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Review and Perspectives of Micro/Nano Technologies as Key-Enablers of 6G

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ABSTRACT To date, 5G (5th generation of mobile communications) roll out has been going on for more than two years, and the most of it has still to come. Meanwhile, Key Performance Indicators (KPIs) and Key Enabling Technologies (KETs) of Beyond-5G (B5G) and 6G (6th generation of mobile communications) are already at stake, looking at 2030. Future networks will leverage autonomous and evolutionary characteristics, triggered by the cornerstone of Artificial Intelligence (AI), falling well-beyond the scopes of 5G. Besides, seamless increase of KPIs, across the transition from 5G to 6G, with 100-1000 times higher data rate per user, latency reduction and reliability improvement, also stepping into the domain of (sub-)THz and optical communications, will set unparalleled demands for Hardware (HW) systems and components. This work focuses on the envisaged gap existing between currently in use strategies for design of Hardware-Software (HW-SW) systems and what the AI-driven 6G will demand, in terms of adaptivity, flexibility and evolution. An important part is forecasted for Micro/Nano technologies, devices and systems, in enabling 6G functionalities, especially at the network edge, stimulating partial reconceptualization of the classical idea of HW, in fact, rising its level of abstraction.

INDEX TERMS 5G, 6G, Artificial Intelligence (AI), Internet of Things (IoT), Microelectronics, Microsystems (MEMS), Millimeter waves, Nanodevices, Nanoelectronics, Nanomaterials, Nanosystems (NEMS), Radio Frequency (RF), Super-IoT, Tactile Internet (TI), Terahertz (THz), WEAF Mnecosystem.

I. INTRODUCTION AND MOTIVATION

The recent scientific literature started to shape what 6G (6th generation of mobile communications) will be in the next decade, while the currently under deployment 5G (5th generation of mobile communications) already took the plunge of becoming the enabler of distributed applications paradigms [1], with Internet of Things (IoT) and Internet of Everything (IoE) first in line – Table 1 at the end of section lists the acronyms used in this work. Already today it is a belief of eminent scholars that 5G will not unleash full potential of IoT/IoE, nor, a fortiori, sustain their evolution to Super-IoT and Tactile Internet (TI) [2]–[4].

The reasons behind such a pouring of expectations from 5G to 6G are twofold. On one side, pivotal applications like XR Extended Reality (XR), Machine-To-Machine (M2M) and Vehicle-To-Everything (V2X) communications, as well as 3D holography [5], will demand for Key-Performance Indicators (KPIs), especially in terms of data, latency and reliability, falling well beyond the most rosy targets of 5G.

Thereafter, networks of the future will have to realize unprecedented features to support full pervasivity of TI, which are orthogonal to the classical KPIs mentioned above. Prime role is envisioned for Artificial Intelligence (AI) to enhance reconfigurability, adaptivity, resilience and evolution of the network, both on the service and operation plane [2],[3].

Wrapping together all these challenges weighting on the shoulders of 6G, this work develops a discussion gravitating around the field of Hardware (HW) technologies. As already anticipated by the authors in [6],[7], turning 6G visions into reality will require adoption of unprecedented strategies in development of Hardware-Software (HW-SW) systems, leveraging increased functional abstraction of HW, leading to its partial reconceptualization. A pivotal role for Microtechnologies and Nanotechnologies, intended as devices, systems (Micro/NanoElectroMechanical-Systems – MEMS/NEMS) and materials, is envisioned in the 6G scenario, with particularly relevant estimated impact on the network edge architecture.

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In light of such a scenario, this work intends to advance the preliminary discussion available in [6],[7], by developing a comprehensive review of state of the art Micro/Nano technologies, which are likely to turn into enablers of 6G services functionalities and (edge) network features.

Now, driven by the target of framing appropriately the underlying motivation of this contribution, a brief outlook is developed around current reviews and perspectives on 6G and Micro/Nano technologies, available in literature.

A. CURRENT STATE OF RESEARCH IN 6G

Referring to the field of 6G, the scientific community is very active since a few years, in elaborating visions and perspectives around enabling technologies and specifications. Beside cornerstone early works, like [2],[3], published in 2019 and 2020, many other pivotal aspects have been recently explored. To this regard, the discussion in [8] offers a useful review of significant tutorials, visions and perspectives, along with a list of past and ongoing projects on 6G.

Having said that, the focus of the scientific community in this field started developing along multiple directions in the last couple of years, briefly summarized in the following.

