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The Future Interface of Neurotechnologies, Security and Drone Warfare

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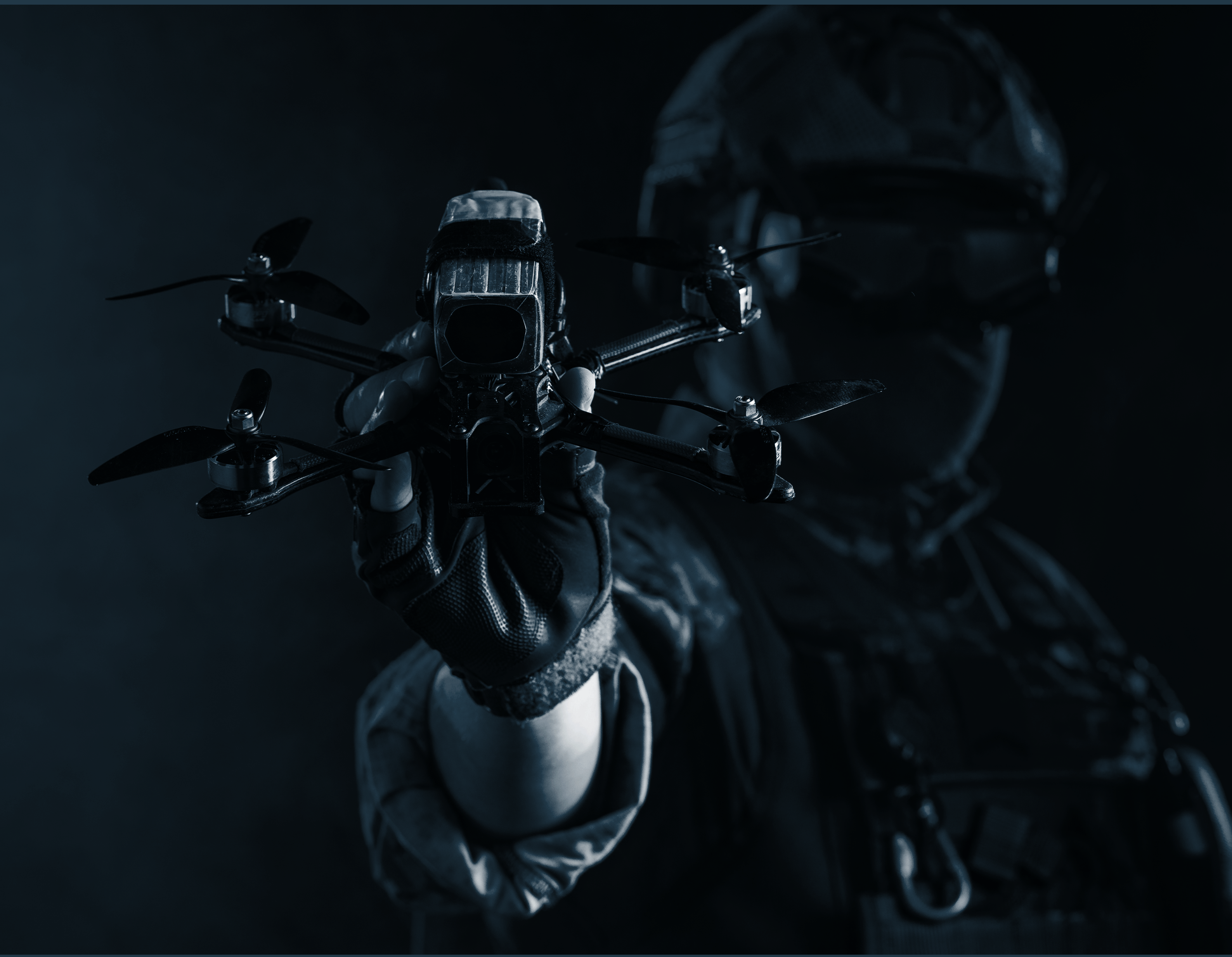

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Key points

- Driven by the integration of multiple fields and technologies, research in neuroscience and brain-machine interfaces is advancing at an accelerated pace.
- As our capacity to bidirectionally communicate with the brain increases, so do the associated security risks.
- In this context, the intersection of neurotechnologies and drone warfare is of particular interest.
- Various security risks linked to neurotechnologies and their intersection with drone warfare could potentially arise, but brain-machine interfaces will be essential in the development of land-based military drones.

