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Opportunities for Implementation of the 4D Printing Technology in the Security and Defense Sector

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Abstract: The rapid technology innovations and mounting geopolitical challenges are actively shaping the trajectory of global security and defense. A significant part of this future depends on the capabilities of the 4D printing technology as a primary change-driver in the field. This paper presents theoretical research on the trends and possibilities for implementation of this new technology in the military end use.

Keywords: *4D Printing, Innovations, Defense, Technologies, Military Doctors*.

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I. INTRODUCTION

Technological innovation is rapidly transforming defense capabilities, with 4D printing emerging as a disruptive force. By combining additive manufacturing with smart materials, 4D printing enables structures that adapt, self-heal, and reconfigure in response to external stimuli. These capabilities open new possibilities for military applications, from adaptive equipment and self-repairing systems to advanced medical solutions. This paper examines the potential of 4D printing in security and defense, highlighting its opportunities and strategic implications.

II. FUTURE TRENDS IN TECHNOLOGY ADOPTION

We live in a time where words such as innovation, artificial intelligent, smart technology, machine learning, virtual and augmented reality actually describe the incredible scientific progress, that is shaping the world into one whole new reality.

Today we need to state the *4D printing technology* as the next revolutionary step which is transforming the human society. The global industry market is constantly adopting these new technologies through the process of learning, accepting and integrating them into existing systems and workflows. This tendency is confirmed by the expectations for future trends in technology adoption across industries by 2027, developed by the World Economy Forum (Figure 1):

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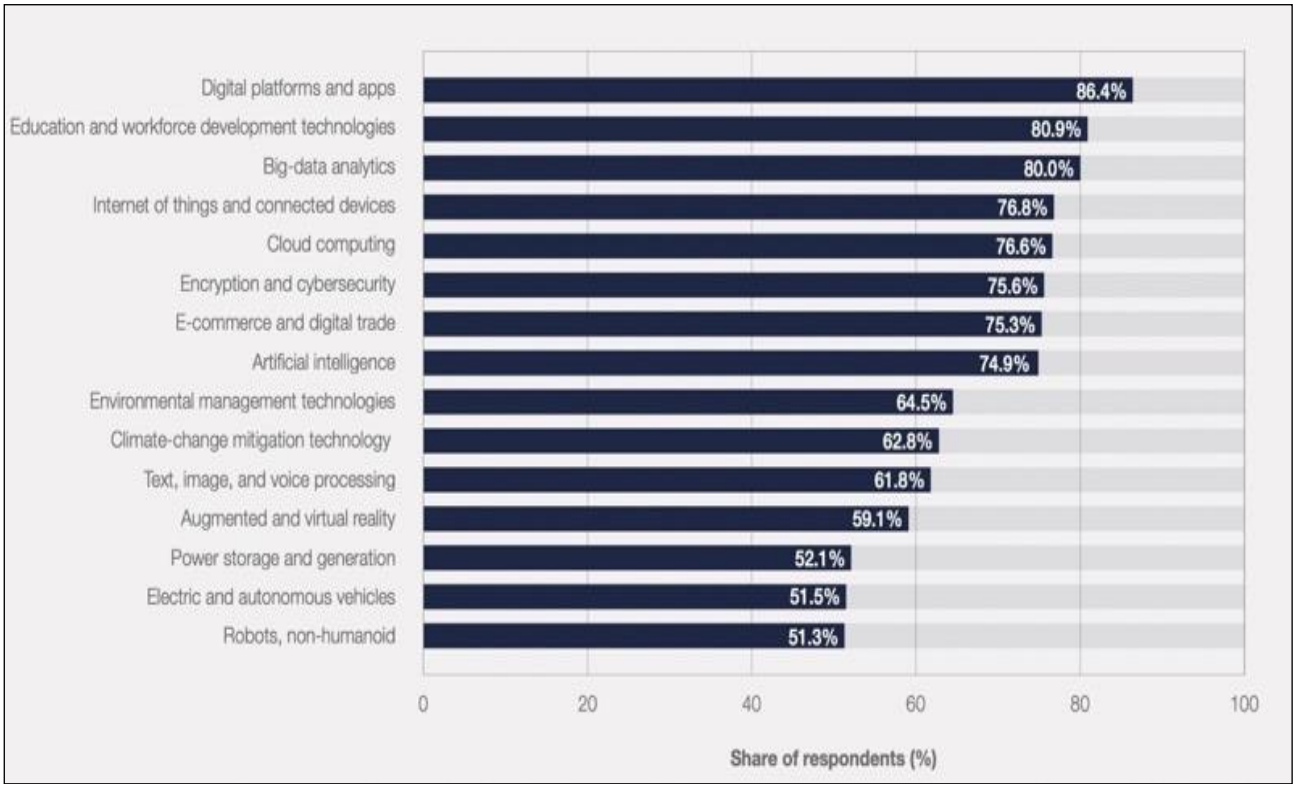