Starting from a rather general outlook, Key-Enabling Technologies (KETs) and drivers, unprecedented architecture requirements, emerging limitations and constraints, along with open research problems, are discussed in [9]–[12].

Concerning more circumstanced technical aspects, detailed discussions are being developed around new spectra and wireless communication technologies for 6G, including mobility, coverage, data throughput (also in terms of reliability and latency), along with time-frequency-space demands [13]–[15]. Moreover, the intricacy of arising security, privacy and trust issues related to 6G are also at stake in literature, as reported in [16]–[18]. Sticking to technologies, the centrality of AI and Machine Learning (ML) was already mentioned before, and they constitute core matter of several scientific contributions, like those available in [19]–[23].

Laying on a different plane of reference, 6G is also being investigated against future application paradigms, thereafter drawing attention around how future networks can, in fact, play the role of enablers of novel and pervasive services. To this end, interesting pieces of literature have recently been published on 6G-enabled ecosystems, like, among the others, massive IoT [24],[25], Industrial IoT (IIoT) [26],[27], Healthcare [28],[29] and Smart Cities [30]–[33].

B. CURRENT STATE OF RESEARCH IN MICRO/NANO HARDWARE TECHNOLOGIES

Stepping now into the technical area of Micro/Nano HW technologies, the frame of reference is significantly scattered down to self-contained solutions and applications, as we are now dealing with low-complexity sensors, transducers and, more in general, physical items.

Despite following different evolution paths and timing, MEMS-based sensors and actuators started to be investigated in literature around mid-1970s [34],[35], while commenced breaking into market products around two decades later, across the 1990s [36]–[38].

The possibility to step down from the micro (50-500 µm typical device size) to the nano domain (50-500 nm typical device size) started to be investigated across the turning between 1980s and 1990s, stimulated by the development of nanostructured materials, like, e.g., Carbon Nanotubes (CNTs) [39]–[41]. In addition, also in the 1990s, MEMS technology was investigated for the realization of devices other than classical sensors and actuators. This is the case of Radio Frequency (RF) passive components, like micro-relays, variable capacitors (varactors), reconfigurable phase shifters and tunable filters, well-known as RF-MEMS [42]–[44].

The current status of MEMS/NEMS technologies in market application is quite diversified, yet underlying a relentless trend to expansion, as reported in [45]. In a nutshell, markets like MEMS-based accelerometers, gyroscopes (gyros) and Inertial Measurement Units (IMUs), are consolidated since more than three decades, and witnessed multiple waves, with the first employments in cars' airbags (1990s), then in game consoles (2000s), and more recently in the smartphone, automotive and other sectors (2010s).

Also, newer exploitations of Micro/Nano technologies, like RF-MEMS, recently commenced to gain increasing room within (mass-)market segments, like telecommunications, on both ends of mobile devices and infrastructure. Of course, the scientific literature is rich of many other valuable examples in the Micro/Nano technologies field. Nonetheless, for the sake of brevity, they are not mentioned in this section, as many of them are reported in the following Section 6.

Now that the fields of 6G and Micro/Nano technologies are framed, it is time to put them together. In doing so, we pursue the twofold target of highlighting the existing gaps between such scientific areas, as well as to stress the motivation and the addressed advancements carried by our contribution.

C. CURRENT GAPS IN LINKING RESEARCH ON 6G AND MICRO/NANO HARDWARE TECHNOLOGIES

Concerning weak or missing links between 6G and HW MEMS/NEMS technologies and, in turn, the corresponding scientific communities, their identification is much linear if analyzed according to a mixed increasing and decreasing trend to complexity.

Starting from the *top-down stream*, i.e. from 6G to MEMS/NEMS, the common ground is that of a community of scholars with strong background in telecommunication protocols, Information and Communication Technology (ICT), AI and ML. Therefore, visions and perspectives of 6G are elaborated always keeping a rather high level of abstraction, i.e. playing on the service and network operation planes.

KPIs and KETs are derived without going too deep into the so-called physical layer. The HW infrastructure is treated as a complex entity made of a plethora of building black-boxes, i.e.

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devices, (sub-)systems and components, without knowing their founding HW technologies, architectures and working principles. This can be easily inferred from taking a look at the reviews, tutorials and perspective papers on 6G, previously cited when reporting the current state of research.