Introduction

Since the full-scale Russian invasion of Ukraine in February 2022, we have witnessed a rapid acceleration of the use of drones in air, naval and land operations, with both belligerents innovating at speed to achieve an edge in reconnaissance and kinetic missions. Evolutions have been rapid in the air and sea domains, with prototypes being iterated every few months and new technologies being continuously field tested. Some aerial drones already include forms of autonomy, with evidence appearing on social media over the summer of 2025 of drones using fully automated terminal guidance to bypass electronic warfare countermeasures.[1] These concrete developments have completely outpaced the political discourse on the use of drones and autonomous weapons in warfare, which had been under way for years with no signs of converging on an internationally accepted legal framework to govern their use.

Simultaneously, neuroscience and neurotechnologies have entered a phase of very rapid development, and brain-machine interfaces and brain stimulation technologies, … are becoming increasingly common.

One of the defining features of this emerging landscape is that of the "cyberpunk" drone operator. Both social and traditional media abound with stories of the people who pilot drones in Ukraine, and there is a particular interest in first-person view (FPV) drone operators, who use a live video feed from the drone's camera displayed on goggles or a monitor to pilot the drone from its perspective. These operators are sometimes pictured lying on loungers in underground bunkers, while the drones they pilot are often one-way attack suicide drones based on racing competition frames, and are used to eliminate enemy vehicles and combatants, and sometimes single infantrymen. Recently these drones have become so ubiquitous as to completely saturate the line of contact and dozens of kilometres behind that line, and are often forward deployed prior to being activated. The drone operators often assume an aesthetic reminiscent of characters depicted in the cyberpunk genre, where themes such as human augmentation by technological means and human-machine fusion are recurrent. Indeed, the various contraptions and wearables, the supine position, and the loss of immediate environmental awareness – acting instead in what is effectively a virtual environment – evoke the fictional persona of so-called "netrunners", who use brain-machine interfaces to live almost entirely online and connect to the internet in the most direct way.

Simultaneously, neuroscience and neurotechnologies have entered a phase of very rapid development, and brain-machine interfaces and brain stimulation technologies, which already have a multi-decades history of development,[2] are becoming increasingly common. It thus seems natural to speculate on future developments along the path where these technologies meet, and this Strategic Security Analysis is thus a forward-looking and speculative piece on the future interface of neurotechnologies, security, and drone warfare.

An accelerated merger of interrelated fields

Neuroscience – the scientific study of the central and peripheral nervous systems – dates back to Greek antiquity, but only emerged as a modern science in the late 19th century, became a separate field in its own right in the 1970s,[3] and really exploded at the turn of the present century.[4] Broadly speaking, its research programme is to understand and, if necessary, heal the brain. Over the last few years, neuroscience has been supplemented by adjacent fields with partially overlapping research programmes, i.e. artificial intelligence (AI) research, which, roughly speaking, aims at mimicking the brain in software; neuromorphic computing research, which aims at redesigning computer processors with new brain-inspired architectures; and brain-computer interface research, which aims at developing augmentation prostheses for the human brain. Far from being separate or parallel efforts, these fields are reinforcing and drawing inspiration from one another. They could thus be considered parts of a single effort to understand, build and merge with general-purpose intelligence to produce what is sometimes called artificial general intelligence. As a result, researchers in these fields are increasingly talking about a new field at the frontier of these efforts that is called NeuroAI.[5]

Far from being separate or parallel efforts, these fields are reinforcing and drawing inspiration from one another.

