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Original Scientific Article

Smart Dust Technology: Convergence of Virtual and Physical

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Abstract—**The advent of advanced technologies such as AI, IoT, and SmartDust is poised to transform not only human life but also human nature itself. SmartDust, in particular, offers unprecedented possibilities for integrating tiny, intelligent devices within human biology, leading to the convergence of digital and biological systems. This integration, often discussed in the context of transhumanism, raises ethical and existential questions as it blurs the boundaries between the physical and digital worlds. While technological convergence promises to enhance intellectual, physical, and mental capacities, it also poses challenges related to control, identity, and privacy. The potential emergence of bio-cyber entities—humans augmented by machine intelligence—marks a profound shift in the human condition, which could lead to irreversible changes in human evolution and societal structures. As we enter this era, it is critical to explore balanced approaches that protect the essence of humanity, ensuring that technology serves as a tool for enhancement rather than a force for subjugation**.

Keywords - SmartDust, Internet of Things, Internet of Bodies, transhumanism.

I. INTRODUCTION

SmartDust [1,2], is a vision of a networked future where intelligent networks composed of millions of miniature sensors continuously sense, smell, see, and hear what is happening in their environment, communicate with each other, and exchange information [3]. SmartDust networks are, in fact, the senses of a virtual cyber entity called the Internet of Things (IoT) [4], and no aspect of SmartDust technology can be viewed outside the IoT [5]. The term SmartDust refers to extremely small computer particles, RFID chips, or other technologies of very small dimensions [6]. Sub-millimeter-sized SmartDust networks detect and transmit data to larger computer systems [7], which then store, process, and use the data. SmartDust devices organized into "clouds of SmartDust sensors" [8] are small enough to be placed anywhere and once pre-programmed, they can operate for years without human intervention. A single collection of SmartDust devices [9] can theoretically contain billions of devices connected to the internet. Although this technology seems utopian, it has already been designed, created, and tested. The sustainable concept first appeared in the early 2000s, and the first miniature smart device was implanted in a mammal in the 2010s [10]. Since then, engineers have reduced the size of IoT devices to one millimeter and continue with miniaturization. Although there are already over 10 billion active IoT devices worldwide, experts predict that by 2030, there will be more than 25 billion [11]. This is still not the full concept of SmartDust scattered across human habitats, but the concept is ready. Scientists believe that full implementation is only a few decades away, while more cautious predictions place this achievement toward the end of this century. To be cost-effective, such devices must be cheap, costing no more than a fraction of a cent. These

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devices run on micro-batteries that power them for ten years and can communicate with each other using low-power radio waves or optical waves. The most common self-organization algorithms replicate existing biosystems, particularly swarm algorithms that mimic the behavior of bee or ant swarms. Communication with the public network goes through special gateways. On average, up to 10 miniature sensors are connected to one device. All devices are divided into groups with different functionalities and can attract each other depending on the task and specific situation. SmartDust devices use the embedded TinyOS operating system, which is the prevalent operating system used on devices connected to the IoT. More details about the operating system can be found on the official website, www.tinyos.com.

The concept of SmartDust was introduced into scientific theory in 2001 by Kristofer S. J. Pister, from the University of California, Berkeley [12], using a literary idea from Stanislaw Lem's novel "The Invincible" from 1964. A paper from 2005 [13] examines different methods for reducing smart devices from more than a millimeter to a micrometer. Some believe that the concept behind SmartDust is a project called Smart Matter [14], with technological foundations in the field of nanoradios [15]. Research on networks consisting of large numbers of tiny devices for military purposes began in the late 20th century under DARPA. Today, the largest companies involved in the development and research of this technology are Dust Networks and Cisco.

II. Current Systemic Limitations of SmartDust Technology

When we talk about SmartDust technology today, we still refer to it as a concept or idea of advanced technology, much like how we discuss Artificial General Intelligence (AGI). The concept exists, there are sustainable rudimentary results, and based on everything known, it is certain that this is a promising technology of the future. At present, there is very little public information about SmartDust technology.