Moving into the *bottom-up stream*, i.e. from MEMS/NEMS to 6G, the research community is mainly formed by scientist with background in electrical engineering and electronics, physics, chemistry, micro-/nano-fabrication technologies, HW (sub-)systems integration and control. Consequently, the level of abstraction is never too high, as it ranges from basic HW components, like sensors and actuators, up to their integration with other HW devices, like control electronics, Microcontroller Units (MCUs), etc., to realize sub-systems and systems.

In fact, in the HW community there exists a lack of high-level vision and a scarce knowledge of service and end-user applications KPIs. On the contrary, specifications and requirements typically fall down like raindrops from the sky, and MEMS/NEMS developers, as well as, more in general, the HW and electronics community, put their efforts in pushing technical solutions to comply those already fixed demands.

The impact of this scenario is evident when looking at the scientific literature on Micro/Nano technologies. Technical papers and reviews on classes of devices, like sensors, actuators, RF-MEMS, etc., often refer just in general terms to broad fields of applications, like IoT, 5G, Healthcare, etc., mainly driven by the need to frame the reported research within a context that is known to a broader audience.

On the other hand, when the actual scientific content of those works is at stake, they report on how design, technology, integration, and so on, can be pushed and tailored, to score specifications the authors have not decided, nor contributed to establish, in synergy with the communities setting standards, services and high-level KPIs.

Driven by the sake of offering the reader deeper insight of the just mentioned context, a few recently published works are now listed. In doing so, we want to stress that the reported items are just a very brief set of examples, as the scientific literature is rich of many other relevant works. Therefore, if considered valuable, we encourage the reader to conduct independently more extensive searches in the state of the art.

Starting from MEMS-based accelerometers, gyros and IMUs, relevant scientific contributions are reported in [46]–[49]. When dealing with gas and environmental miniaturized sensors, the literature is also populated by remarkable works, like those in [50]–[54]. Mentioning other applications of MEMS/NEMS technologies as sensors and actuators, it is worth reporting that they are exploited to enable nano-positioning handling and manipulation platforms for various types of analysis and applications [55]–[57], along with endo-microscopes for medical purposes [58], as well as deformable mirrors and a variety of other actuators for optical signals conditioning [59],[60].

Now, moving the focus on different employments of Micro/Nano technologies, RF-MEMS have certainly to be mentioned. Across two decades of research and development, many RF passive components have been reported in literature, including resonators, micro-relays, capacitors/inductors, along with reconfigurable/tunable complex networks, like phase shifters, filters, RF power attenuators, and so on [61]–[65].

In summary, having analyzed the scarcity of links between the 6G – more in general, the high-level paradigms – and the MEMS/NEMS – more in general, the HW – scientific communities, the likelihood to identify one or more HW technologies for low-complexity components as KETs of 6G, has to be regarded as remote.

D. MOTIVATION AND ADVANCEMENTS OF THIS WORK

In light of the just sketched scenario, the main target of this work is to strengthen the connections between high-level 6G KPIs and KETs, and low-complexity HW components, with a specific focus around Micro/Nano technologies. This will nurture the unprecedented bottom-up approach of regarding MEMS and NEMS sensors, transducers and actuators themselves as KETs of 6G, rather than one among the various available HW technologies to realize the smallest building blocks of the network physical infrastructure, according to a classical top-down approach.

Given such a motivation, the current work embodies some crucial features that, to the best of our knowledge, are not covered in the currently available state of the art. The first, and more obvious aspect, is that we develop a broad high-level description of 6G and a comprehensive literature review on Micro/Nano technology-based HW sensors, actuators and transducers, within a unique article. In doing so, our care is to treat MEMS/NEMS HW components attributing them the same value that in other works is associated with high-abstraction level technologies, like millimeter-Wave (mm-Wave) and THz data transfer, M2M communications, XR, AI, and so on.

Then, after introducing the frame of 6G, we report what we identified as potential limiting factors, in the previous and current development flow of HW-SW systems. In a few words, we believe that the standard co-design approach, despite effective up to date, builds upon excessive asymmetry between SW and HW, with the former as main carrier of self-adaptivity and intelligence, and the latter as mere physical platform for implementing SW-centric functions.

As following step, we propose a partial reformulation of the standard concept of HW, which capitalizes on increased *separation* and *symmetry* between HW and SW. These two pivotal concepts will be detailed in the following page. What it is worth to briefly mention here, is that we envisage an augmented level of abstraction for low-complexity HW items, like sensors and actuators, as a cornerstone feature to make full realization of 6G possible in the next decade.