The development of brain-machine interfaces is of particular interest here, because this is the (neuro)technology that is the most natural continuation of the cultural and operational trends in drone warfare described above. Indeed, the idea that brain-machine interfaces could one day be used to pilot drones as the most direct connection between the operator and the machine is not as far-fetched as it seems.[6] The next section describes in non-technical terms the current state of the art in these neurotechnologies, and what lies in the near- to mid-future.

What are neurotechnologies?

“Neurotechnologies” is an umbrella term for all technologies that relate directly to the brain or peripheral nervous system. As such, it is not a very specific term and is sometimes used for relatively simple wearables, such as electroencephalogram headbands that can be purchased online for a few hundred euros (e.g. see the products of companies such as EMOTIV or IDUN Technologies). These simple devices permit brain activity in the form of electrical signals to be recorded non-invasively through the skull, scalp and hair. However, these recordings are of limited resolution and quality, and there is only so much that can realistically be achieved with such data. The brain is an incredibly complex organ at the microscopic scale, and the richness of its dynamics and capacities resides entirely in the individual activity of its billions of neurons and non-neuronal cells at that scale. By design, these devices can only capture a fraction of that activity, mostly from neurons, and offer at best a mesoscopic resolution, effectively averaging out the activity of millions to billions of cells.

Currently, invasive neurotechnologies are still needed to get better quality data from and access to the brain. Such devices already have a long history. For instance, deep-brain stimulation – where a stimulator and electrodes are surgically implanted deep into the brain to treat Parkinson’s disease – received approval from the US Food and Drug Administration in 1997, almost 30 years ago, following decades of experimental development after the Second World War.[7] However, recently there has been a rapid technological acceleration in this field, catalysed by a combination of fundamental and technological advances in basic biology and neurobiology and various advances in microelectronics, advanced materials, battery technologies, and AI. While historically these technologies focused entirely on electrical stimulation and recordings, there is now a vast array of other methods to interface with the brain using magnetism, optics and ultrasound, to name a few.[8] Rather than focusing on technical and scientific details, the current state of the art is described below in terms of capabilities.

The current state of the art

As mentioned above, surgically implanting stimulating electrodes into the brain to stimulate specific neurons has been an approved and relatively common procedure for almost three decades. Electrodes can also be used to record the electrical activity of neurons, and it is thus possible to communicate with the brain directly and bidirectionally, i.e. read information from the brain, but also write information to the brain (more on that below). Other technologies than electrodes have since been developed, but all aim to reach this gold standard of bidirectional communication. Among other promising technologies, optical methods combined with genetic manipulations (optogenetics)[9] and focused ultrasounds[10] appear to be particularly promising, because they could become more selective and less invasive than electrodes, which need to be physically embedded inside the brain, which is a soft tissue with the approximate consistency of jam, which is an important biomechanical limitation that is possibly under-appreciated by non-experts.

> Making neurons more excitable or active does not translate into writing information to the brain.

Here it is important to clarify that brain-stimulation technologies have existed for decades. Mostly, a brain area is stimulated by some technical means, which increases the excitability and activity of the neurons in that area. However, it is important to understand that the areas that are stimulated tend to be quite large, encompassing millions or even billions of cells. This is obviously very unspecific. Individual neuron stimulation is possible in transgenic animals using a method called optogenetics, but as yet is impossible to do so in the central nervous system of human subjects.[11] Also, making neurons more excitable or active does not translate into writing information to the brain, because we do not know what “code” neurons employ to communicate with one another. It is not even clear that all neurons in a brain use one single code, or that all brains use the same code. This is a fundamental limitation in our ability to write information to the brain. There is no reason to think that this problem is about to be imminently resolved after more than a century of modern neuroscience and decades of research in computational neuroscience. Finally, neurons constitute only 20% of the cells in the cortex,[12] and we have very little understanding of the role that the other cells play in storing or processing information, even though evidence is currently rapidly accumulating that they do.[13] The effect of various stimulation technologies on these non-neuronal cells is also critically understudied.