Once fully developed, the SmartDust concept will represent a device whose dimensions do not exceed the threshold of visibility—about 0.05 mm [6]. The weight must be such that the "particle" can float in the air. SmartDust should include: the ability to perform complex operations and labor-intensive computations, wireless communication, autonomous movement in space without displacement due to air or water currents, self-organization, and minimal size and weight. Based on these requirements, scientists have identified several key limitations currently preventing the full implementation of SmartDust technology [16,17].

The primary unresolved issue with SmartDust technology is powering the devices. So far, no satisfactory solution has been found. Even if the required amount of energy could be implemented easily, strategies for careful energy use and balancing resources among the tasks and the number of devices in a SmartDust cloud—potentially containing millions of devices—are still relatively unknown [18]. Some progress has been made, such as energy supply based on thick-walled batteries and solar cell components. Another potential energy solution could be pulse-based solid-state supercapacitors (nano-ionic supercapacitors) [15]. Advances in nanoradio technology may provide the technical foundation for powering SmartDust devices [19].

Communication remains an unsolved issue due to limited energy resources. Radio waves and optical communications are the best options, each with pros and cons. Radio waves require shortwave transmission, which is energy-intensive due to small antennas, while optical communications need precise alignment for line-of-sight transmission. In control theory, actuators, such as vibrating motors or changes to the device's shell, position SmartDust devices, but long-distance movement is still underdeveloped. Currently, SmartDust devices are limited to identifying and transmitting data without computing power due to their small size. Sensors, like actuators, depend on the task at hand.

While current SmartDust devices don't fully meet the concept, progress has been made in specific areas. For example, SmartMesh, an IoT protocol based on blockchain [20], integrates blockchain light nodes and second-layer networks like Raiden and Lightning for digital payments without the internet. SmartMesh

forms decentralized Mesh networks that self-repair and provide higher speeds than standard internet connections, advancing IoT and IoE [20]. It's possible that SmartDust will soon coexist with regular dust. The first steps have been made, and it's quite possible that in our lifetime, SmartDust will float alongside ordinary dust.

III. Transhumanism and the Convergence of SmartDust Technology with the Human Entity

The goal and purpose of every new technology is always to make human life easier. With the development of computer technologies, especially AI, KM, and IoT, for the first time, we are witnessing coherent research into the potential of technology to not only improve human life but also enhance physical and mental abilities. It is only with the miniaturization of hardware, brought about by SmartDust technology, that extensive research has begun on the possibility of using SmartDust devices to control human bodily functions and improve health. However, as with most major technological innovations, SmartDust technology, at its rudimentary developmental stage, as we see today, necessarily operates within a very limited existential and ethical scope. This phase is characterized by mere belief in the possibility of converging technology with humans and achieving a transhumanist transformation that could lead to a fundamental enhancement of human life. Specifically, this may occur through the development and application of accessible technologies that improve intellectual and psychological capabilities, as well as the psychobiological aspects of human life [21]. In this way, a new, more advanced version of humans and their bodies may emerge.

Countless SmartDust devices already exist on the periphery of billions of IoT entities [22]. These devices do not yet meet all the conditions to be called SmartDust devices, but they steadily perform their functions while continually becoming more miniaturized [23]. Something similar is happening with the implementation of SmartDust technology in the human body. The Internet of Bodies (IoB) [24] represents a massive collection of SmartDust devices that are implanted, ingested, or worn, tracking processes within the human body, gathering health information, and transmitting that data via the Internet to interested users [25]. The possibilities of the impending Internet of Everything (IoE) [26] seem overwhelming, and its uncontrolled power is concerning. The University of Cambridge defines IoE [27] as "the seamless interconnectivity and autonomous coordination of a vast number of computing elements and sensors, both non-living and living beings, humans, processes, and data, through Internet infrastructure. IoE is a new research direction that will enable the existence of a connected universe using molecular sensors embedded in vehicles and humans. This new framework has enormous potential to transform the way we connect with the universe and understand it, enabling new methods of interacting with processes at the molecular level and expanding human awareness and control with the help of smart agents that sense and act upon environments previously unexplored by any other paradigm. The realization of IoE requires new engineering solutions to overcome unique challenges related to connectivity, spectrum scarcity, miniaturization, interoperability, and energy efficiency" [27].