Thereafter, we identify Micro/Nano technologies as pivotal items to deploy the HW reconceptualization mentioned above,

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and the subsequent increase of abstraction and thinning down of the gap currently existing against SW. This is supported by pronounced characteristics in terms of flexibility, functional diversification, integration and substantial fabrication inexpensiveness of MEMS and NEMS.

To simplify the understanding of the Micro/Nano technologies envisaged role within the wide frame of 6G, we propose classification of such devices based on their functional and operation diversification. In particular, we build an analogy between the characteristics of MEMS/NEMS devices and the four classical elements in nature. This bring to the creation of the so-called WEAF Mnecosystem, standing for the Water, Earth, Air, Fire Micro/Nano technologies ecosystem, discussed into more details later.

E. SUMMARY OF THE PAPER STRUCTURE

Following the current introductory Section 1, the paper is structured as follows. Section 2 develops a comprehensive insight of 6G KPIs and KETs, reasoning in terms of Paradigm Shifts (PSs). Section 3 discusses the concept of HW-SW divide, introduced in [6],[7], capitalizing on detailed description. Section 4 summarizes the WEAF Mnecosystem concept, upon which reformulation of HW concept is based. Section 5 makes explicit how Micro/Nano technologies can support 6G, with particular focus on the network edge frame of application. Section 6 reviews state of the art research in Micro/Nano technologies for 6G. Section 7 reports quantitative performances analysis of the HW items in Section 6. Eventually, Section 8 collects conclusive considerations.

TABLE I
LIST OF USED ACRONYMS

4G	4^{th} generation of mobile communications
4G-LTE	4G-Long Term Evolution
5G	5^{th} generation of mobile communications
6G	6^{th} generation of mobile communications
AI	Artificial Intelligence
AM	Additive Manufacturing
ANN	Artificial Neural Network
ASIC	Application-Specific Integrated Circuit
B5G	Beyond-5G
BS	Base Station
CIM	Computing In-Memory
CMOS	Complementary Metal-Oxide Semiconductors
CNT	Carbon Nanotube
E2E	End-To-End
EADO	Energy Awareness-Driven Operation
EH	Energy Harvester/Harvesting
EH-MEMS	MEMS for EH applications
EH-NEMS	NEMS for EH applications
EM	Electromagnetic
EMI	Electromagnetic Interference
ES	Enhanced Security
FinFET	Fin-like Field-Effect Transistor
HW	Hardware
IC	Integrated Circuit
ICT	Information and Communication Technology
IIoT	Industrial IoT
IMU	Inertial Measurement Unit
IoE	Internet of Everything
IoT	Internet of Things
KET	Key-Enabling Technology
KPI	Key-Performance Indicator
LOS	Line Of Sight
LTE	Long Term Evolution
M2M	Machine-To-Machine
MCU	Microcontroller Unit
MEMS	MicroElectroMechanical-System
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
mm-Wave	Millimeter Wave
NEMS	NanoElectroMechanical-System
NLOS	Non-LOS
PDMS	Polydimethylsiloxane
PLS	Physical Layer Security
PS	Paradigm Shift
PVDF	Polyvinylidene fluoride
PZT	Lead Zirconate Titanate
QKD	Quantum Key Distribution
QT	Quantum Technology
RF	Radio Frequency
RF-MEMS	MEMS for RF applications
RF-NEMS	NEMS for RF applications
Rx	Reception
SC	Seamless Coverage
SD	Spectrum Diversity
SDN	Software Defined Network
SI	Scattered Intelligence
SiP	System in Package
SOI	Silicon On Insulator
SW	Software
TFET	Tunnel Field-Effect Transistor
TI	Tactile Internet
TRL	Technology Readiness Level
TSV	Through Silicon Via
Tx	Transmission
UAV	Unmanned Air Vehicle
UE	User Equipment
V2X	Vehicle-To-Everything
VLC	Visible Light Communications
WEAF Mnecosystem	Water, Earth, Air, Fire Micro/Nano technologies ecosystem
WPT	Wireless Power Transfer
XR	Extended Reality

II. TOWARDS THE FUTURE 6G – A SIMPLIFIED OVERVIEW OF A MASSIVELY-COMPLEX SCENARIO

The scenario of 6G, for its nature of transversal permeability with respect to the concepts of networks, functions and ecosystems, is going to be far more complex than any preceding paradigm, 5G included. At present time, 6G is in the process of being shaped according to different reference planes, among which those of functions and services to be implemented, as well as of KPIs and KETs, are worth to be mentioned. This, of course, invites a plurality of visions and opinions about what 6G will be, which adds to the desirability of a simplified framework for understanding 6G.