Likely developments in the near- to mid-future

Writing information to the brain in any meaningful way seems like a distant prospect. It is, of course, possible that we make significant and sudden advances over the next few years, but it is very difficult to predict when or if that will happen. It is probably worth mentioning that claims about modifying specific memories in rodents were published more than ten years ago;[14] however, it is difficult to see how these results would translate to humans in the short term and reach the rather granular level of detail we associate with our own memories.

As mentioned earlier, brain stimulation is relatively well established, but rather unspecific. However, it is already being extensively used in clinical scenarios such as post-stroke rehabilitation[15] or for treating mood disorders.

These and similar applications currently constitute the low-hanging fruits for these technologies used in this mode of communication (i.e. from a device to the brain). It is likely that in the next two decades this (clinical) domain will see significant developments before we see any specific encoding of detailed memories in humans.

On the other hand, recording activity from the brain and using this data to control devices is much easier and better established, and large-scale datasets in combination with machine learning methods continuously expand the realm of possibilities in this regard.[16] This is where the more immediate future interface of neurotechnologies, security and drone warfare resides.

Neurotechnologies in drone warfare

Recording activity from the brain and using this data to control devices is much easier and better established, and large-scale datasets in combination with machine learning methods continuously expand the realm of possibilities.

So where do the risks of neurotechnologies and their interface with drone warfare lie, and where will the fusion of more advanced devices and drone warfare lead us? In some ways, one can argue that this fusion is already in effect and expands on the concept of human-machine teaming.[17] If we return to the subject of FPV drone operators (see “Introduction”, above), their essential piece of kit besides the drone itself and its controls is the FPV goggles used to display the drone’s camera feed directly to the operator. Some startups already include such products under the broad umbrella of neurotechnologies, even though I would argue that this is merely enhanced virtual reality and not strictly speaking a neurotechnology. But where do we go from here?

The battlefields of Ukraine have seen the deployment of drones in remarkable numbers and variety, but mostly in the air and sea domains, and the interface described above is arguably only significantly present in the air domain, and not for all types of drones. In fact, it is difficult to imagine that neurotechnologies would play a significant role in the air and sea domains in the future.

In the sea domain, this can be explained by the size constraints of seaworthy vehicles and the comparatively large size of potential targets. Naval drones are also likely to require significant power generation, and there are thus no real constraints on deploying AI in naval drones. Additionally, naval drones operate in a relatively simple and largely empty three-dimensional environment. Arguably, even a limited AI should be able to function effectively in such an environment. Adding neurotechnologies to this would only lead to additional expense and more failure points, but for no obvious added value.

Similar arguments can be made for aerial drones, in particular the fact that they operate in a mostly empty three-dimensional environment, with the ground as a natural boundary. Aerial drones will probably evolve along three parallel paths. Firstly, large, costly drones will be developed to carry out complex missions for which speed is not a primary concern. These are likely to remain piloted by human operators using traditional controls, possibly with some level of embedded automation. Secondly, small attack drones are likely to become mostly or entirely controlled by low power, possibly distributed, edge AI and deployed in swarms. Some reports from Ukraine already suggest the presence of autonomy in small attack drones for terminal guidance and to defeat electronic warfare countermeasures. Another interesting recent development is the increasing use of drones remotely controlled by fibre-optic cables as a way of defeating electronic warfare countermeasures during terminal guidance,[18] despite the obvious disadvantages of unrolling very long cables on the battlefield. It is thus not clear that neurotechnologies would play a role there either. In fact, it is probable that the current model for FPV drone operators described earlier represents the peak for human in-the-loop involvement in the control of individual drones, and that the future will see more on-the-loop human operators or maybe even full autonomy. As a counterpoint to this, the possible third path for aerial drone development is the concept of the loyal wingman that is discussed a great deal in the context of future-generation jet fighters, where one of the human crew members would be tasked with flying supporting aerial drones (the "loyal wingmen") in collaboration with an AI.[19] This concept is actively being investigated (in Australia, for instance, using Boeing MQ-28 Ghost Bat drones),[20] and the use of brain-computer interfaces for this role is being explored.

