intelligence.

The comparison between old and modern radar systems underscores the benefits of advancements in antenna technology, transmitter, and receiver components, as well as radar signal processing techniques. The adoption of solid-state components phased array antennas, and software-defined receivers has significantly improved radar coherence, stability, and overall performance.

Challenges in the field of radar systems, such as computational power requirements, synchronization issues, and the complexity of contemporary systems, are acknowledged. However, the future holds promising prospects with the potential integration of AI methods, cognitive radars, and MIMO radars. These technologies aim to address current challenges and further optimize radar systems for real-time signal processing, adaptability, and efficiency.

In summary, the continuous development of radar technology and signal processing techniques has paved the way for more sophisticated, adaptable, and efficient radar systems. As we navigate into the future, the integration of cutting-edge technologies and innovative approaches holds the key to overcoming current challenges and unlocking new dimensions in radar system capabilities.

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TRIBOTECHNICAL DIAGNOSTICS - DEGRADATION OF ENGINE OIL PROPERTIES SAE 10W-40 IN IVECO CROSSWAY DURING LONG JOURNEYS

Radovan STEPHANY, Vladimír KADLUB, Miroslav MARKO

Abstract: This paper addresses tribotechnical diagnostics, specifically by examining the properties of the engine oil (MO) type i-Sigma top MS; SAE 10W-40 used in the IVECO CROSSWAY bus with a higher number of total mileage from the inter-vehicle standard. In the abstract of the paper, the characteristics of the measured technique, tribodiagnostic instruments of measurement and a more detailed specification of the oil properties and the monitoring of its gradual degradation during long-term operation are presented. Long-term operation in the sense of the article means a continuous mileage run of more than 200 km (one race without stop) and a MO temperature in the range of 80 ºC to 130 ºC. All measurements were carried out in the tribodiagnostic laboratory of the Department of Mechanical Engineering of the Armed Forces Academy of General M. R. Štefánik (hereinafter referred to as „AOS") in Liptovský Mikuláš.

Keywords: Motor oil; ACEA; API; SAE; VW 501 01; 505 00; 504.00; 507.00/MB-Approval 229.31/229.51; Kinematic viscosity; Motor oil condition; Motor oil degradation.

1 INTRODUCTION

Oils are technologically very complex products with many parameters that must meet performance requirements under different load conditions. Despite the manufacturer's declaration of service life and mileage, there may be cases where accelerated degradation occurs and the associated risk of premature wear or engine failure. In this work, we focused on the measurement of engine oil quality indicators during operation and the detection of the degree of degradation. The sampling was carried out by IVECO CROSSWAY EVADIS Fig. 1a, b.

Fig. 1a IVECO CROSSWAY EVADIS
Source: author.

Fig. 1b IVECO CROSSWAY EVADIS
Source: author.

We carried out measurements of a reference sample and 2 measurements of the oil charge. The sampling was carried out in the workshop area of the Department of Mechanical Engineering and the measurements were carried out in the tribodiagnostic laboratory also belonging to the Department of Mechanical Engineering. The thesis consists of a theoretical and a practical part.

2 VEHICLE IVECO CROSSWAY EVADIS

The IVECO CROSSWAY EVADIS is a vehicle equipped with an in-line 6-cylinder diesel engine, which has a power output of 331 kW at 2100 rpm and an engine capacity of 10 308 cm^3. At the beginning of the measurements the vehicle had covered 320,574 kilometres and at the last measurement 336,588 kilometres. ENGINE CURSOR 10. In-line turbocharged diesel 6-cylinder, VGT turbocharger with controlled geometry, 4 valves per cylinder, OHC timing with electronically controlled cylinder head injection units, ITB decompression engine brake with power controlled turbocharger. Electromagnetic fan clutch. Emission standard EURO 5 or EEV 5 (SCR method - use of AdBlue).

3 i-Sigma top MS SAE 10W-40 ENGINE OIL

Eni i-Sigma top MS 10W-40 is a modern high-performance engine oil with synthetic technology capable of saving fuel for the highest load, extended drain intervals for commercial vehicles, especially for vehicles with the new generation of diesel engines equipped with exhaust aftertreatment system (EURO 5) *i-Sigma top MS 10W-40.*

Tab. 1 Selected features MO Eni i-Sigma top MS 10W-40

Grade SAE		10W-40
Density at 15 °C	$kg.m^{-3}$	860
ACEA	-	E6, E9, E7
ACI	-	CI-4
Kinematic viscosity at 100 °C	$mm^2.s^{-1}$	13.1
Kinematic viscosity at 40 °C	$mm^2.s^{-1}$	86
Viscosity index	-	150
Dynamic viscosity at –25 °C	mPa.s	6500
Flash point (o.k.)	°C	230
Freezing point	°C	-36

Source: author.

4 MEASUREMENT RESULTS

4.1 Kinematics

Kinematic viscosity (measured on SpectroVisc Q 3050). The main and essential characteristic for the usability of engine oils in a vehicle.

For the assessment of the quality parameter kinematic viscosity MO, an interval of maximum +20 % and minimum -20 % from the reference sample of engine oil of the prescribed specification SAE; API; ACEA; or company specification (e.g. VW; MB ...) has been established.

- Kinematic viscosity/40 °C: 90.90 [cSt], the decrease compared to the reference sample is by 7.68 [cSt] - MO glass transition by 8.44 [%]. Degradation in terms of kinematic viscosity decreased first (glass transition by 12.02 [cSt]/-9.71 [%]). In the second measurement, the MO compared to the reference sample stacked us by +7.68 [cSt]/-8.44 [%] at that the tendency of kinematic viscosity compared to the reference sample was a tendency of decreasing (more fluid). The trend between the first and the second sample was upward (slightly more viscous). The allowable tolerance derived from the reference sample is 90.09 [cSt], ±20 % (+20 %=118.29.00 [cSt], -20 %=78.86 [cSt]) - the sample value of the MO used is satisfactory**.**

Tab. 2 Kinematic viscosity values of crankcase oil at 40 °C a 100 °C

	Unit of meas.	Ref.s.	i-S/1	i-S/2	i-S/3
Date of collection	d.m.y.	4.4.2023	21.6.2023	5.10.2023	10.1.2024
Date of measurement	d.m.y	12.4.2023	26.6.2023	6.11.2023	18.1.2024
Bus tachometer status	[km]	320,574	325,703	336,588	341,881
Running in MO	[km]	0	5,129	10,885	5,293
Viscosity index	Dimensionless	159	159	159	159
K. viscosity at 40 °C	cSt	118,29 +20% 98,58 78,86 -20%	86,8 12,02 -13,68%	90,90 7,68 -8,44%	97,23 1,34 -1,38%
K. viscosity at 100 °C	cSt	18,04 +20% 15,03 12,02 -20%	13,57 1,46 -9,71%	14,13 0,89 -6,31%	14,87 0,16 -1,07%

Source: author.

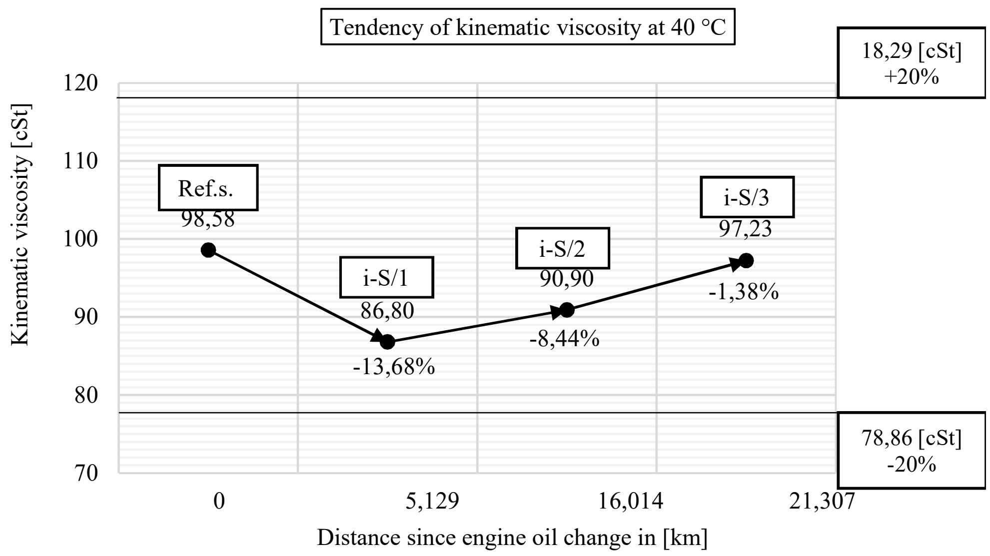


Fig. 2a The course of kinematic viscosities of MO at 40 °C
Source: author.