Fig 1 Technologies Ranked by the Share of Organizations Surveyed Who are Likely or Highly Likely to Adopt this Technology Over the Next 5 Years

Source: World Economic Forum, Future of Jobs Survey 2023., Fig. 1 is also reproduced in G. O. de Barros, "Forging AI Pathways: Portugal's Journey within the EU Digital Landscape," GEE Paper no. 177, Gabinete de Estratégia e Estudos da Economia e do Mar, Lisboa, Jul. 2023.

Figure 1 ranks technologies by the percentage of organizations that are *very likely* to implement them by 2027, presenting the main priorities and expected investments. The key figures are defined as *platforms & applications (86%), big data, cloud, AI (75%)* and *e-commerce/digital trade (75%).* This shows a trend towards pressure for digital skills, investment in IT/cybersecurity, and potential changes in business models (Future of Jobs Survey 2023).

The defense industry, being a symbol of dynamically investing, developing and adopting advanced technologies will depend on these primary change-driver in the geo-political relations and power. The increased application of unmanned systems, space-based assets, improved sensors, automation, and artificial intelligence with hypersonics is essential for maintaining strategic advantages and plays a critical role in modern military operations, resulting in enhanced military capabilities.

For this reason, the investments in the defense industry have shown a significant growth in the last few years and this trend is even expected to rise higher.

In 2024, the Stockholm International Peace Research Institute (SIPRI) estimated the global military expenditure to $2718 billion in 2024, meaning that spending has increased every year for a full decade, going up by 37 per cent between 2015 and 2024 (Liang et al. 4 2023). The United States stood out as the world’s foremost military spender with military expenditures totaling the staggering $916 billion (Defence Tech: Shaping the Future of Global Security, 2024).

In addition, SIPRI further found that the five largest arms exporting nations were the United States, France, Russia, China and Germany (taken together, they supplied approximately 75% of the world's arms exports during this period), (Trends in International Arms Transfers Report, 2023; Liang et al. 4 2023).

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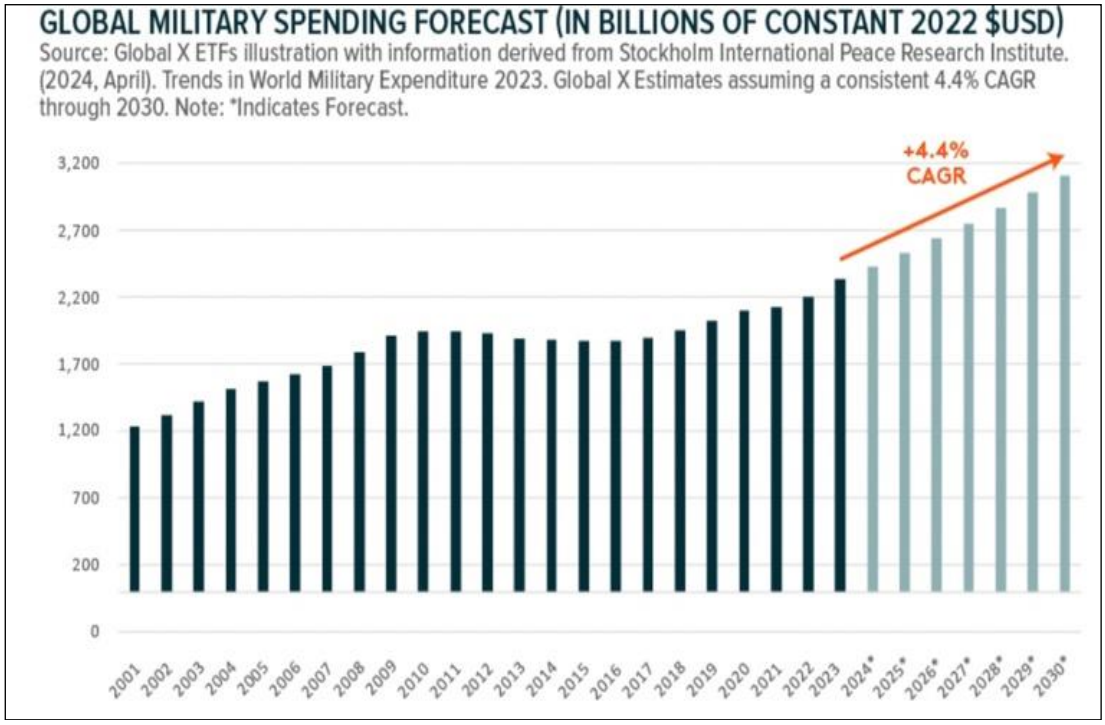