We are already seeing a data explosion driven by Knowledge Management (KM). The rise of mobile devices, sensors, cameras, and wireless networks has exponentially increased data collection. With SmartDust's full implementation, the volume of data collected, stored, and used will become unimaginable [28].

Following the available information, we inevitably conclude that SmartDust technology represents, for the first time, a technology capable of radically transforming human life. As it has been noted, "when determining the boundary between humans and the rest of the animal world, we observe a simple but crucial difference: while animals adapt to their environment through evolution, humans use their intelligence to adapt the environment to themselves. Fortunately, nature has always fought back and found its own way to retaliate against attempts by humans to ignore it [29]. However, with the advancement of technology and human thinking, the human race is approaching a new era in which, besides having control over the natural environment, humans will gain complete control over their own

evolution, health, and potentially, their mortality" [30]. Thus, we arrive at transhumanism, which, moving from fiction and a favored topic of utopian or dystopian literature, is slowly becoming a probable future reality through the convergence of SmartDust devices and human entities.

Transhumanism, in this context, is understood as an intellectual and cultural movement that promotes the possibility and desirability of fundamentally improving human life through the development and application of technologies that eliminate the degeneration of the human body and mind [31]. At present, there is not only no clear answer but also no response regarding whether this movement has grown out of salon, chamber, or internet-based forms into more practical ones.

Since the beginning of this century, the increasing interconnection of computer systems and networks, combined with the rise of intelligent automation, has led to rapid changes in technology, industries, as well as social patterns and processes [32]. At the same time, embedding sensor and computing capabilities into everyday IoT objects [33] and their integration into living organisms (IoB) [34] has blurred the boundaries between the physical, digital, and biological worlds. As a result, formerly unrelated technologies are becoming increasingly interdependent and applicable across multiple domains. This phenomenon, known as "technological convergence" or "converging technologies" (CT), represents a shift in the socio-biotechnical paradigm, marked by the pervasive distribution of computing and sensing capabilities, and the consequent dissolution of boundaries between previously unrelated fields of technological innovation [32]. For the purposes of this paper, we will refer to one definition [32] that defines "technological convergence" as "a new socio-biotechnical phenomenon characterized by three fundamental aspects: The increasing ubiquity and comprehensive distribution of sensing and computing capabilities on both physical objects and biological organisms; The erosion of clear distinctions between the physical, digital, and biological domains due to new technologies such as artificial intelligence (AI), gene editing, nanotechnology, biomedical engineering, neurotechnology, and robotics; And the more frequent simultaneous emergence of these technologies and their large-scale expansion in ways that are difficult to detect, protect, and manage" [32].

The integration of previously unrelated technologies offers benefits for socio-biotechnical innovations and human well-being but poses significant ethical and governance challenges. These disruptions, often called the "fourth industrial revolution," are leading to "Society 5.0" [35]. This merging of the human body with digital technologies forms a bio-cyber-physical system ([Bio-]CPS), or a bio-cyber entity, combining cybernetic and biological components.

IV. Bio-Cyber Entities, Neo-Luddism and the New Ethics

Any symbiosis between humans and technology inevitably leads to humanity's cyberization. The merging of humans with machines could transform humanity and allow entities that are only partially human to control all aspects of life. The final product of the transhumanist convergence of SmartDust-based technologies and human entities could result in a "Bio-Cyber-Physical System" ([Bio-]CPS). Increasingly, experts warn that this could be the first irreversible evolutionary change, altering humanity's very essence. Through this, humanity might voluntarily surrender control to an unknown "someone".

This bio-cyber entity might be Nietzsche's Übermensch, but from a moral perspective, it could be seen as a moral and mental abomination. The ethics of coexistence between ordinary humans and bio-cyber humans are not yet fully developed. Our prior research on this new ethics [36,37] suggests that it revolves around AI's ontological and epistemological interventions into the human "self." While AI has enhanced human capability, the human body and mind must remain the foundation of existence. Non-human entities may assist in certain tasks, but ultimate control must remain with humans. AI should be bound by the laws of robotics; losing control opens the door to errors and abuses, leading to human redundancy.