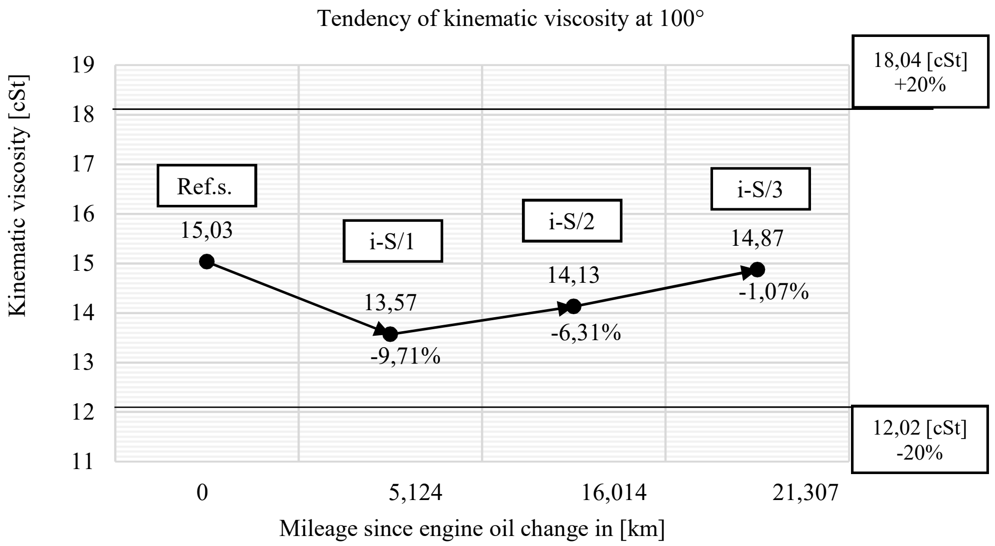


Fig. 2b The course of kinematic viscosities of MO at 100°C
Source: author.

- Kinematic viscosity/100 °C: 14.13 [cSt], the decrease compared to the reference sample is 0.89 [cSt], the MO glass transition is 6.31 [%]. Degradation in terms of kinematic viscosity decreased first (glass transition by 1.46 [cSt]/-13.68 [%]). In the second measurement, the MO stacked by 0.89 [cSt]/-6.31 [%] when compared to the reference sample, the tendency of kinematic viscosity compared to the reference sample was decreasing (more fluid). The trend between the first and the second sample was upward (slightly more viscous). The allowable tolerance is derived from the reference sample of 15.03 [cSt], ±20 % (+20 %=18.03 [cSt], -20 %=12.02 [cSt]) - the sample value of the MO used is satisfactory [4].

4.2 Criterion for Assessing the Performance of Engine Oils *(measured on FluidScan Q-1000)*

TBN - alkalinity number (parameter for acid sludge dispersion)
Do not allow operation of the engine oil if the TBN value changes by more than 50 % of the value of the reference sample.

TAN - acid number (parameter for dispersion of alkaline sludge)
Do not allow operation of the engine oil if the TAN value changes by more than 50 % of the value of the reference sample.

Antioxidant content (resistance and strength of MO structure...)
Do not allow operation of the engine oil when the antioxidant content drops by more than 50 % of the value of the reference sample.
Wear elements (concentration - density of elements - assessment of the state of wear of working surfaces).
Assessment of wear elements by statistical observation and comparison of values for the same engine types, focusing on ISO 14830 values.

Total contamination (to assess particulate matter in engine oil).
Assessment of total contamination according to ISO 14830 focusing on distance and hours worked, not to allow operation at above limit, i.e. - very high contamination according to cleanliness class.

Glycol content (ethylene glycol-$C_2H_6O_2$ or propylene glycol-$C_3H_8O_2$) is not allowed in motor oil.
Glycol causes some of the additive to separate from the base oil in the MO and causes a change in the overall viscosity and thickening of the engine oil. The presence of glycols in engine oil is not permitted.

The total amount of additive in the engine oil.
The engine oil must be usable in the working parts of the engine under all conditions. It must have this serviceability no matter how hot, cold, harsh or dusty the environment in which it is used and regardless of the extent of engine use. Additives are chemicals of complex composition, the addition of which to the base oil improves the performance of engine oils, slowing their ageing and degradation, enabling the oils to safely and reliably meet all the demands of modern engines. Not allowing the engine oil to operate when the total additive value is reduced by more than 50 %. [1]

Soot content (carbon residue (CCT)).
Increased soot content in the exhaust gases is a manifestation of the high mixture richness (λ) of the engine. An engine that operates with a rich mixture not only produces black smoke from the exhaust, but also produces more soot and unburned hydrocarbons (HC). These soot and unburned HC are trapped on engine contact parts and also enter the engine oil, leading to faster carbonization (low and high temperature sludge build-up). piston rings, oil filter plugs or lubrication passages through which the engine oil flows. As a result, engine oil deterioration and inadequate lubrication occur, leading to increased wear on individual engine parts. The specified value for the maximum concentration of CCT is up to 2 % w/t [5].

Water content
Has the effect of triggering chemical reactions, such as sulphation, in which additives fall out of the base oil.
Water is a strong activator of corrosion (rusting) of engine parts. The limit value for the water content in engine oil is 0.5 % w/w/5 000 ppm (concentrations as low as 0.1-0.3 % w/w/1 000-3 000 ppm are already a risk factor) [5].

Fuel content
It has the effect of triggering chemical reactions such as nitration, in which additives are dropped out of the base oil. The limit value for fuel content in engine oil is 5 % w/w/50,000 ppm (some engine manufacturers already quote a value of 4 % w/w/4,000 ppm). The percentage of fuel in the engine oil also affects the flash point of the engine oil. For diesel engine oils, the limit value is 180 °C (the risk factor is already 190 °C). The limit value for spark-ignition engine oils is 160 °C (the risk factor is already 170 °C). This refers to engines with a directly normal reciprocating piston movement [5].

Nitration products.
Nitration is the introduction of one or more NO2 groups into organic compounds. Nitration is the conversion of ammonium salts to nitrite by bacterial action. These processes in engine oil cause the breakdown of the components and additives of the base oil. It is a negative parameter in engine oil [5].

Sulphation products.
Sulfation is the process of sulfate formation. Sulfates are salts of sulfuric acid, sulfates. These processes in engine oil cause the breakdown of the components and additives of the base oil. It is a negative parameter in engine oil [5].

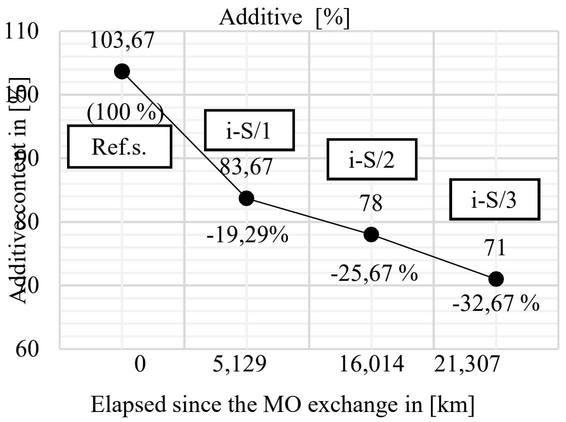
Ferroparticle content (26Fe55,845; 27Co58,933; 28Ni58,693)
- measured with a laboratory tribodiagnostic instrument - FerroCheck 2000 series: ferromagnetic metals are metals with magnetic properties. Their presence in engine oils indicates wear of the respective engine contact surfaces. For the evaluation of engine oils, the following limitation has been set for ferro particles:
- FerroCheck 2000 is set to an interface of 1 000 ppm.
- Amount <0 ppm - 30 ppm> Occurrence of ferroparticles.
- Amount <30 ppm - 70 ppm> Increased occurrence of ferroparticles.
- Amount <70 ppm - 100 ppm> Dangerous amount of ferroparticles.
- Amount <101 ppm and above> Intolerable amount of ferroparticles.

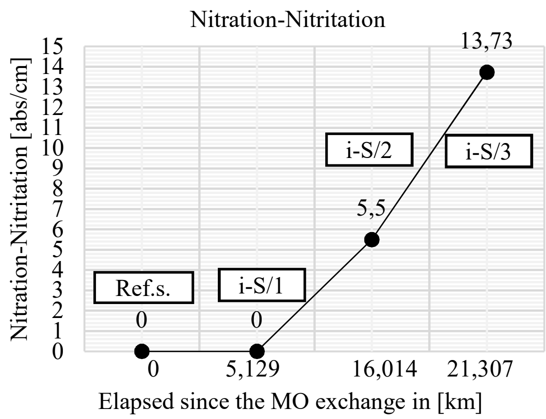
Note: 1 ppm = 0,0001 %
Test methods and procedures used

Tab. 3 Measured values of selected MO properties

	Unit of meas.	Ref.s.	i-S/1	i-S/2	i-S/3
Unit of meas.	d.m.y.	4.4.2023	21.6.2023	5.10.2023	10.1.2024
Date of measurement	d.m.y.	12.4.2023	26.6.2023	6.11.2023	18.1.2024
Number of kilometres	[km]	320,574	325,703	336,588	341,881
Driven distance since replacement MO	[km]		5.129	16.014	21.307
Additives	[%]	103,67	83,67 $^{-19,29}$	36,00 $^{-65,27}$	71,00 $^{-32,67}$
Glycols	[%]	0,00	0,00 ^{0,00}	0,00 ^{0,00}	0,00 ^{0,00}
Nitritation/Nitration	[abs/cm]	0,00	0,00 ^{0,00}	5,50 ^{5,50}	13,73 ^{13,73}
Oxidation [abs/0,1]	[abs/0,1]	20,10	20,23 ^{0,13}	20,83 ^{0,72}	23,98 ^{3,88}
Soot	[% wt]	0,00	0,10 ^{0,00}	0,18 ^{0,18}	0,08 ^{0,08}
Sulfation	[abs/0,1]	20,50	19,23 $^{-1,27}$	16,18 $^{-4,33}$	20,90 ^{0,40}
TBN	[mg KOH]	4,73	5,43 ^{0,70}	2,43 $^{-2,31}$	3,18 $^{-1,56}$
Water content	[ppm]	773,33	348,00 $^{-425,33}$	615,50 $^{-157,8}$	850,75 ^{77,42}
Pherochastics	[ppm]	0,00	27,33 $^{+27,33}$	33,18 $^{+33,18}$	10,50 $^{-90,50}$

Source: author.