Fig 2 Global Military Spending Forecast
Source: Global X ETFs Illustration With Information Derived from Stockholm International Peace Research Institute (2024, April)

Between 2010 and 2020, the global military spending grew with an approximate compound annual growth rate (CAGR) of 1%. But since 2020, the military spending growth has accelerated by roughly 4x to 4.4% YoY CAGR. It is anticipated that growth may continue at these elevated levels through 2030, surpassing $3.3 trillion (InvestEngine Insights, 2024; Defence Tech: Shaping the Future of Global Security, 2024).

Forecasts indicate that by 2030, global military spending could increase by nearly 40%, reaching approximately $3.3 trillion; an increasing proportion of these funds is likely to be directed towards artificial intelligence, cybersecurity, and other modern defense technologies - including 4D printing, which offers opportunities for adaptive and self-healing materials for military platforms. This requires increased investment in R&D, a shift in procurement and supply priorities, a rethinking of personnel training and skills, and a stricter focus on regulations and ethical issues; in all cases, however, this is a forecast whose realization will depend on political, technological, and budgetary factors.

III. THE 4D PRINTING TECHNOLOGY

"Rather than construct a static material or one that simply changes its shape, we're proposing the development of adaptive, biomimetic composites that re-program their shape, properties or functionality on demand, based upon external stimuli."

Anna C. Balazs, Distinguished Professor at University of Pittsburgh (Source: IDST)

4D printing is an innovative, multidisciplinary technology with predictive significance, whose application is rapidly expanding in various fields. The combination of 3D printing and smart materials (SMMs) allows the creation of dynamic and adaptive products that respond to physical, chemical, or biological stimuli. These structures are categorized as 4D-printed (4DPed) products which change their shape and properties over time - the fourth dimension (Khalid, Arif & Ahmed 2022).

The way the stimulus and material interact with each other under the influence of time or manual regulation of the given parameters is called a mechanism of interaction (Figure 3). An example is the so called constrained-thermo-mechanism – where in order to reach the desired effect the material must be placed at high-temperature, then transformed at lower temperature until the desired shape is achieved. Later, one can easily go to the start position reheating the printed object (Momeni, Liu & Ni 2017).

Unlike 3D printing, 4D printing introduces temporal dynamics - it anticipates and controls changes in shape, properties, and functionality over time, enabling self-assembly, multitasking, and self-healing of products.