Another argument for the progressive abandonment of any direct human involvement in aerial drone warfare is the need for speed – i.e. speed for drones in their final approach to a target and speed in making decisions – and accuracy. Arguably, the future use of small drones in aerial warfare will involve the deployment of large swarms of fully or partially automated drones. China appears to have made significant advances in this area, as demonstrated by regular large and impressive displays of small aerial drones during civilian visual performances.[21] This really leaves only the cyber and land domains as sites for the possible direct involvement of neurotechnologies. These domains are discussed in the following sections.

As devices that both record and stimulate the brain become more widespread, these risks will increase.

Security risks associated with neurotechnologies in the cyber domain

Probably the main security risk currently associated with neurotechnologies resides in their online nature (even for simple wearables), paralleling similar security risks that have been identified with regard to smart watches and other such devices. In other words, if these neurotechnologies are hacked, it is possible to identify the location of individuals wearing them and have access to the biological data they collect. Currently, the intelligence value of such biological data is unclear, but as capabilities increase, it is conceivable that such data could be used to infer the mental state of individuals fitted with brain-machine interfaces, and their decision-making abilities could be altered when combined, for instance, with appropriate alterations of their social media feeds. In fact, experiments of this type are already under way in some countries.[22]

As devices that both record and stimulate the brain become more widespread, these risks will increase. For technical and surgical reasons, most of these devices will probably communicate using wireless protocols and will thus be vulnerable to hacking. This will open up the possibility of manipulating individuals fitted with brain-machine interfaces more directly, without the need for additional modalities, and probably with increased granularity and reliability. Additionally, it is also conceivable that brain stimulators could be hijacked to injure their recipients. For instance, it is possible to overstimulate brain tissue with electrical currents, which can lead to the pathological overactivity of the stimulated neurons and in extreme cases to their death, leading to secondary immune responses. Obviously, any device that receives ethical approval will only operate within well-constrained parameters, but it is likely that some of these limits will be soft coded in the operating software and could thus be reprogrammed. Accidents of this type have already happened with radiotherapy equipment,[23] and this could very obviously be weaponised.

Finally, in the decades to come, we will most likely develop the capacity to directly manipulate memories, as has already been demonstrated in animals, and maybe even to implant false memories.[24] These possibilities will be limitless as we develop the capacity to manipulate the reality perceived by wearers of brain-machine interfaces. However, for the reasons given above, while this is theoretically possible and will almost certainly happen at some point in the future as we eventually crack the neural code, currently this remains only a very distant possibility.

Here it is important firstly to understand that while the timeline for these developments is difficult to establish with certainty, all the scenarios described above already exist, at least at the proof-of-concept stage in some laboratories around the world. Some of these advances are already decades in the making. Secondly, immense financial and human resources are currently being poured into this field because of the needs that these devices address in terms of treating illnesses, but also – and probably mostly – because of the strong desire in some communities with access to financing to augment healthy humans apart from ways that result from direct clinical necessities.[25] In the future, the clear benefits that these devices provide for brain health will continue to drive these developments, which will then inevitably be repurposed for human augmentation. Finally, it would be easy to believe that the risks involved in such procedures are overblown, given the high bar to accessing a surgically implanted device, and indeed, these devices will probably never be as widespread as mobile phones or smart watches. But the risks will remain and could have significant implications if an organisation's senior personnel or leadership were treated for medical conditions by using these implants, who could be selectively and individually targeted for nefarious purposes.