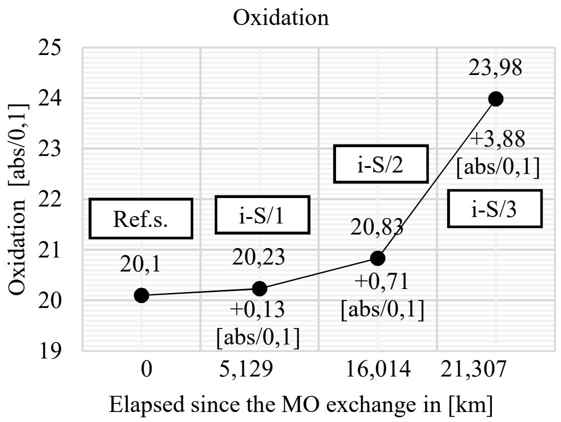




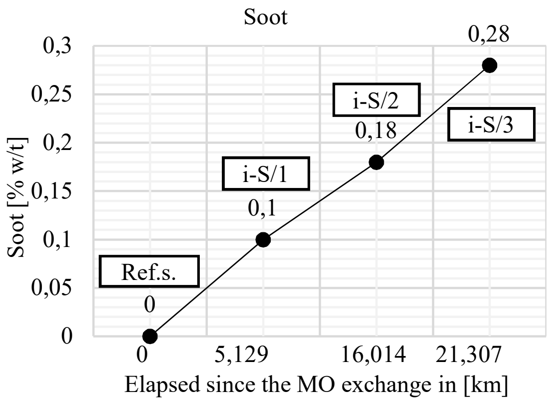
- **Additivity [%] -** Decrease in total additivity vs. (~103.67 %) was as follows for individual measurements:
  After 5,129 km/26.6.2023 - decrease by 19.29 % (to a value of 83.67 %), after 16,014 km since MO replacement/06.11.2023 - decrease by 25.67 % (to a value of 78.00 %), further after 21,307 km since MO replacement/18.1.2023 - decrease by 32.67 % (to a value of 71.00 %). In the course of the 21.307 km travelled, 4.8 lit. MO.
  - The sample value of the MO **used is satisfactory.**

- **Glycols [%] 0,00** - Value the same as Ref.ref - The presence of glycols in the engine oil has not been detected. During the operation from the change of MO/4.4.2023, until the measurement on 18.1.20024 a positive value was measured - 0,00%
  - The sample value of the MO **used is satisfactory.**

- **Nitration-Nitritation** [abs/cm] After 5,129 km/26.6.2023 - a value of 0.00 abs/cm was measured, after 16,014 km from MO replacement/06.11.2023 - a value of 5.50 was measured (to a value of 5.50 abs/cm), then after 21,307 km from MO replacement/18.1.2023 - a value of 13.73 was measured (to a value of 13.73 abs/cm). The measured values of Nitration-Nitritation tell us about the fuel absorption in MO. In the course of 21,307 km travelled, 4.8 litres were replenished. MO. Nitration is the conversion of ammonium salts to nitrites, these processes in the engine oil cause the decomposition of the components and additives of the base oil. It is a negative parameter in engine oil.
  - The sample value of the MO **used is satisfactory.**

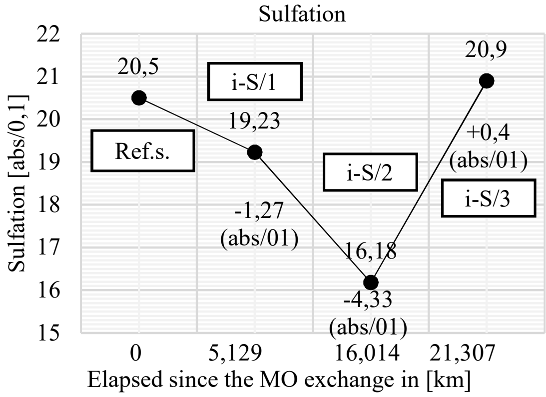


- **Oxidation** [abs/01] When measuring Ref.vz. MO oxidation was found to be 20,1 abs/01 (4.4.2023 - MO replacement in vehicle). This oxidation was due to the fact that the MO was topped up from 200 litres. barrel to several types of equipment. MO was stored in this way for more than 1 year, i.e. there was constant oxidation of MO - the oil was not secured against oxidation by a hermetic seal. After 5,129 km/26.6.2023 - a value of 20,23 abs/01 was measured (increased by 0,13 abs/01), after 16,014 km from the MO replacement/06.11.2023 - a value of 20,83 abs/01 was measured (increased by 0,72 abs/01), then after 21,307 km from the MO replacement/18.1.2023 - a value of 23,98 was measured (increased by 3,88 abs/01). In the course of the 21,307 km driven, 4.8 litres of fuel was added. MO.
  - The sample value of the MO **used is satisfactory.**

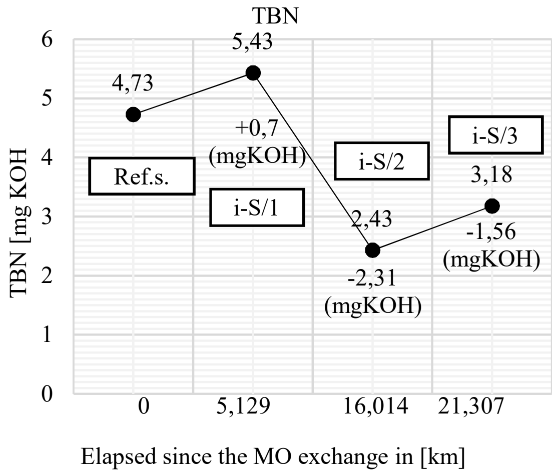


- **Soot** [% w/t] After 5,129 km/26.6.2023 - a value of 0.10 % w/t was measured (increase of 0.10 %w/t), after 16,014 km from MO replacement/06.11.2023 - a value of 0.18 %w/t was measured (increase of 0.18 %w/t), then after 21,307 km from MO replacement/18.1.2023 - a value of 0.28 was measured (increase of 0.28 %w/t). The measured soot values are within the standard given that the soot limit is 0.00 %w/t MO. During the 21,307 km travelled, 4.8 litres of MO were replenished.

  - The sample value of the MO **used is satisfactory.**



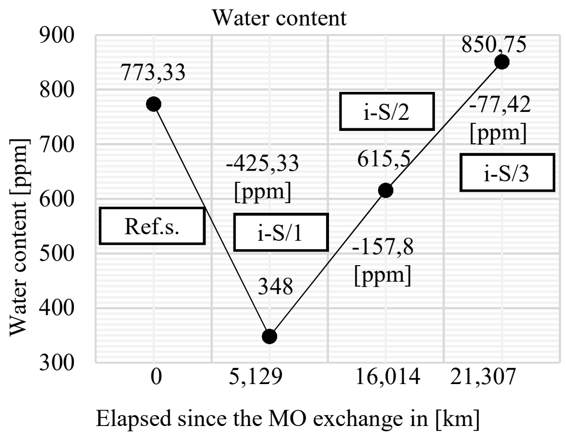
- **Sulfation** [abs/01] When measuring Ref.vz. MO sulphation 20,50 abs/01 was detected (4.4.2023 - replacement of MO in the vehicle). This sulphation was caused by the hydrophilicity of the MO and the humid environment. Thus MO was stored for more than 1. year, that means that there was a constant dissolution of moisture – water in MO from the air. The MO was not secured against moisture ingress by a hermetic seal. After 5,129 km/26.6.2023 - a value of 19,23 abs/01 was measured (decrease by 1,27 abs/01), after 16,014 km from the MO replacement/06.11.2023 - a value of 16,18 abs/01 was measured (decrease by 4,33 abs/01), then after 21,307 km from the MO replacement/18.1.2023 - a value of 20,90 (decrease by 0,40 abs/01) was measured. The decrease in sulphation values and subsequent increase was due to the change in water quantity during operation. During the 21,307 km travelled, 4.8 litres were replenished. MO.
  - The sample value of the MO **used is satisfactory.**



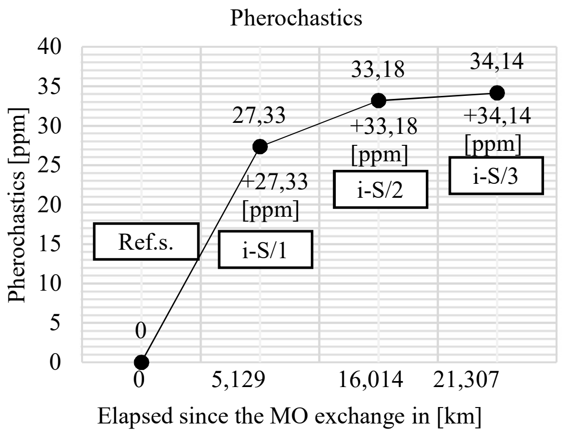
- **Alkalinity (TBN) [**mg KOH/g] When measuring Ref.vz. MO alkalinity was found to be 4.73 mg KOH/g (4.4.2023 - MO replacement in vehicle).

