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Humanitarian demining: How can UAVs and Internet of Things help?

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ABSTRACT The history of active mine use spans nearly two centuries. In this relatively short historical period, mines have become a global problem. Explosive objects and mines, remnants of wars and military conflicts, continue to pose a threat to people residing in these areas for a long time. As of the beginning of 2023, the State Emergency Service of Ukraine reported that approximately 40% of the territory (over 250,000 km^2) had been mined. In terms of the extent of mined land, the United Nations classifies Ukraine among the most heavily mined countries. The scale of mine contamination surpasses countries where military conflicts have lasted for decades. The invention and improvement of mines have contributed to the development of methods to counter them. Today, more than fifty different methods and their modifications are known, but none guarantee a 100% success rate, underscoring the relevance of further scientific research. The creation and use of unmanned aerial vehicles (UAVs) have been a significant breakthrough in the field of intellectual achievements. Innovations manifest in all aspects, from modern composite materials to state-of-the-art navigation equipment and software. UAVs are actively deployed in various areas of human activity, demonstrating excellent results. The primary advantage of UAVs in humanitarian demining is the safety they provide, allowing individuals to operate in hazardous conditions beyond physiological and psychophysiological capabilities. The Internet of Things (IoT) is a relatively new combination of information and telecommunications technologies whose popularity is rapidly growing, opening up previously unexplored possibilities for practical applications. UAV and IoT technologies do not fall into the traditional classification of humanitarian demining methods. However, they serve as a connecting link for implementing, based on them or with their direct participation, other technological solutions (including geoinformation system (GIS), neural networks, artificial intelligence, Big Data, etc.). The prospects of implementing 5G communication networks in Ukraine will enhance spatial accuracy when combining both technologies, which is especially crucial for humanitarian demining. The recent advancements in communication technologies, such as 5G, and programs like the IoT, play a crucial role in aerial communication using UAVs. Depending on the application and operational region, UAVs have also been utilized to enhance coverage and throughput in 5G wireless communication. In such cases, UAVs act as intermediate nodes or flying base stations. This helps conduct operations in remote and challenging-to-reach locations. The idea of integrating cloud computing with UAVs enhances their role by providing additional computational capabilities.

KEYWORDS UAVs, georadar, humanitarian demining, Internet of Things.

I. INTRODUCTION

As of 2023, over 250,000 km^2 of Ukrainian territory is contaminated and affected by explosive objects. These figures classify Ukraine as the most heavily mined country in Europe, and with ongoing military activities, the area of affected territories is only expected to increase. Mine danger is a global problem, as 67 countries are contaminated with mines, putting at least 60 million people at risk daily [1]. The primary threat of mines lies in causing a complex of negative social, economic, and ecological consequences. Clearing territories of all explosive objects, including landmines, is vital for the recovery of any region. Demining requires significant effort, time, and resources, resulting in high costs per unit of cleared territory [2]. Despite various methods for detecting landmines and explosive devices using specialized technical means based on important parameters such as remote operation, sensitivity, selectivity, and speed, none fully satisfies the requirements of current UN standards for humanitarian demining or the overall need for global and operational demining of the planet [3].

In his renowned work 'The History of Civilizations,' historian Henry Bookle argues that the invention of gunpowder led to rapid societal changes. Traditional weapons such as swords, bows, and spears were replaced by firearms like muskets and pistols. Engineers later developed heavy artillery, including cannons, mortars, and bombs. These innovations prompted fortifications near defensive structures such as castles and fortresses to incorporate additional defensive features like walls, moats, and more. Mines became an effective means of destroying fortification walls. Initially, mines were simple tunnels dug under walls for collapse, but with stronger walls, traditional mining became impractical. Powder mines, which gained wide use in the late 15th to early 16th centuries, were introduced for wall destruction [4].

The explosive power of gunpowder was initially low, compensated by quantity. The search for optimal proportions and reduced explosive element weight ensued. The first modern-type mine was created by General Gabriel J. Rains in 1862 during the American Civil War to protect Confederate positions (Battle of Yorktown). In 1873, German inventor Sprengel discovered a means of detonating explosive material, now known as a 'detonator.' In 1876, German engineer Hertz invented the anchor mine, using pyroxylin and an electric detonator instead of gunpowder. The Russian Empire ordered 350 such naval mines in 1876 for use against Turkey, marking the first serial use of mines in a military conflict. Further mine development occurred with the advent of English tanks in World War I. By the war's end, Germany produced over 3 million anti-tank mines. During World War II, the USSR had mines detonated by a coded signal from a distance of up to 1200 m.