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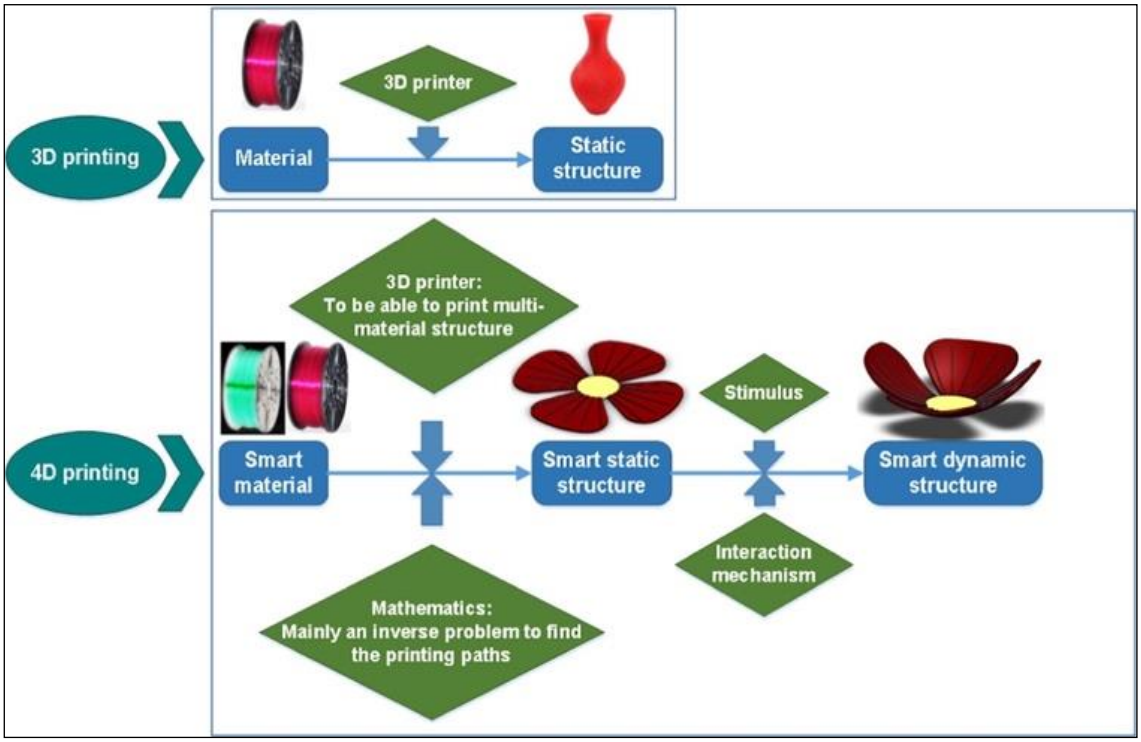

Fig 3 4D vs 3D Printing Process. A Mechanism of Interaction.
Source: Momeni, Liu & Ni 2017

The innovation of 4D printing hides behind the use of smart materials that are more flexible, precise and can transform according to the external stimulus. These materials can be classified (Hassan et al., 2025) as:

- Thermo-responsive
- Moisture-responsive (hydrogels)
- Photo-responsive
- Electro-responsive
- Magneto-responsive

The potential of 4D printing is reflected in a wide range of interdisciplinary applications. These include smart blinds that automatically adjust the level of light in rooms; modular furniture delivered in flat packs that can be assembled at home; and adaptive shoes, clothing, and sports equipment that respond to physical activity and changes in the environment, providing optimized comfort, performance, and aesthetics (Uppal, 2018).

In 2023, the aerospace and defense end use dominated the 4D printing market with a total share of 35.6% due to their needs for advanced and adaptive materials that enhance the operational effectiveness and lead to mission success in warfight.