The change in alkalinity is related to changes in oxidation, and fuel and water content of MO. Based on the alkalinity values we can estimate the ageing. After 5,129 km/26.6.2023 - a value of 5,43 mg KOH/g was measured (decrease by 0,70 mg KOH/g), after 16,014 km from MO replacement/06.11.2023 - a value of 2,43 mg KOH/g was measured (decrease by 2,31 mg KOH/g), then after 21,307 km from MO replacement/18.1.2023 - a value of 3,18 mg KOH/g was measured (decrease by 1,56 mg KOH/g). This oscillation of values is due to oxidation, fuel saturation to MO, hydrophilization of water to MO and oil upgrading by adding it to the lubrication system. During the 21,307 km travelled, 4.8 litres of MO were replenished.

- The sample value of the MO **used is satisfactory.**



- **Water content** [ppm] When measuring Ref.vz. the amount of H_2O in the MO was measured to be 773,33 ppm (4.4.2023 - replacement of MO in the vehicle). This presence of water was due to hydrophilization of MO from the humid environment. Thus MO was stored for more than 1 year, i.e. there was a constant dissolution of moisture - water in MO from the air. The MO was not secured against moisture penetration by a hermetic seal. After 5,129 km/26.6.2023 - a value of 348,00 ppm was measured (decrease by 425,33 ppm), after 16,014 km after MO replacement/06.11.2023 - a value of 615,50 ppm was measured (decrease by 157,8 ppm), further after 21.307 km after MO replacement/18.1.2023 - a value of 850,75 ppm was measured (increase by 77,42 ppm). The change in measured values is related to the type of operation and is evaporation from the crankcase into the intake manifold. During the 21,307 km travelled, 4.8 litres of MO were replenished. Considering that the limit value for the amount of water in the engine oil of 5,000 ppm the MO **used is satisfactory.**



Other parameters of the monitored properties, measured in the Laboratory of tribodiagnostics of AOS on device FERROCHECK 2000, are within the tolerances of usability of MO (Table 3. Measured values of selected properties of MO), valid for the used MO Samples i-S/2 MO i-Sigma top MS SAE 10W40, IVECO CROSSWAY Evadis, EVČ LM780CT:

- Pherochastics-Fe, Ni, Co [ppm](1 ppm=0.0001 % of the whole) /33.18/ - Increased occurrence - the ranges of applicability are given above in Table 2.1. Do not allow operation when greater than 101 ppm of Ferroparticles are found in the MO - The sample value of the MO used is satisfactory [2].

4.3 Performance Evaluation Criterion for Spectrocube Engine Oils

(measured on SPECTROCUBE)

Content of measured elements:

- Measured with a laboratory tribodiagnostic device - Spectrocube:

Elements are detected by X-ray lamp irradiation (radiation - evaluation of the frequency characteristics of individual elements)

- Measured parameters reference sample MO i-Sigma top MS SAE 10W40, IVECO CROSSWAY Evadis, EVČ LM780CT.
- The selection of the parameters of the individual elements was chosen according to the possible contamination from the engine, and dropped elements from the additive and impurities from the external environment (air intake into the engine) [3].

Tab. 4 Resulting assembly from SpectroCube and reference sample (Ref.) MO i-Sigma top MS SAE 10W40, IVECO CROSSWAY Evadis, 12.4.2023

No.	ET	Element	Concentration	Error	Unit	No.	ET	Element	Concentration	Error	Unit
16	**S**	Sulphur	2625	1	ppm	51	**Sb**	Antinoma	< 1,7	-	ppm
20	**Ca**	Calcium	1255	2	ppm	27	**Co**	Coblat	< 1,0	-	ppm
30	**Zn**	Zincum	849,5	0,8	ppn	47	**Ag**	Silver	< 0,4	-	ppm
15	**P**	Phosphorus	696,8	1,1	ppm	25	**Mn**	Manganese	< 0,4	-	ppm
12	**Mg**	Magnesium	610	12	ppm	24	**Cr**	Chromium	< 0,3	-	ppm
17	**Cl**	Chlorine	93,9	0,2	ppm	28	**Ni**	Nickel	< 0,3	-	ppm
14	**Si**	Silicon	79,5	0,7	ppm	56	**Ba**	Barium	< 0,3	-	ppm
13	**Al**	Aluminium	18,7	0,4	ppm	40	**Zr**	Zirconiun	< 0,2	-	ppm
42	**Mo**	Molybdenum	7,6	0,2	ppm	29	**Cu**	Copper	< 0,2	-	ppm
19	**K**	Potassium	6,9	0,2	ppm	80	**Hg**	Mercury	< 0,2	-	ppm
53	**I**	Iodine	3,3	1,9	ppm	22	**Ti**	Titanium	< 0,2	-	ppm
26	**Fe**	Irone	1,94	0,05	ppm	48	**Cd**	Cadmium	< 0,2	-	ppm
38	**Sr**	Strontium	0,40	0,04	ppm	50	**Sn**	Tin	< 0,2	-	ppm
83	**Bi**	Bismuth	0,16	0,05	ppm	34	**Se**	Selenium	< 0,1	-	ppm
35	**Br**	Bomine	0,11	0,02	ppm	82	**Pb**	Lead	< 0,1	-	ppm
81	**Tl**	Thallium	0,09	0,05	ppm	74	**W**	Tungsten	< 0,1	-	ppm
33	**As**	Arsenic	0,5	0,03	ppm	23	**V**	Vanadium	< 0,0	-	ppm

Source: author.

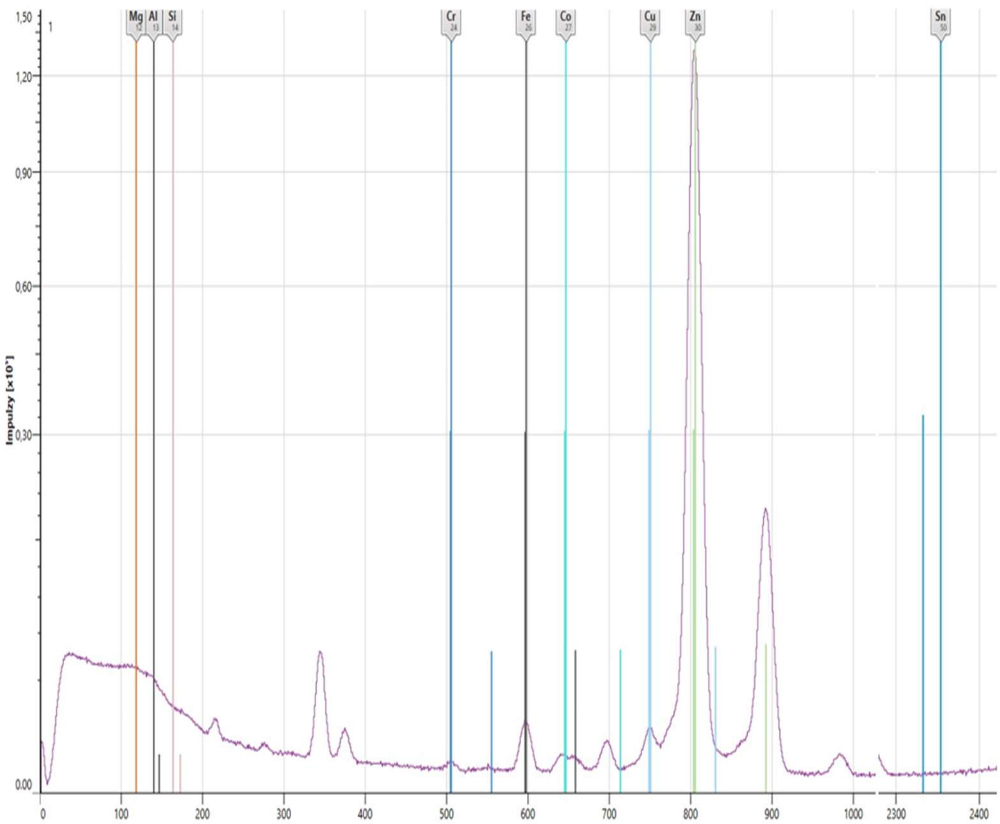


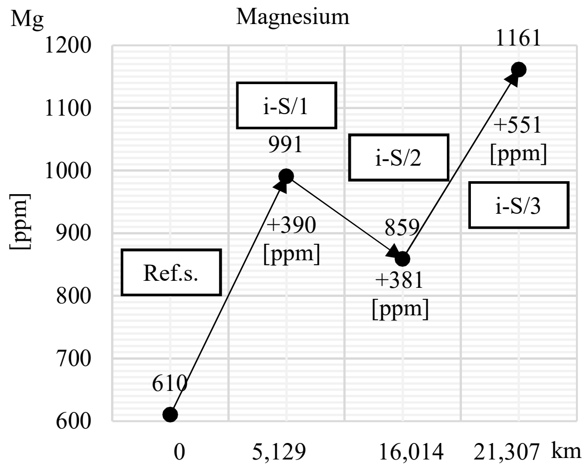
Fig. 3 Frequency response graph: reference sample (Ref.sample) MO Samples i-S/2 MO i-Sigma top MS SAE 10W40, IVECO CROSSWAY Evadis, EVČ LM780CT, v Impulse / eV [mA]
Source: author.