The complexity of modern mine construction allows various installation methods, both manual and fully remote (using aircraft, helicopters, mine rockets, portable manual remote mining systems). 'Smart mines' assume combat positions after installation and can detonate under various conditions, such as movement, changes in the Earth's magnetic field, the duration of power source action, expiration of the set time, etc. Modern anti-transport mines are even more complex and may contain acoustic, thermal, optical, seismic, and thermal sensors, making demining more challenging and prohibiting direct approach.

There are many methods for detecting explosive devices and landmines, limited by sensitivity and operational difficulties due to terrain, climate, and obstacles in the soil, such as metal fragments that create numerous false signals and slow down the detection rate to an unacceptable level. The classification of detection methods by the physical principle of interaction with decoy features and separately from information-measuring means and platforms where these means are located is proposed in [5] and includes: 1) mechanical; 2) electromagnetic; 3) chemical; 4) magnetic; 5) acoustic. Researchers conventionally divide all mine detection methods into two groups: invasive and non-invasive. The former (invasive) is based on earthmoving techniques (earthmoving machines) that detonate mines. Their main drawback is a shorter service life. Georadar (GPR), thermal imagers, metal detectors, and other systems that penetrate the ground without contact are examples of non-invasive mine detection methods.

Important information for differentiation lies in the depth of target burial, so it is preferable to use methods to assess this physical property. The most common type of mines is anti-personnel mines, which are usually placed on the surface (hidden under leaves or rocks) or buried at a depth of 10-15 cm. In a study [6], a large-scale examination of a mined area covering 41808 m^2 with 1593 hazardous objects allowed establishing statistical regularities of their depth placement. Figure 1 illustrates the histogram of the distribution of mine burial depths. Mines buried at depths ranging from 2.5 to 15.2 cm constitute 87.5% of the total number of detected targets, compared to 12.5% of mines found on the surface or buried at ground level.

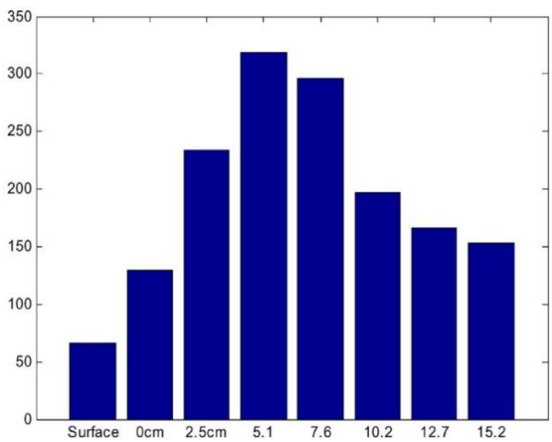

FIG. 1. Distribution of mines at different depths (based on data from [6]).

To date, none of the existing methods provides a 100% guarantee of territory clearance, necessitating the search for innovative methods and possibilities for combining them with existing ones. Therefore, the aim of this study is to determine the role, place, and possibilities of combining UAV and IoT technology for humanitarian demining of territories.

II. UTILIZING UAVs AND IoT FOR HUMANITARIAN DEMINING

The Fourth Industrial Revolution, also known as Industry 4.0, marks a new industrial era in the 21st century that combines the capabilities of information and communication technologies, enabling them to interact through the exchange, analysis, and application of information via wired or wireless communication. Hermann et al., 2016, identifies Industry 4.0 based on six principles [7, 8]:

1. Interaction: the ability of machines, devices, sensors, detectors, and humans to connect and interact to achieve a common goal.
2. Virtualization: cyber-physical systems (CPS) monitor physical processes, constantly comparing the real-world model (based on sensor data) with an edited model of the desired world. CPS control each other and provide alarm signals when they detect a failure.
3. Decentralization: the growing demand for individual products and services complicates centralized control systems. Embedded computers enable CPS to make decisions independently, but constant monitoring of the system as a whole is necessary.
4. Real-time adaptation: CPS collect, exchange, and analyze data in real-time, allowing for timely responses to system component failures by redirecting information or parts to another machine.
5. Service orientation: services provided by "smart" systems can be offered to other participants beyond the company, discipline, and international borders. All CPS can offer their functions as a separate service, allowing the right combination of CPS to create a specific product or service that meets the needs of end-users.
6. Modularity: systems can adapt to changing requirements by replacing or extending individual «Plug&Play» modules. Thanks to standardized software and hardware interfaces, new modules can be identified and requested automatically for immediate use.