Neurotechnologies for land drones: the future of telepresence

Let us now return our attention to the interface between neurotechnologies and drone warfare, specifically in the land domain. Unlike the air and sea domains, where it has been argued that in the future direct human involvement is likely to become increasingly limited, the land domain presents some specific challenges that could be resolved by a fusion of neurotechnologies and robotic frames. Humanoid robotic frames seem particularly promising because of the possibility they offer to potentially perform all the missions that a human operator currently can or needs to perform. Specifically, having a brain-machine interface-controlled robotic land drone solves four problems: it provides a human in the loop for decision-making in a complex environment; it prevents issues with the so-called "Sim2Real problem" (see below); it provides an energy-efficient remote brain, leaving onboard power generation for movement and action; and, finally, it provides the level of immersion that might be necessary to safely and remotely conduct dangerous infantry missions. We will now explore these points.

Humanoid robotic frames seem particularly promising because of the possibility they offer to potentially perform all the missions that a human operator currently can or needs to perform.

The first point is obvious. Having a remote land drone controlled by a human operator offers the possibility to retain a human in the kill chain to take decisions. It might even improve the quality of these decisions, because the physical distance of the operator from the drone would arguably allow them to keep a cooler head, even in a complex and stressful situation. This is especially true because an infantry drone could operate in a highly heterogenous and complex three-dimensional environment like a partially ruined urban setting containing a mix of combatants and civilians. This is a highly challenging operational environment where the need for speed is likely less than in the air and sea domains, but where it is more difficult to make the right choices. Arguably, ethical arguments to retain a human in the loop are valid in all domains, but because of the reasons highlighted above, they are likely to carry more weight in the land domain than in the air and sea domains.

The second point is the so-called Sim2Real problem, which is an important limitation in the deployment of AI in the air domain. It is no secret that current AI technology requires enormous amounts of training data. For instance, the training of modern large-language models (LLMs) currently requires a very significant amount of written text in an easily accessible digital format. It seems therefore that progress in improving LLMs might have plateaued, in part because of the lack of new training data. Studies have shown that generating further synthetic texts to use in training leads to a progressively worsening of the LLM's performance.[26] Training an AI to deal with complex battlefield situations would also require a vast trove of real-world data that might not exist and might be prohibitively expensive to acquire. Warfare is also a realm of continuous adaptation and evolution in which the enemy's actions and decisions play a vital role. One alternative that has therefore been developed to train aerial drones is to train them in a flight simulator, which leads us to the so-called Sim2Real problem. The obvious advantage here is that it allows the AI to be trained completely *in silico* (i.e. in a simulated environment), which is faster and cheaper than training it by running physical experiments or having to acquire enough real-world training data. The term Sim2Real refers to the difficulty of transferring the learning acquired in a simulated environment to the real world.[27] No matter how accurate the simulation is, it can only ever be an imperfect approximation of the real physical world. As a result, it is not uncommon for an AI's real-world performance to be potentially highly limited by being trained using an imperfect simulator. In other words, the AI can perform exceptionally well in simulations that exploit gaps between the simulation and reality, but this subsequently leads to very poor performance or catastrophic mishaps when it is deployed in the real world. The reason for this is currently unclear, and it is also not clear how to resolve this problem algorithmically.[28] This has proved to be a problem in the air domain, and would arguably be even more problematic in the more complex land domain, without even considering the need to deal with the presence of civilians in a militarily contested environment. A use of a remotely controlled drone resolves this issue by having an already trained pilot with an intuitive understanding of the environment and its physics, and could therefore be seen as a form of human-machine teaming.[29] Again, this issue is present in all domains and is a roadblock to the training of AIs to control advanced avionics. There are no reasons to think it would not also be an issue in the land domain.

> Any future drone will have to balance onboard intelligence with range and autonomy.