Tab. 5 Comparison of the elements of the reference sample and the used samples i-S/1, i-S/3. These are the underlined elements from the above resulting assembly from SpectroCube

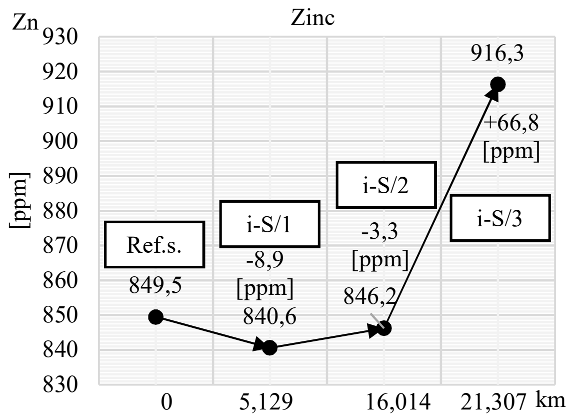
Number in Mendelian table sign	Element tag	Title	Measured value				Unit
			Ref.	i-S/1	i-S/2	i-S/3	
12	Mg	Magnesium	610	991 +390	859 +381,0	1161 +551	Ppm
30	Zn	Zinc	849,5	840,6 -8,9	846,2 -3,3	916,3 +66,8	Ppm
14	Si	Silicon	79,8	41,8 - 38,0	34,6 -45,2	124,6 +44,8	Ppm
13	Al	Aluminum	18,7	17,8 +0,9	4,6 -14,1	1,5 -17,2	Ppm
26	Fe	Iron	1,94	11,1 +9,16	15,1 +13,16	20,6 +18,66	Ppm
82	Pb	Lead	0,1	2,2 +2,1	2,2 +2,1	2,7 +2,6	Ppm
29	Cu	Copper	0,2	1,8 +1,6	3,2 +3,0	4,7 +4,5	Ppm
24	Cr	Chrome	0,3	1,4 +1,1	2,1 +1,8	2,8 +2,5	Ppm
50	Sn	Tin	0,2	1,1 +0,9	1,1 +0,9	1,2 +1	Ppm
27	Co	Cobalt	1	1 0	1 0	0,3 -0,7	Ppm

Source: author.

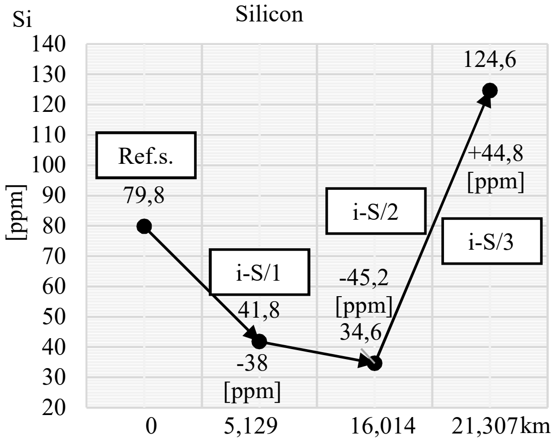
4.4 Evaluation of non-radiation of the monitored elements on the SpectroCube



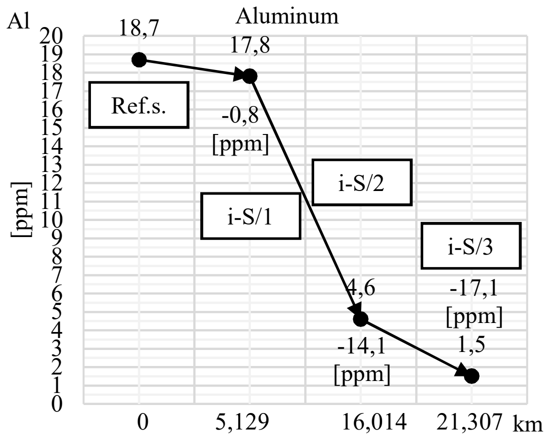
Mg:
There was an increase in the measured value of Mg = +381ppm; - abrasive particles are part of the metal alloys / admixtures of the engine interactive surfaces and MO additive residues (Mg is part of the metals of the interactive surfaces but also of the additive viz. occurrence in the reference sample). From this point of view, I consider this value in MO to be acceptable.



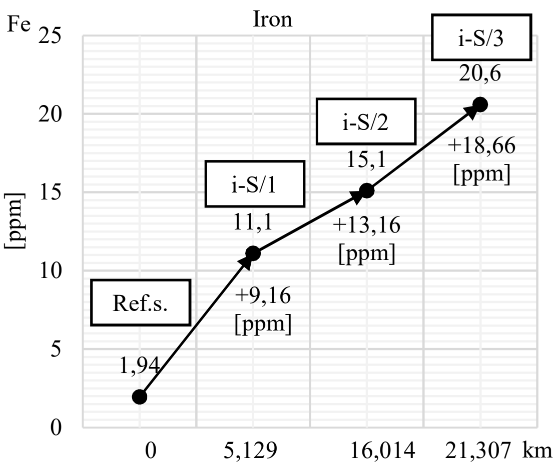
Zn:
There was a decrease in the measured value of Zn= -3.3 ppm; - abrasive particles are part of metal alloys / impurities of the engine interactive surfaces and MO additive residues (Zn is part of the metals of the interactive surfaces but also of the additive viz. occurrence in the reference sample). From this point of view I consider this value in MO as negligible - tolerable.



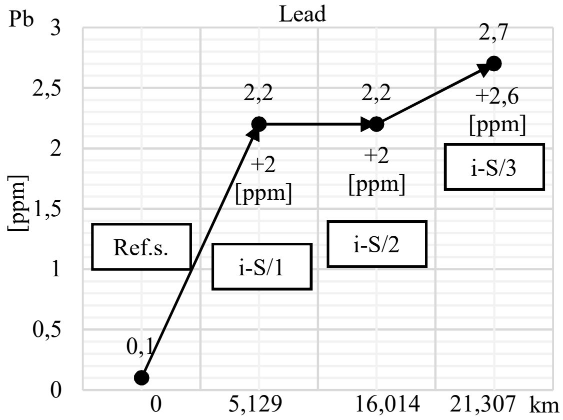
Si:
There was a decrease in the measured value of Si= -45.2 ppm; - Dust particles present in both the reference sample and the used sample are in the minimum values for normal occurrence in the MO. I consider this value to be acceptable.



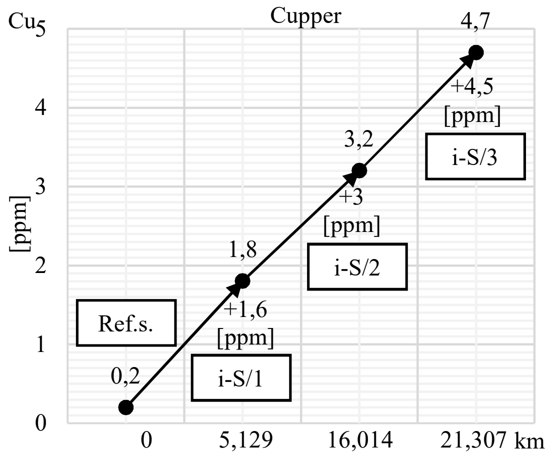
Al:
There was a decrease in the measured value of Al= -14.1 ppm; which is a negligible value in MO, aluminium is found in the engine parts (block, head, piston) there was an atomic dropout from the surface of those parts. I consider this value to be acceptable.



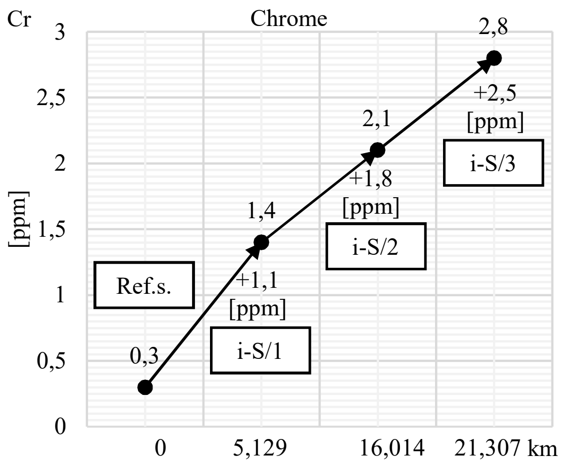
Fe:
There was an increase in the measured value of Fe=+ 13.16 ppm; I consider this value to be a usable occurrence for contact processes in MO. I consider this value to be acceptable.