The rapid progress in the development of information and communication technologies has facilitated the

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integration of various technologies and smart devices to achieve ubiquitous network connectivity. IoT is an advanced technology that combines numerous intelligent technologies and smart devices. The term IoT was proposed by Kevin Ashton in 1999, and as of 2023, the number of IoT-connected devices is approximately 16.7 billion. An increase in connections to 29 billion units is projected by 2027 (Figure 2).

One successful example of IoT application is presented in [10], involving a platform that combines and interacts with two microwave radars, including a multisensor UWB array, a holographic thermal imager, as well as three-dimensional optical cameras, remote navigation, and GPS tracking. This system is promising as experimental and operational field data are collected in real-time through a web architecture, and the processing of sensor data by artificial neural networks remains unrealized.

In [11], a two-wheeled robot with a metal detector on board is controlled via Bluetooth using an Android application. Three sensors in this system can detect metallic objects under various soil conditions at a depth of up to 20 cm. For comparison, most anti-personnel mines are usually buried at a depth of less than 4 cm, and their detonation requires a pressure of more than 9 kg. Another four-wheeled robot, ROBO-PI, equipped with a metal detector, detects mines at a depth of 15 cm [12]. One research team developed a system consisting of a base station and several detection blocks that can exchange data with the base station [13]. The common issue with ground-based detector robots is the risk of accidentally activating mines during the detection process [14].

The creation and use of UAVs have been a significant breakthrough in the field of technological advancements. Innovations are evident in all aspects, from advances in avionics and power systems to increased battery capacity, the introduction of composite materials, state-of-the-art navigation equipment, and software [15]. UAVs are devices paving the way for IoT. The miniaturization of embedded sensor technologies not only contributes to their development but also enhances the potential for interaction with IoT through specialized applications. Use cases of IoT-based UAVs are outlined in Table 1 [16].

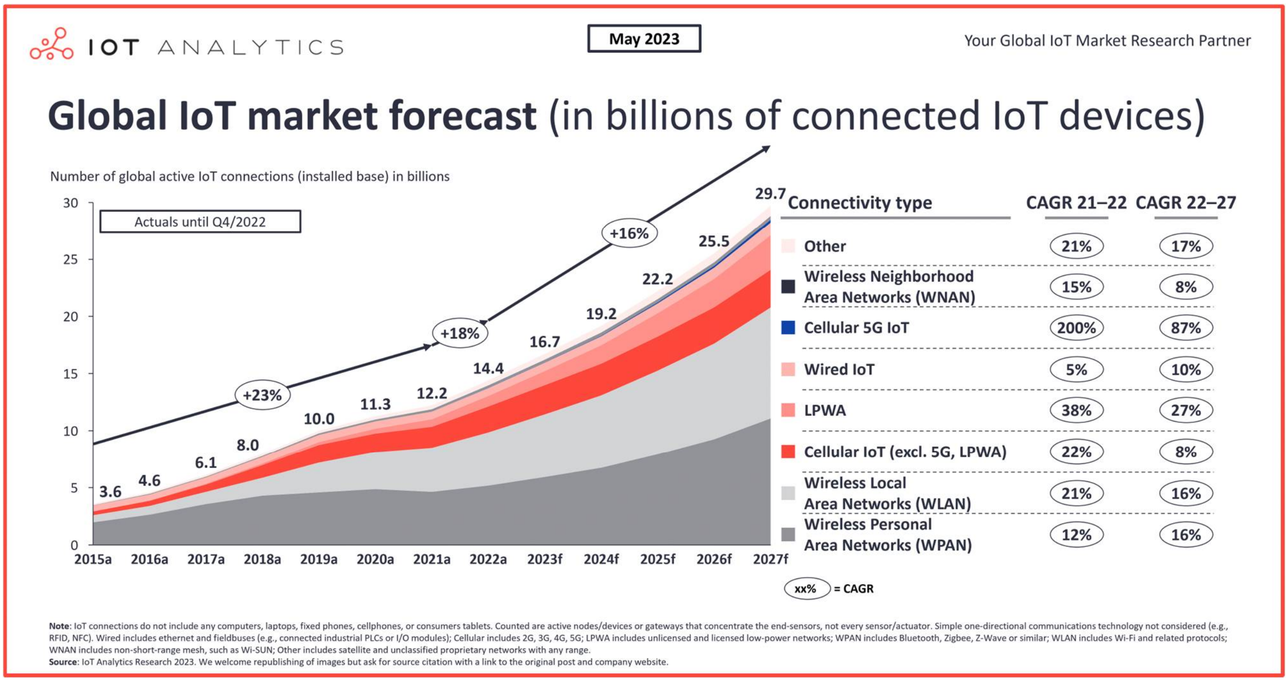

FIG. 2. The dynamics of the market for IoT device connections (according to [9]).