Studies suggest the risk of misuse lies more with human nature than technology, but scientists warn SmartDust systems could

reshape the world into something alien to humanity. Powered by neural networks and invisible, high-speed computers, these systems could displace humans from many areas of life, altering minds, habits, communication, and freedom, threatening privacy and autonomy.

There are two general approaches to the convergence of technology and humanity [38]. Neo-Luddism [39] opposes this convergence, viewing it as a threat to humanity that must be resisted. Transhumanism, on the other hand, sees technology as humanity's salvation, focusing on maximizing human-machine integration. Both approaches envision radical changes in human life and identity. Neo-Luddism fears the unpredictable and often invasive consequences of uncontrolled convergence, while transhumanism promises life extension and the transition to a cyberized existence. Scientists advocate a moderate path, promoting balanced coexistence between humanity and technology to preserve human identity. The enhancement of human physical and mental abilities through technology raises important ontological and ethical dilemmas. Technologies such as genetic modification, bionic prosthetics and biomimetic entities, neurostimulators, and even brain-computer interfaces must be used ethically and responsibly. We have defined eight principles of human enhancement that, in our view, must hold an almost sacred status. These principles are autonomy, the right of individuals to make decisions about their own bodies; justice and equality, ensuring equal access regardless of economic status; nonmaleficence, the assurance that enhancement technologies do not cause serious or lasting harm to health; beneficence, the belief that these technologies should bring real benefits to people, improving quality of life and enabling them to realize their potential; natural human autonomy and integrity, determining the limits to which technologies should be allowed to alter natural human abilities; the right to refusal, the inalienable right of every individual to decline enhancement technologies without fear of discrimination or social marginalization; transparency and accountability, the stance that all aspects of the development and application of enhancement technologies must be transparent; and long-term impact on the human species, a clear understanding of how these technologies will shape the future of human evolution, identity, and social structures. Scientific papers sporadically discuss the sort of threat that AI-based technologies might pose to the ontological being of humanity. This threat could, if not extinguish humanity as we know it, at least stifle its natural impulses. A superintelligent machine could dramatically alter the nature of human existence. Russell wrote that "people who live beyond a certain natural limit will most likely be filled with envy, malice, selfishness, and rage. They may become wrathful and cruel, or, on the other hand, they may completely lose the joy of life, to the point where they no longer have the strength for any effort" [29]. We are not talking about one or a hundred or a thousand people, but about billions of people.

V. Conclusions

Technological entities, including SmartDust, becoming the ontological substitution for humans, can lead to dramatic technological inferiority, complete loss of identity, and irreparable ontological disability [38]. In the process of sociopsychological adaptation, humans have fused with technology and no longer see themselves outside the comfort that technology offers, whose advancement has greatly influenced the development of human culture. Assessing the vulnerability of extreme alternative approaches, neo-Luddism and transhumanism, more and more research is exploring the possibility of a middle path—a possibility of proportional, peaceful coexistence between humans and technology, with the aim of preserving the innate and unchangeable mental apparatus of humans and their stable and coherent identity amidst the constant development of technological progress. By maintaining the intrinsic civilizational need for humans to expand technology, this middle path could or must ensure that technological interventions in altering the ontological being of humans are limited and proportional to natural possibilities and capabilities in the objective conditions of life on the planet.

Addressing the ethical and societal risks is essential for maintaining privacy, security, and social justice. Sensors can collect data about the environment and individuals, which could be misused for surveillance, profiling, or control.

Governments must implement strict privacy laws, require user consent before data collection, enforce data encryption, and limit access to information. Given that SmartDust technologies transmit data wirelessly, they are vulnerable to hacking and manipulation. Therefore, governments should develop advanced security protocols, ensure regular software and hardware updates, and establish standards for sensor deployment. Governments also must maintain democratic oversight of the technology, balancing its benefits with privacy rights and promoting ethical guidelines for its use.