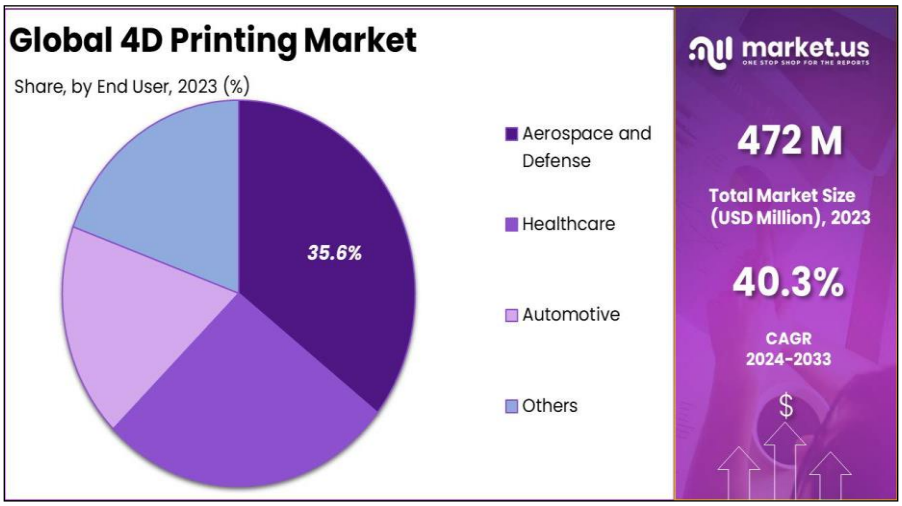

Fig 4 Global 4D Printing Market by Sector
Source: Market.us

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It is expected, that in the near future the Global 4D Printing Market is going to expand drastically from 472 Million USD to almost 14 Billion USD (Figure 5).

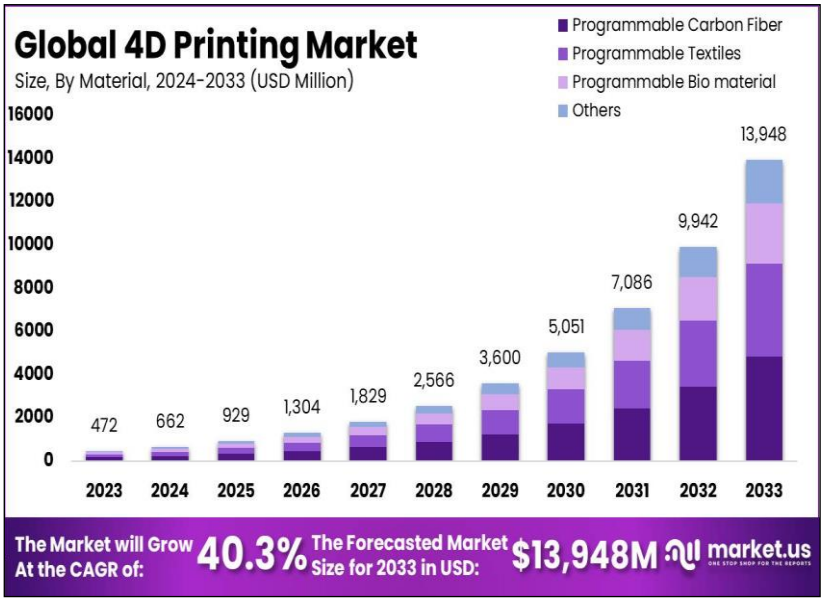

Fig 5 Global 4D Printing Market Forecast
Source: Market.us

IV. MILITARY APPLICATION OF THE 4D PRINTING TECHNOLOGY

In 2013, the U.S. Army Research Office awarded $855,000 to a team of three researchers from University of Pittsburgh's Swanson School of Engineering, Harvard School of Engineering and Applied Sciences and the University of Illinois to take advance 3D printing further, hopefully to develop 4D materials that can exhibit behavior changes over time (In Compliance, 2013). Ten years later, the global military 4D printing market is 74.6 $M and is going to be valued 651,5 $M in 2030, registering a CAGR of 43.5%.