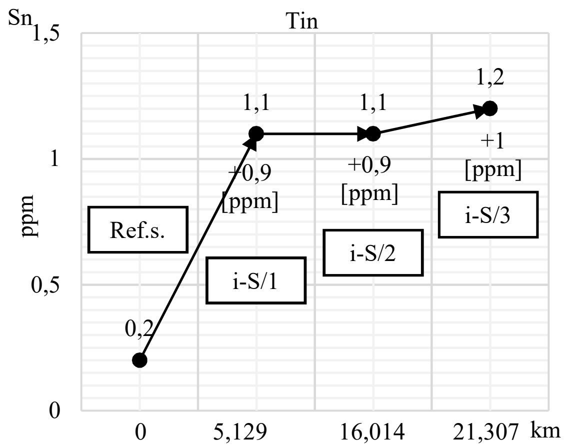
Pb:
There was an increase in the measured value of Pb= + 2.1 ppm; I consider this value to be a usable occurrence for contact processes in MO. Lead is part of the composite alloys in the engine. I consider this value to be acceptable.



Cu:
There was an increase in the measured value of Cu= +1.8 ppm; I consider this value to be a usable occurrence for contact processes in MO. Copper is part of the composite alloys in the engine. I consider this value to be acceptable.



Cr:
There was an increase in the measured value of Cr= +1.1 ppm; I consider this value to be a usable occurrence for contact processes in MO. Chromium is a component of the surface finishes of piston rings and bearings in the engine. I consider this value to be acceptable.



Sn:
There was an increase in the measured value of Sn= + 0.9 ppm; I consider this value to be a usable occurrence for contact processes in MO. Tin is a component of composite alloys in the engine. I consider this value to be acceptable.

Co:
There was no change in the Co = 0.0 ppm value; cobalt is part of the ferrocarbons in the engine.

The overall conclusion of the measurements on the SpectroCube is that the MO sample is suitable for further use.

4.5 Separation filter, separation membrane for detecting the density of solid particles in the MO

The criterion is:
Assessment of the degree of soiling; Detergent-dispersion properties.

Drop test on chromatographic paper and separation filter is a simple test to quickly (informative only) about the quantity of MO. It provides information on the quality and extent of lubricant contamination. This test gives an indication of the content of dispersible particles (substances insoluble in n-Hexane; n-Heptane). N-Hexane insoluble substances include oil insoluble substances formed as a result of the degradation of MOs and additives as products of thermo-oxidation reactions. Excessive content of these substances deteriorates engine lubrication conditions (thickening of MO, formation of hard varnish or low and high temperature sludge). Continued operation with excessive levels of these substances in the MO can cause engine overheating or deterioration of the function of the lubrication system cleaners - the so-called sticking of the filter cartridge surface.

The lines indicate the individual spectra of deposits or yellowing on the chromatographic membrane [6].

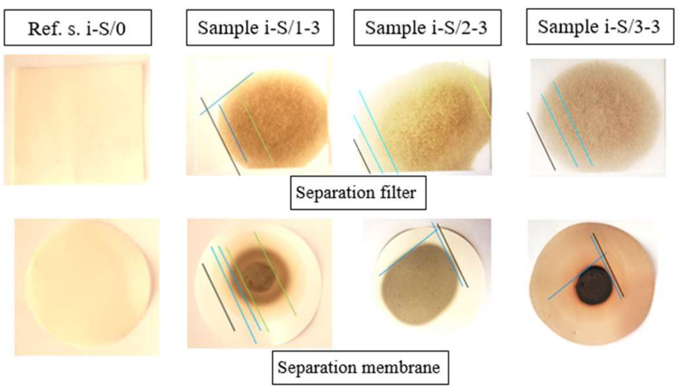


Fig. 4 Visualization of separation filters (square sample and separation membranes (circular sample)
Source: author.

Tab. 6 Degree of contamination (drop test-separation filter)

Motor oil	Degree of pollution **i-Sigma top MS**	Pattern number
The reference sample was clean, clear with no signs of densities		
1. i S/1 after 4 days	2	Litght pollution
2. i S/2 after 4 days	3	Medium pollution
3. i S/3 after 2 days	4	Medium pollution

Source: author.

Separation filter, separation membrane for detecting the density of solid particles in MO

Degree of contamination (drop test-separation filter):

Sample i-S/2-2 - (after running 10,885 km from measurement i-S/1 - total after running 16,009 km), after 3 hours after liquefaction; density of non-transparent material is in the range 0.30-0.50 [D] - density of impurities in the sample 0.0008-0.0016 [g] - **moderate fouling - evaluated from the separation filter**

Sample i-S/2-3 - (after running 10,885 km from measurement i-S/1- total after running 16,009 km), 4 days after liquefaction; density of non-transparent material 0.030-0.050 [D] - density of impurities in the sample 0.0008-0.0016 [g] **- medium fouling - yellow edges indicate good detergent dispersion properties of the MO - evaluation of the separation membranes.**

Sample i-S/3-3 - sample after two 2 day.

Measured MO after running 21.307 km 2 days after liquefaction; density of non-transparent material 0,050-0,070 [D] - density of impurities in the sample 0,0016-0,0024 [g] - medium fouling - yellow edges indicate good detergent dispersion properties of MO - evaluation of separation membranes.

After running 10,885 km since the i-S/1 measurement-a total of 16,009 km-there was no significant change in the density of non-transparent material-dispersible particles (substances not degradable in n-Hexane; n-Heptane) and there was no measured change in the detergent-dispersive properties of the MO.

The lines indicate the individual spectra of deposits or yellowing on the chromatographic membrane.

The degree of separation filter fouling and detergent-dispersion properties were compared with a comparison sample and classified by grade:

- Sample **i-S/3** (after 21,307 km) - rated grade number 4 mild to 4 moderate pollution, MO EXEMPT for further use with restriction to soot monitoring.

[Note]: the above samples are compared in terms of grain size - density. The separation membrane is darker, because the photochromic layer does not transmit the liquid component of the MO, which dries on the membrane at the separation filter the liquid component is absorbed into the filter, and therefore appears to us as paler and solid particles stand out in the foreground.

5 OVERALL CONCLUSION

Kinematic viscosity
Initially, the kinematic viscosity decreased. It increased with further operation due to refilling of new oil and due to long-distance trips. The engine oil is complaint.

Motor oil properties
None of the measured samples (additives, glycols, nitration, oxidation, soot, sulphation, TBN, water content, pheromone) show significant and borderline values of MO properties. The motor oil is complaint.

Evaluation of motor oil properties by Spectrocube
Selected parameters (magnesium, zinc, silicon, aluminium, iron, lead, copper, chromium, tin, cobalt) increased and decreased variously within the specified tolerances during the measurement. The engine oil is **complaint**.

Evaluation of separation filters and membranes
Density of non-transparent material - The density of impurities in the sample during the measurement was - Mild and moderate fouling. Motor oil is **compliant**.

The aim of the research was to determine the degradation of MO with atypical viscosity in the commonrail engine with oil viscosity - 10W-40. This vehicle was in the operation during long routes over 100 km. Typical oil viscosity used in common rail engine is 5W-30. The aim of the research was to determine the degradation of MO with atypical viscosity in the commonrail engine with oil viscosity - 10W-40. This vehicle was in the operation during long routes over 100 km. Typical oil viscosity used in common rail engine is 5W-30. Life of measured MO is 15,000 km or 2 year (guaranteed by producer). Our purpose was to measure maximum life of MO including his parameters to find out, if we can exceed the above stated parameters of measured MO.

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OBJECT RECOGNITION SYSTEM FOR THE SPINBOTICS ROBOTIC ARM

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Abstract: This study focuses on the development of a visual system designed to facilitate object detection for the Spinbotics robotic arm in spatial environments. The primary objective is to enable accurate detection and classification of diverse objects, enhancing the arm's capability to grasp and manipulate items effectively. The system employs the YOLOv7 deep neural network, fine-tuned using transfer learning on a local computing infrastructure. Compared to traditional methods like R-CNN and SSD, YOLOv7 offers superior real-time processing capabilities and efficiency, making it well-suited for dynamic environments. Through extensive training and testing, the system demonstrates robust performance in detecting objects across varied scenes and identifying optimal grasp points. This research underscores the effectiveness of integrating advanced computer vision techniques to enhance the operational efficiency and versatility of robotic manipulators in real-world applications.

Keywords: Robot arm; Visual system; YOLO; Object detection.

1 INTRODUCTION

The aim of this task is to design and test a visual system capable of detecting various objects in space that the robotic manipulator can grasp and transfer. The system needs to learn, reliably detect, and classify these objects in different scenes and determine the position of the point where the object can be grasped by the arm. The process of learning and transferring objects is designed with user assistance.

Fig. 1 Spinbotics 6-axis Serial Modular Robot
Source: www.spinbotics.com

The chosen sensor for this task is the Intel RealSense D455 camera. This is a stereoscopic depth camera with a global shutter and compact dimensions (124 mm x 26 mm x 29 mm) with USB-C connectivity. The camera is supported in ROS2 (robot operating system) thanks to the realsense-ros driver. The sensor outputs both RGB and depth images, combining which we obtain a colored 3D point cloud. To train and use the model, a computer with an Nvidia graphics card is required, the GTX1070m card is used. The camera is mounted on the Spinbotics robotic arm (Fig. 1) using a 3D printed holder, positioned between the fifth and sixth axes of the arm near the end effector (Fig. 2). The camera is temporarily connected via a USB-C cable routed externally along the robot, with future plans for connection through the robot's tool connector.