Thirdly, advanced inference can use large amounts of energy,[30] so any future drone will have to balance onboard intelligence with range and autonomy. This is less likely to be an issue for naval drones, which must be large and heavy enough to be seaworthy, and can thus include significant built-in power generation capability, or for large aerial drones. But any advanced robotic frame for land warfare would have to optimally balance its energy use between mobility in a difficult-to-navigate, complex physical environment and inference. Even for humans or non-human primates, this is not a trivial issue. For instance, the human brain is responsible for about 20% of the overall body's energy use in adults, a much larger share than its weight would presuppose (about 2% of the total body's weight).[31] Similarly, it has been argued that large body sizes and large brains impose significant constraints on the behaviour of non-human primates,[32] and there is abundant evidence that the operation of neural networks is heavily constrained by their energy consumption.[33] For instance, because of their low-calory diet, great apes must spend a large part of their waking hours feeding. Evolution has only partially resolved the issue by making our brains remarkably power efficient (in absolute terms, but not relative to our overall body's energy budget). If we assume that the sensors necessary for inference would be present on a robotic land drone, it would then make sense to outsource inference to a remote brain, and no such brain will be cheaper to operate than a human brain. This again argues for the use of a remote operator.

To summarise the argument so far, a human remote operator will be better able to deal with complex situations that might be present in the land domain, and will also be better able to deal with the more complex physical environment in that domain. Finally, a human remote operator will probably represent the most energy-efficient solution for high-quality inference while allowing a drone to have a useful range and level of autonomy. In short, intelligence is energetically expensive.

> A human remote operator will probably represent the most energy-efficient solution for high-quality inference while allowing a drone to have a useful range and level of autonomy.

Let us now turn to the last point, namely that neurotechnologies will provide the necessary level of immersion to safely conduct the most dangerous infantry missions. As mentioned in the introduction to this study, in Ukraine we are already witnessing the introduction of cheap and simple neuro-technologies for the FPV remote control of one-way attack drones, with operations and an overall aesthetic reminiscent of the cyberpunk genre, where human augmentations abound. For the reasons highlighted above, as neurotechnologies become more common in the future, and probably more invasive, with increased bidirectional communication capabilities, this trend is likely to continue. This, taken together with the increased availability of humanoid robotic frames, will most likely lead to the rise of remotely controlled humanoid robotic operators. These will be best able to make the complex decisions necessary in a complex social and physical environment at a reduced cost while simultaneously protecting the lives of the operators. Neurotechnologies will therefore be able to provide an unprecedented level of sensory fusion and immersion to the operator that will enable them to feel fully *in situ*.

Conclusion

The war in Ukraine has demonstrated that infantry operations remain necessary, but have become difficult and costly because of the battlefield's saturation with sensors. This is likely to drive the use of ever more remote capabilities, but aerial drones cannot be the solution to every problem, especially in dense urban or forested environments (and possibly also in dense and complex underwater environments). Because of this, we will likely see the development of remotely controlled robotic frames for infantry operations. Interestingly, this is a common trope in Japanese pop culture, where stories about robots and piloted suits have been common since the 1950s (known as the mecha genre), and in which ideas of augmented humans fusing with machines have been explored at length. This was in fact the inspiration for the original title of this piece.

It is likely that the desire to augment humans will represent an unstoppable force for the development of these technologies and their broad adoption, including in the military domain.

Far from constituting science fiction, it can be argued that the first signs of such a fusion are already visible today, and that the advances that have been developed in neuroscience laboratories around the world over the last few decades have already laid down the scientific and technological foundations for this trend to continue. In the future, as the interface between neurotechnologies, security, and drones will inevitably expand, this process will pose important ethical and philosophical questions about what it is to be human and to experience the world as a human, and will give rise to new security risks, some of which have been speculated upon above. These risks will necessitate careful regulatory efforts at the international level, probably focusing more on capabilities than on specific technologies, because the technological landscape around neurotechnologies remains extremely fluid. However, it is likely that the desire to augment humans will represent an unstoppable force for the development of these technologies and their broad adoption, including in the military domain.

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