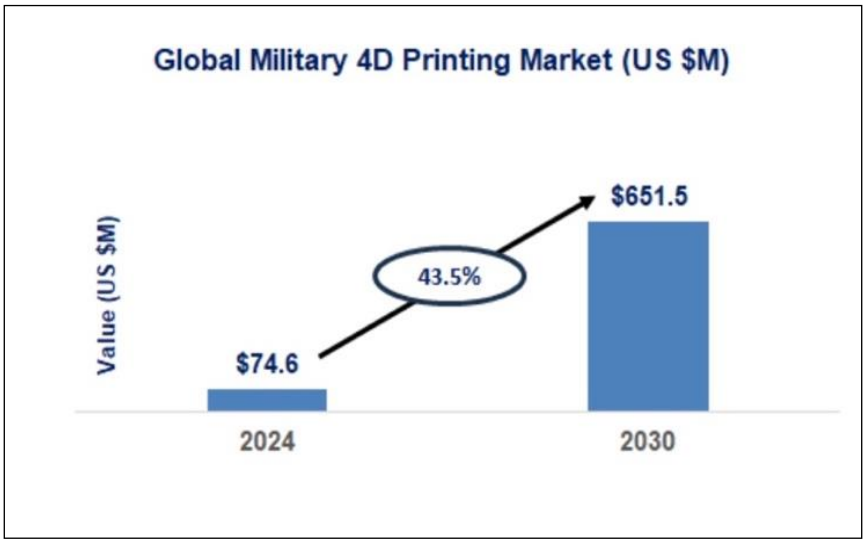

Fig 6 Global Military 4D Printing Market Forecast
Source: Lucintel

Based on application, the army segment is expected to account for the largest share in 2030, contributing to nearly half of the global military 4D printing market, and is projected to maintain its lead position during the forecast period. This is attributed to increased demand for advanced weapons to be present with the army across the globe (PR Newswire, 2022**)**; Lucintel, 2024).

The US Army is looking to self-assembling weapons and coating of defense vehicle which can adapt to the different environmental conditions. They are already using 3D printed spare parts in the field or on the ship that are lighter, cheaper, and more effective. 4D printing can boost this to another level: In the future, it is envisaged that programmable voxels will be used, which can be converted into various tools or spare parts as needed and then disassembled for reuse. Such technologies

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have the potential to revolutionize equipment maintenance in remote or extreme conditions. In this context, the global market for 4D printing is expected to grow significantly beyond its current level of 472 units (Campbel at al. 2014).

Furthermore, the 4D-printing shows great advantages regarding the environmental protection for it gives the opportunity to recycle and reuse self-healing pipes and hydrogels when damage occurs (Nkomo, 2018). This leads to the following concept for the application of 4D printing in the military sphere (Arya et al. 2021):

- Coatings for combat vehicles – 4D printed materials can be used to create protective layers that change according to environmental conditions (e.g., temperature, humidity, radiation, mechanical impact). This would make the vehicles more adaptable and resilient.
- Weapons – materials that can self-assemble enable the rapid "construction" of weapons or their parts in a combat situation.
- Advantages – this technology saves time (no need to wait for delivery or complex assembly) and space (soldiers can carry compact elements that can be turned into weapons or equipment when needed).

In fact, 4D printing introduces dynamism and adaptability to military equipment, which can be a decisive advantage in combat conditions.

How can this be in use for the soldiers themselves? Most of the opportunities that are to be presented refer to their uniforms. 4D printed uniforms can adjust insulation and cooling to the surrounding environment (humidity, temperature, pressure, moisture, etc.) and the biometrics of the individual, like altering permeability or stiffness (Li, 2023). They can alter its shape after encountering a sharp object and toxic gases. Moreover, such as clothing vehicle coats, the uniforms can change their camouflage pattern adjusting itself to the light and surroundings (Campbel at al. 2014). Finally, a 4D-printed uniform consumes less volume for easier shipping and arrangement.

Other proposed uses for 4D printing include building bridges that can self-heal if cracks form, and “adaptive pipes” that can expand or contract on their own (Uppal, 2018). Imagine a 3D-printed textile that could adapt to camouflage a soldier in different environments (or hide them by bending light!). Or a metal that adapts to environmental conditions to improve the performance of a tank or truck.

A. 4D Printing Technology in the NAVY

According to the Lucintel report, the Navy segment is expected to portray the largest CAGR of 47.3% from 2030 to 2040, due to the increased trend toward upgradation of naval services across the globe. This forecast is also confirmed by the Research & Markets Report 2024-2034, where the frigate segment is expected to be the largest segment and account for approximately 30.4% of the global naval vessels and surface combatants market from 2024 to 2034. The demand for frigates is anticipated to be mainly driven by the increased focus on developing new technologically advanced frigates with AESA radars and vertical launch systems to replace the aging fleet of legacy vessels (Naval Vessels and Surface Combatants Market Analysis, Competitive Landscape and Forecast Report 2024-2034).