SmartDust could exacerbate social inequalities, particularly between wealthy and poorer countries, social groups, and individuals. Equal access to technology and data must be ensured, and its use in public and private spaces must be regulated to prevent discriminatory practices. Another major concern is the environmental impact of millions or billions of tiny sensors, especially when they stop functioning. These devices could contribute to soil, water, or air pollution, as collecting all devices after use is challenging. A solution could involve mandating the use of eco-friendly, biodegradable materials and establishing systems for the collection and disposal of these devices at the end of their lifecycle. As with many technologies, there is a risk of SmartDust being misused for unethical purposes, such as military applications or non-consensual experiments. Governments should establish ethical committees to monitor the development and application of SmartDust technologies, and the international community should create conventions and agreements to ensure these technologies are used in line with humanitarian law. At this moment, it is impossible to predict whether the bio-cyber entity will be ontologically closer to humans or robots, and which path the evolution of this binary biomimetic being will take. One of the less important unknowns is whether SmartDust will be a collective, aggregated entity of AI, or if some form of SmartDust will acquire its own personality, thus becoming what we have called a biomimetic entity. What is known is the fact that scientists continually warn humanity that the loss of "human control over humans" could easily mean the end of the world. Scientists claim that the concentration of metadata, power, and wealth in the hands of a few can make the entire system non-transparent and "opaque," which will certainly lead to increased social tensions and, in particular, a deterioration and drastic violation of democratic rights and freedoms of citizens and nations. Scientists, especially philosophers, sociologists, and theologians, are not ready to entrust the development of the ethics of artificial intelligence and bio-cyber entities solely to engineers. Philosophers, sociologists, and theologians should collaborate with engineers, programmers, and decision-makers in multidisciplinary teams that oversee the development and application of technologies. These teams can help identify potential risks and consequences of new technologies, developing sustainable and ethical strategies for their advancement. Ultimately, philosophers, sociologists, and theologians can provide the intellectual foundation for creating laws and regulations that responsibly govern technologies.

The invasion of privacy is the primary reason why people are wary of the implications of SmartDust in life. SmartDust devices are invisible and difficult to detect. They will record everything they detect. People likely won't know who is collecting the data and what they are doing with it, nor will they be able to prevent the data about them from falling into the wrong hands. When SmartDust is used as part of the Internet of Bodies (IoB), freedom of choice will necessarily come into question. There are well-founded opinions [40] that the decision to "enhance" mental and physical abilities should be the sovereign right of the individual. But would it be morally right for ambitious parents to make such a decision for a child who wishes to succeed in sports or the arts but is not capable of doing so? This is where we can consider the most extreme goal of transhumanism: eternal life achieved through technology [30]. Among the criticisms of this goal is the possibility of complete relativization and loss of morality. The fear of death and eternal life in hell has long driven people to adhere to the moral norms of this life. But in a world where that fear no longer exists, moral and ethical values that are unconditionally respected could become unnecessary and discarded anachronisms. The integration of SmartDust and bio-cybernetic

entities could radically transform social structures, the labor market, and human rights, bringing both progress and significant challenges. There is a high potential for deepening social inequalities, making the development of new legislative and ethical frameworks essential to ensure fair and humane use of these technologies. A future where technology shapes human capabilities and social relationships requires careful planning to distribute benefits equitably and minimize risks.

The combination of SmartDust and bio-cybernetic entities will fundamentally alter societal functions, particularly in terms of control, surveillance, and interactions between individuals and institutions. Corporations and governments could gain significant influence by controlling the SmartDust and bio-cybernetic infrastructure, playing a key role in regulating, monitoring, and distributing these technologies.

The labor market would be drastically impacted, leading to massive job losses, especially in manual labor industries, further widening income and opportunity gaps between social classes. These technologies may exacerbate existing inequalities or create new forms of discrimination and social exclusion. Those who can afford bio-cybernetic enhancements could form a new elite, dominating the workforce, politics, and societal structures. Moreover, the integration of SmartDust and bio-cybernetic entities raises fundamental questions about redefining human rights, as they reshape the relationship between technology and humanity. This also introduces legal debates over the "rights of robots" and, similarly, the "rights of bio-cybernetic entities".

As we noted in earlier papers [41], controlling bio-cyber entities or aligning them with human values may be harder than assumed. Many researchers believe that the superintelligence of these entities will resist humanization or goal alteration—a principle called instrumental convergence. Pre-programming them with human values will be a highly challenging technical task [42]. Additionally, once billions of SmartDust devices are deployed, neutralizing them will be extremely difficult.

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