TABLE 1. Options for using the Internet of Things (IoT) based on UAVs (according to [16]).

Usage options	Details
Network Coverage	Integration of UAVs in IoT enhances network coverage in heterogeneous 5G IoT networks.
Aerial Communication	IoT networks based on UAVs provide fast, reliable, and flexible wireless communication to enhance security.
Connectivity	UAVs in IoT improve network connectivity and support ground networks, extending information dissemination.
Data Aggregation	With increased coverage of cellular networks, UAVs in IoT collect vast amounts of data in smart cities from large areas for business insights.
Energy Efficiency	UAVs offer reliable, flexible, and energy-efficient connections to the IoT network.
Large-Scale Deployment	UAVs are deployed over large territories to provide massive networks with multiple inputs and outputs, 3D networks, and millimeter-wave communication.

One of the modern approaches to the use of unmanned aviation for demining tasks is based on the deployment of mine detectors mounted on UAVs as useful payloads. Another approach involves the use of multispectral equipment mounted on drones for minefield reconnaissance and detection. Yet another approach utilizes infrared equipment installed on UAVs, which reacts to temperature differences between the mine and the surface terrain.

Recent advancements in telecommunications technologies, such as 5G and IoT, play a crucial role in aerial communication using UAVs. Depending on the operational region, UAVs can be employed to fill and extend communication gaps in coverage and bandwidth of wireless networks beyond 5G. In such cases, UAVs also act as intermediate nodes or flying base stations. This facilitates operations in hard-to-reach areas, allowing for monitoring, and the integration of cloud computing with UAVs enhances their role by providing additional computational power [17]. We are entering the era of "big data," accelerated by UAVs transmitting data packets of significant weight from onboard cameras [18].

IoT and UAVs have their strengths and weaknesses. Their integration can mitigate issues associated with IoT, given the geometrically increasing number of connected IoT devices complicating compatibility due to different protocols and communication technologies implemented on various devices. However, companies, eager to maintain market advantage, are not rushing to adopt common universal data standards and rules across different protocols and architectures, turning their quantity into a cumbersome and practically useless construction of hardware.

The next challenge is related to the security of the system responsible for its proper functioning. Additionally, the required multi-user data processing in real-time in a cloud environment can create delays in data transmission, low bandwidth, etc. UAVs can increase coverage in networks with poor infrastructure and weak internet connectivity, supporting low-power wide-area networks (LPWAN), wireless local area networks (WLAN), and satellite networks. Weak wireless communication is often associated with geographical environmental features, such as dense construction, transportation zones, forest areas, and places affected by natural disasters. UAVs allow circumventing obstacles located between line-of-sight.

UAVs easily interact with cloud services and enable the prompt processing of large datasets through intelligent algorithms aimed at making real-time decisions. Object identification technologies utilize UAVs to achieve stereoscopy and geographical diversity. Stereoscopic diversity is based on spatial positioning, while geographical diversity relies on geographical features [16].

One research group developed a quadcopter-type UAV equipped with a thermal imager and a metal detector [19], while another group attached an infrared camera, X-ray camera, and metal detector to a DJI S1000+ UAV [14]. However, the excessive weight significantly reduced its performance. One quadcopter had a magnetometer weighing 775 g, and researchers realized that the magnetic noise created by the quadcopter strongly affected the magnetometer readings [20]. A UAV with georadar detected mines at depths less than 20 cm [21]. This research demonstrates the possibility of developing an inexpensive system that can fly over a contaminated mine area, detect them, and report their location to the demining team. Detection technology should be effective in terms of weight and energy consumption.

III. CONCLUSION

UAV and IoT technologies do not fit into the traditional classification of humanitarian demining methods. However, they serve as a connecting link for the implementation of other technological solutions based on them or with their direct participation. Since none of the known humanitarian demining methods provides a 100% guarantee, only the search for ways to combine data obtained by other methods can come closest to achieving high performance. The article explores the essence of IoT technology and UAV capabilities, reviewing prototypes based on them that can be applied for humanitarian demining. The strengths and weaknesses of both technologies are identified during their mutual integration.