4D printing opens up new possibilities for adaptive infrastructure that is resistant to natural disasters and extreme weather events, such as:

- Coastal structures – construction with programmable materials for greater erosion resistance, longer life, and lower maintenance costs (ports, dykes, flood protection systems).
- Bridges – ability to redistribute loads in real time and maintain structural integrity.
- Facades and barriers – adaptation to climatic conditions for protection against storms, floods, and hail.
- Shipbuilding – hulls – dynamic change of shape according to sea conditions to reduce drag and increase energy efficiency.
- Fouling control – surfaces that react to marine organisms and reduce the need for maintenance.
- Self-healing materials – ability to repair corrosion or mechanical damage, extending the service life of vessels.
- Adaptive components – ability to switch between different operating modes (e.g., high speed ↔ quiet and stealthy movement), providing efficiency and tactical flexibility.

Additionally, 4DP enables components to change shape to suit various operational scenarios. For instance, a vessel could seamlessly transition their operational status from high-speed navigation to a more stealthy, slow-silent mode. This adaptability not only enhances efficiency but also offers unprecedented versatility in maritime operations (Klimczak, 2024).

B. 4D Printing in the Field of Military Medicine

Military doctors play a significant role on and off the battlefield because of their dual job: they are both soldiers and doctors. They need to be ready to be in combat, but also to save soldiers’ lives.

So, as this is not an easy job, should it be even more complicated by applying the new technologies to it? The answer is yet to be given but there is no doubt that 4D-printing can be of great benefit for its’ development in medicine.

The first two reasons for evacuation of the soldiers from the battlefield are traumas and burns and the 4D-printing gives the opportunity to overcome their consequences. Considering the fractures, 4D-printed prosthetics can be used to initiate the proliferation of bone tissue cells and adjust to the bone defect according to the needed stimulus (Bajpai et al. 2020).

In addition, 4D-printed biomaterials can be used in skin regenerating using a mechanism like bone tissue regeneration. The defect is removed by a surgeon, who places new biocompatible printed skin layer instead. As a porous material it initiates the proliferation of the cells through the pores, which makes the new structure more stable.

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In patients-body, blood factors such as glucose levels, enzymes, proteins, and nucleic acids play a significant role in controlling the normal mechanism and normal functioning of organs (Lui et al. 2019) Therefore, recognizing these important parameters and biomaterials that respond to biological stimuli is essential for the better performance of 4D printing technology to address the manufacture of biocompatible parts (Akrami et al. 2022).

The combination of 3D printing and smart materials opens up new horizons for medicine, as it allows the development of products that are not only individually tailored to the patient, but can also respond dynamically to changing conditions. Adding the time dimension through 4D printing gives structures the ability to transform under the influence of stimuli such as temperature, humidity, or electric fields. This leads to a wide range of applications - from personalized implants and adaptive tissue scaffolds for regenerative medicine to drug delivery systems that release active substances according to the body's physiological signals (Ibanga, 2023). The main advantages of the technology include higher treatment precision, minimally invasive procedures, improved patient comfort, and reduced side effects through targeted dosing. However, a number of challenges remain, including the need for biocompatible and durable materials, ensuring reliability and stability, and overcoming regulatory and manufacturing barriers (Hallem & Javaid 2019; Iyengar et al., 2022; Biswas et al., 2021).

Another application of the 4D-printing in biomedical-/battlefield are the stents – for coronary arteries and tracheal/bronchial stents, when they are placed over the trachea/bronchus and help them to shrink and expand, adjusting to the airflow (Bajpai et al. 2020).

Last but not least, 4D-printing can be used as drug delivery system, providing capability different medications and drugs to be delivered to the human body.

V. CONCLUSION

The 4D-printing brings new capabilities in the Defense sector and the military market will continue to expand, driven by the incredible scientific progress in this sphere.

This will require more sophisticated approach and great number of researches in order to define all possible application of this new technology and develop new smart materials to be applied.

In order to be in line with this process, investments in Research and Development not only at cooperative level, but also at military educational level shall be planned and conducted, since the private sectors usually follow the indications from the Defense and it is more appropriate to initiate such development in strictly military environment, which to be further developed in cooperation with the private sectors.

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