Fig. 2 Placement of the Intel RealSense D455 camera on the Spinbotics Robotic Arm
Source: author.

2 DATA COLLECTION AND PREPARATION

For development and initial testing, six objects were selected: a wooden cube, a wooden prism, and a wooden cylinder. A rod, a coin, and a ring are made of metal. The challenge is to correctly distinguish individual objects despite their very similar shapes from certain viewing angles (cube/prism and coin/ring).

The training dataset was created by capturing the objects on a contrasting surface from multiple viewing angles and distances (Fig. 3), as well as various groups and arrangements of objects. Hundreds of such captured samples underwent manual annotation in the YOLO (You Only Look Once) [1] standard format. Each image was accompanied by a corresponding .txt file with the position of the rectangle and the object identifier on a separate line.

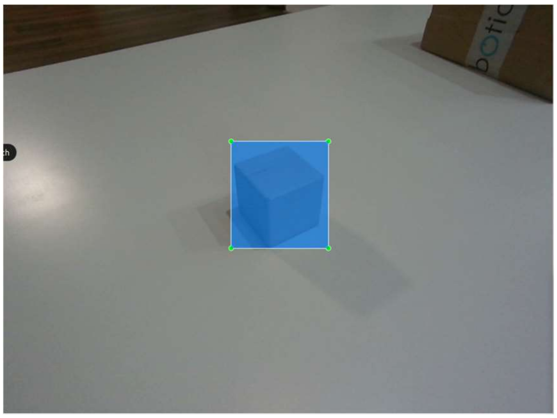

Fig. 3 Cube annotation
Source: author.

To expand the dataset, several augmentation methods were used, where the resulting training image is composed of multiple images from the dataset with slightly altered properties such as HSV (hue, saturation, value) [2], rotation of the original image, translation, scale, etc. We used the following methods: changing HSV parameters within a range of ±30 %, which allows us to simulate different lighting conditions, color distributions and brightness levels. We also used rotation within a range of -15 to 15 degrees, translation within ±30 %, and scaling within ±20 %. Finally, we used vertical mirroring method to the images. We did not use perspective changes or shear deformations.

These parameters contribute to robust detection in other environments.

The collection and extensive annotation will be automated using depth camera data and the position of the robotic arm in the future. For automated dataset collection of new objects, a single object on a contrasting surface at a known position is scanned, around which the robot plans a trajectory to capture the object from as many viewing angles as possible.

Each training batch includes a diverse set of images, generated by applying different augmentations (Fig. 5).

Fig. 4 Multiple augmentation methods were applied to the original image of wooden prism object. First row (left-to-right): original image, altered HSV values; second row: rotation + scale, altered HSV values, vertical mirroring + rotation.
Source: author.

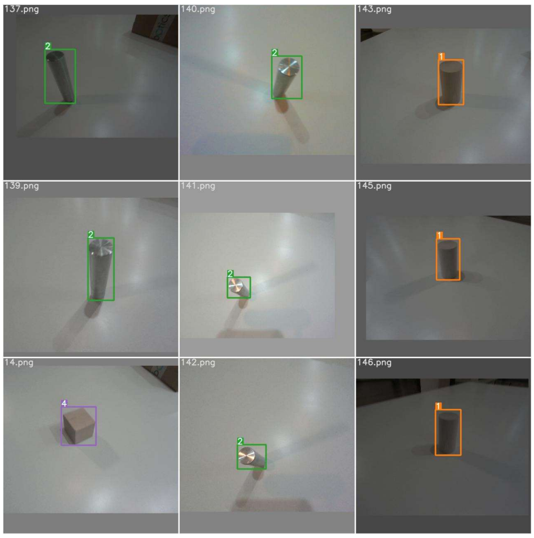

Fig. 5 Sample training batch
Source: author.

3 MODEL TRAINING

The detector is based on the YOLOv7 [1] deep neural network. This single-shot detector was chosen based on previous experience with this model and its good real-time detection capabilities. YOLOv7 is fine-tuned on custom data using transfer learning. In this method, parameters, weights resulting from long training on different objects from the COCO (Common objects in context) dataset [3]. Significantly more powerful hardware was used. In our case, we train locally on a computer with an Nvidia graphics card, and such training takes only a few hours since only the weights of the last layers of the network are changed.

For training, we always create a dataset split, typically in an 80:20 ratio, where 80 % of the images are used for training and 20 % for testing detection accuracy [4].

The success of the training is indicated by a confusion matrix (Fig. 6). Training continues until detection accuracy stabilizes; in this case, we trained for 700 epochs.

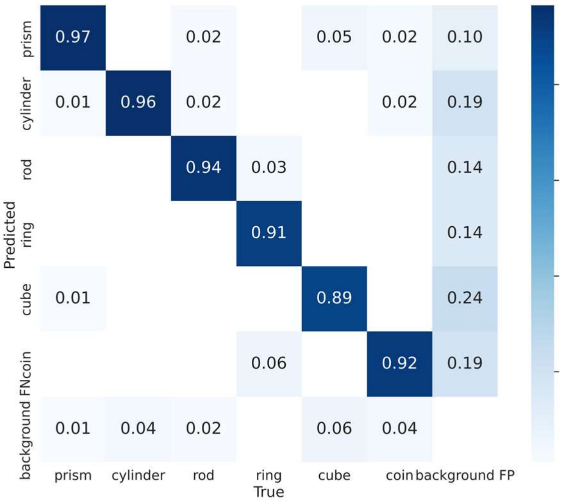

Fig. 6 Confusion Matrix after four hours of training
Source: author.

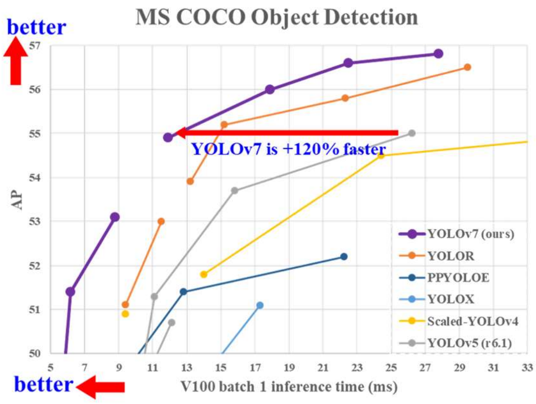

Fig. 7 Comparison of the YOLOv7 model's success and detection time with its previous versions
Source: [1].

4 TESTING THE TRAINED NEURAL NETWORK

The robotic arm should be able to select various stored objects from a view of the scene and move them from their original location to a new place. A database of known objects will be available, from which the user can choose which objects the robot should manipulate.

The trained detector is then integrated into the ROS2 environment. Object detection occurs only from the RGB image, with the detector outputting the coordinates of the rectangle in the image for the detected object.

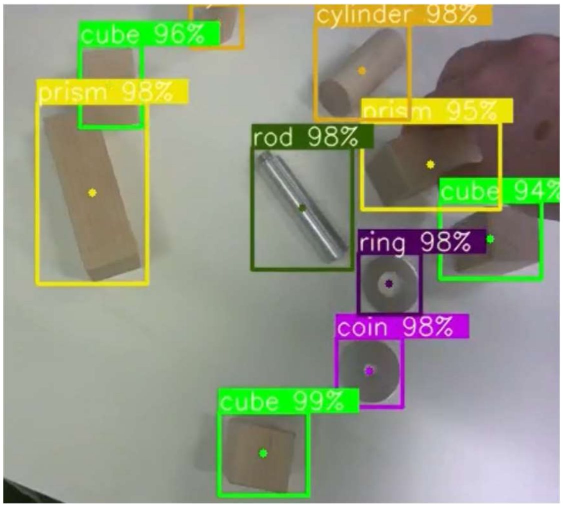

Fig. 8 Detected object in the RGB image
Source: author.

After determining the centroids of the rectangles, their position in the 3D space is calculated by projecting the 2D point from the calibrated depth image. The depth image is pre-processed using algorithms to fill in holes and filter out noise. With our hardware, the detector reliably distinguishes objects at a sampling rate of 15fps, which is sufficient for this type of task. Thus, the robot has information about the position of all recognized objects in the given scene. Measuring the distance of objects with the chosen camera is possible from a distance of 400 mm.

The method for selecting a candidate for grasping and the method of grasping is determined by the user. Either the object closest to the robot's end effector or the object with the most space around it to avoid collision with surrounding objects can be selected.

The images show the detection of objects in the scene (Fig. 9) and the estimation of the centroid distance of all “cube” type objects in the point cloud (Fig. 10), with the cube position marked in green in the rviz2 environment (Fig. 11).

Fig. 9 Output of the trained neural network on a series of test images from the dataset
Source: author.

Fig. 10 Position of points detected on objects in 3D space
Source: author.