The plan for implementing a fifth-generation mobile communication system in Ukraine, scheduled for October 2021, began but was not fully realized due to objective reasons. In addition to providing quality communication and access to various services, this infrastructure will complement the mobile devices of average users. Solutions based on IoT will enhance the accuracy of A-GPS mode and the speed of spatial coordinate determination, which is particularly important for navigation in areas affected by post-war consequences.

The role of UAV technologies has expanded from ordinary technical surveying of terrain to field exploration using various sensors before demining begins. Close interaction with other information and communication technologies (GIS, neural networks, artificial intelligence, Big Data, etc.) opens up prospects for one of the most innovative solutions in the field of humanitarian demining of territories.

One of the most popular sensing methods is magnetometric probing. A magnetometric sensor is utilized to visualize magnetic anomalies by measuring the intensity of the magnetic field of magnetized objects, especially in the IoT environment. The process can be automated using UAV platforms, employing signal processing and computer vision methods based on captured images.

AUTHOR CONTRIBUTIONS

T.H., V.T., M.K. – conceptualization, methodology; T.H., V.T., M.K. – investigation; T.H., M.K. – writing (original draft preparation), T.H., M.K. – writing (review and editing).

COMPETING INTERESTS

The authors declare no conflict of interest.

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Гуманітарне розмінування: Як можуть допомогти БПЛА та технології Інтернету речей?

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АНОТАЦІЯ Історія активного застосування мін нараховує майже два століття. За такий відносно короткий історичний період часу вони стали проблемою світового масштабу. Вибухонебезпечні об'єкти та міни як пережитки війн та військових конфліктів ще довго ставлять під загрозу перебування людей на цих територіях. На початок 2023 р. прес-служба ДСНС проінформувала про мінування ≈ 40 % території (понад 250 000 км^2). За площею замінованих земель ООН відносить Україну до найбільш замінованих. Масштаби мінування перевершують країни, де військові конфлікти тривали десятиліттями. Винайдення та вдосконалення мін сприяло розвитку методів їх протидії. На сьогодні відомо про більш ніж пів сотні різноманітних методів та їх модифікацій, проте жоден не гарантує 100% результату, що тільки посилює актуальність подальших наукових пошуків. Створення і використання безпілотних літальних апаратів (БПЛА) стало серйозним проривом у сфері інтелектуальних досягнень. Інновації проявляються в усіх елементах: від сучасних композитних матеріалів до новітнього навігаційного обладнання та програмного забезпечення. БПЛА активно впроваджуються в різні сфери людської діяльності, демонструючи відмінні результати. Основна перевага БПЛА для застосування в гуманітарному розмінуванні – безпека використання, оскільки вони дозволяють людям не перебувати в загрозливих життю умовах, провадити діяльність за рамками фізіологічних та психофізіологічних здібностей. Інтернет речей (ІР) – відносно нове поєднання інформаційно-телекомунікаційних технологій, популярність якого стрімко зростає відкриваючи нові незвідані раніше можливості прикладного використання. Технології БПЛА та ІТ не потрапляють в традиційну класифікацію методів гуманітарного розмінування. Однак, вони є зв'язною ланкою для реалізації на їх основі або з їх безпосередньою участю інших технологічних рішень (зокрема, доповнення технологіями геоінформаційних систем, нейронних мереж, штучного інтелекту, даних BigData та ін.). Перспективи впровадження в Україні мереж зв'язку 5G сприятимуть просторовій точності при поєднанні обох технологій, що особливо важливо для гуманітарного розмінування. Останні досягнення в комунікаційних технологіях, таких як 5G, і таких програмах, як ІР, відіграють вирішальну роль у повітряному зв'язку за допомогою БПЛА. Залежно від застосування та регіону експлуатації, БПЛА також використовувалися для розширення покриття та пропускної здатності бездротового зв'язку 5G.У таких випадках БПЛА також виконують роль проміжних вузлів або літаючих базових станцій. Це допоможе проводити операції у віддалених труднодоступних місцях. Ідея інтеграції хмарних обчислень з БПЛА підвищує їх роль, надаючи їм додаткові обчислювальні можливості.

КЛЮЧОВІ СЛОВА БПЛА, георадар, гуманітарне розмінування, Інтернет речей.