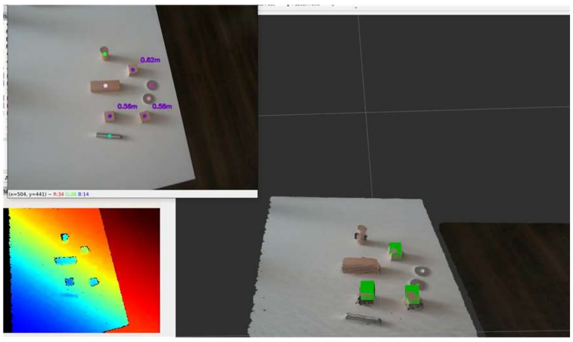

Fig. 11 Candidates for the robot to grasp objects labeled as "cube"
Source: author.

5 DISCUSSION

Our YOLO-based detector offers several key advantages that make it an excellent choice for a visual system. Firstly, it excels in speed and efficiency. Unlike traditional methods that process images multiple times at varying scales, YOLO treats object detection as a single-step process, predicting bounding boxes and class probabilities directly from full images. This streamlined approach reduces computation time, making YOLO well-suited for real-time applications.

Moreover, YOLO's unified architecture processes images in a single pass, enhancing accuracy and performance. It learns generalized object representations effectively, which improves its ability to detect a wide range of objects, even in complex scenes. This contrasts with other detectors that may compromise between speed and accuracy.

Compared to alternatives like R-CNN (Region-based Convolutional Neural Network) [6],[7] and SSD (Single Shot Multibox Detector) [8], YOLO stands out for its real-time processing capability. Traditional methods often rely on multi-stage pipelines, resulting in slower performance. While SSD offers real-time processing, YOLO frequently matches or exceeds its detection accuracy with simpler implementation.

Additionally, YOLO's flexibility in model size allows deployment across various hardware platforms, from powerful servers to edge devices with limited computing resources. This adaptability is crucial in robotics applications, where deployment environments vary widely.

In contrast to expensive industrial vision systems, our YOLO-based solution offers cost advantages. Industrial systems typically require specialized hardware and software, driving up costs. In contrast, our system leverages affordable, off-the-shelf components without sacrificing performance.

Furthermore, our visual system operates locally, eliminating the need for reliance on costly cloud services. Many industrial systems depend on cloud-based processing, which incurs ongoing expenses and requires consistent internet connectivity. Our local processing approach ensures data security and reduces operational costs, making it suitable for environments with unreliable connectivity or strict privacy requirements.

Overall, the YOLO-based visual system strikes a balance between speed, accuracy, and versatility. Its real-time performance and cost-effectiveness are particularly beneficial for applications such as autonomous driving, security surveillance, and industrial automation, where precise object detection is critical.

By adopting the YOLO detector, our visual system not only meets the demands of real-time object detection but also provides a practical, cost-efficient solution compared to many industrial vision systems.

6 FUTURE DEVELOPMENTS

The current solution has not yet been tested with the actual Spinbotics 6-axis Serial Modular Robot. Further development of the task will proceed after verifying the correctness of the proposed system. Gradually, efforts will focus on automating data collection and annotation, optimizing the learning process, designing the user interface, and specifying the use of the proposed system for a real task with a different set of objects.

7 CONCLUSION

This study presents the design and implementation of an object recognition system for the Spinbotics robotic arm, leveraging the Intel RealSense D455 camera and YOLOv7 neural network. Challenges such as distinguishing similar objects and ensuring robust detection in varied environments were addressed. The system reliably detects and classifies objects, crucial for pick-and-place tasks.

In comparison to traditional methods like R-CNN and SSD, the YOLOv7-based system stands out for its speed and efficiency, making it suitable for real-time applications. Unlike many industrial vision systems that rely on expensive, specialized hardware and cloud-based processing, our solution operates entirely on affordable, off-the-shelf hardware and runs locally. This not only reduces costs but also ensures data security and independence from prepaid cloud services.

Future efforts will focus on real-world testing, automating data handling, optimizing training processes, enhancing user interfaces, and adapting the system to different object sets. These steps aim to refine the system's performance and usability further. By continuing to improve the system's capabilities and versatility, we aim to create an effective and accessible solution for a wide range of industrial applications.

Additionally, the local operation of the system eliminates dependency on internet connectivity and cloud services, which can be a limitation in environments with unreliable connectivity or stringent data privacy requirements. This ensures that our system remains robust and functional in diverse settings.

In summary, the developed object recognition system for the Spinbotics robotic arm not only meets the demands of real-time object detection but also provides a cost-effective, secure, and versatile solution. This positions it as a competitive alternative to more expensive industrial vision systems, paving the way for broader adoption in various industrial applications.

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Patrik ŠTEFKA Studied robotics on Slovak University of Technology in Bratislava. Presently he is working in RoboTech Vision Ltd. company where he is responsible for development and integration of AI methods and neural network data processing into human interaction, navigation and localization algorithms.

Peter PÁSZTÓ studied robotics on Faculty of Electrical Engineering and Information Technology of STU in Bratislava. He is one of the founders and CEOs of RoboTech Vision Ltd. Throughout his university studies he has focused on image processing algorithms and their application in the field of mobile robotics (navigation and localization). During PhD studies he was awarded together with his team (now already CEOs of company) at a scientific conference in Rijeka, Croatia for an image processing algorithm detecting obstacles in front of a mobile robot navigated only by a smartphone running on Android OS.

Marian KĽÚČIK studied robotics on Faculty of Electrical Engineering and Information Technology of STU in Bratislava. He is one of the founders and CEOs of RoboTech Vision Ltd. During his studies he focused on the development of a robot with a combined chassis. He was also working on development of genetic algorithms for navigation and localization of his robotic platform. His skills include programming in multiple programming languages, controlling various operating systems, control system development, mechanics, control software and electronics. He focuses on the development of communication layer software and the configuration of OS in his company.

Martin SMOĽÁK has been involved in mobile robotics since secondary school. He was also involved in telemedicine projects and developed smart cars for the police in the past. He studied robotics on Faculty of Electrical Engineering and Information Technology of STU in Bratislava. Within RoboTech Vision Ltd. (of which he is also on of founders and CEOs), he focuses mainly on the development of lower-level control software, hardware, mechanics, and navigation algorithms and mobile robotic platforms design.

Matej VARGOVČÍK studied robotics on Faculty of Electrical Engineering and Information Technology of STU in Bratislava. During his studies he was developing number of significant scientific works. He implemented his knowledge in RoboTech Vision Ltd. company in which he is currently working. He is responsible for development of autonomous navigation an localization algorithms. He also activelly collaborates with the scientific comunity in his field and is contributing his solutions on GitHub platform.

Jakub LENNER studied robotics on Slovak University of Technology in Bratislava. Presently he is working in RoboTech Vision Ltd. company where he is cooperating on development of visual navigation and path-planning methods. He is also author of several scientific publications in the field of precise robot path-planning for docking algorithms using visual systems and image processing.

SCIENCE & MILITARY - WRITER´S GUIDELINES

1. Scientific articles submitted for publishing have to be original, topical and never been published before.

2. Articles have to be written in English language and in accordance with ethical standards. For moredetails, please visit the website of the Science & Military Journal (http://sm.aos.sk/index.php/en/for--authors-en/ethical-standards).

3. Length of the article should not exceed 6 pages in defined format. Microsoft Word text editor must be used for writing. Articles must be written using Times New Roman, single line spacing and follow the following form: Title -12 point bold capital letters aligned to the center. Full author´s (co-author´s) name – 10 point normal letters aligned to the center. Abstract – 9 point normal letters, extent 3-5 lines. Keywords – 9 point normal letters. The article text – 10 point normal letters. Contact - full author´s (co-author´s) name, affiliation, e-mail – 9 point normal letters at the end of the article. The article text will be written in 2 columns format with a 75 mm column width and 10 mm empty space separating the columns. The first line of each paragraph must be shifted 5 mm to the right.

4. Upper and lower margins must be set to 25 mm, left and right margins to 20 mm. Select mirror margins and set binding margins to 10 mm. The distance between the header/footer and the page margin must be 12,5 mm, while different odd and even pages must be selected.

5. Photographs for publication must be in black-white (not in color) of excelent quality with good contrast.

6. Equations in the text are also to be written using the equation editor. (Equation must be typed in Microsoft Equation, which is an integral part of Microsoft text editor.) They must be numbered. Numbers are to be enclosed in parentheses and aligned to the right margin of a column.

7. Figures, graphs and tables must be included in the text and numbered and must contain description. Figures must be identifi ed as Fig. 1 followed gradually by the fi gure description. Graphs must be identified as Graph 1 followed by the graph description. Tables must be identifi ed as Tab. 1, followed by the table description.

8. References must be fully and accurately documented (according to ISO 690). References should be quoted in the text in square brackets and listed in the order they have appear in the text.

9. The specimen article that can be found on the web-site: http://sm.aos.sk/index.php/en/for-authors-en can be used as an example of the correct format.

10. The editorial board will consider submitted articles in the next scheduled meeting. If it decides to include the article in the next issue it submits the manuscript to the editors for the peer review. The final version (before printing) will be sent to the author for the final revision. The authors are fully responsible for the level of language.

11. Contributions in A4 format edited according to the specimen article should be submitted in one hard copy and also in electronic form to the Editorial board.

12. The deadlines for the delivery of the articles in calendar year are: March 1 and September 1.

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