Given these premises, the scope of the current section is that of providing the reader with a brief overview of the most critical disruptions that future 6G is expected to bring. Such a discussion will be a basis for the focus on HW-SW systems design approaches and HW technologies, developed in the following sections of this paper.

Taking the first steps on a quantitative plane of reference, it is useful to summarize the most relevant key specifications envisaged for 6G. Also in this case, the discussion is still rather open, and the literature offers a variety of viewpoints. A rather recent comprehensive picture is proposed in [3], where the transition of requirements, stepping from 5G, to B5G, and finally to 6G, is considered. Starting from the numbers provided in this work, a subset of critical target KPIs can be extracted for what concerns:

a) **Average data rate per user**, rising from 1 Gbps (5G), to 100 Gbps (B5G), to 1 Tbps in (6G);
b) **E2E latency**, decreasing from 5 ms (5G), to 1 ms (B5G), to below 1 ms (6G);
c) **E2E reliability**, stepping from 99.999 % or $1/10^5$ (5G), to 99.9999 % or $1/10^6$ (B5G), eventually to 99.99999 % or $1/10^7$ (6G).

Despite the fact that the such specifications, especially for 6G, are not yet part of a commonly agreed-upon standard, they already provide significant insight into the leap, in terms of data rates, latency and reliability, anticipated for these evolving networks. Expanding the discussion around KPIs, the relevant work in [66], published in 2014, when reporting crucial technology enablers of 5G, forecast 20 Gbps peak data rates, 0.1 Gbps data rate experience by each user, as well as 1 ms E2E latency and 100 times improvement of energy efficiency, compared to the 4G-LTE. Looking at these numbers now, it is clear that such KPIs, originally attributed to 5G, are being moved forward to 6G.

In a nutshell, despite different visions, common elements can be clearly highlighted. If, on one side, everybody agrees that an increase between 10 and 100-1000 times in terms of data rates, latency and reliability is in demand, on the other hand, it is rather straightforward that 5G will not be able to satisfy these requirements.

Moving now the focus to a qualitative plane of reference, the context becomes more scattered and difficult to frame. In fact, 6G is expected to drive disruption at so many levels that the plethora of current and perspective technologies and technical solutions that can contribute to enabling the paradigm, must be grouped according to some sort of classification, to be properly understood.

A notable list of categories is proposed in [67], where the envisioned 6G is reduced to four PSs, that group relevant HW and SW technologies. Here we offer a slightly modified version of this classification, with the aim of tailoring it to the scope of this work. Bearing in mind this, the four main PSs driven by 6G are graphically shown in Fig. 1, and are named as follows:

1. **Scattered Intelligence (SI)**, related to the extensive exploitation of AI, with reference to the twofold reference plane of network services and operation;
2. **Seamless Coverage (SC)**, targeting continuum deployment of services worldwide, without any implication linked to the specific geographical area at stake (e.g., metropolitan, rural, remote);
3. **Spectrum Diversity (SD)**, aiming at seamless telecommunication services, over frequency bands ranging from sub-GHz to optical wavelengths (including the visible spectrum);
4. **Enhanced Security (ES)**, concerned to the augmented and diversified issues, in terms of security, privacy and trust, which 6G will unavoidably rise.

FIGURE 1. Graphical representation of the four main Paradigm Shifts (PSs) driven by the envisioned 6G, inspired by the comprehensive review in [67]. [All the images and thumbnails used to compose the graphic are powered by Freepik.com].

Differently from the discussion developed in [67], the PS termed SI, which massively leverages AI, is posed here at the center in Fig. 1, as it acts transversally with respect to all the others. More comprehensive discussion is provided below.

A. SCATTERED INTELLIGENCE (SI)

As outlined before, it is envisioned that 6G will massively capitalize on AI and ML. This is expected to happen at multiple levels. On one side, the employment of such technologies at the services level is rather straightforward, as it connects seamlessly with what is already going on today, with 5G and the spread of IoT applications. More disruptive is that AI and ML will play a crucial role at the 6G network operation level, as well.

Starting from a given set of resources, optimization of network operation is typically a rather complex multi-objective problem, with diverse variables involved, such as available spectrum, energy, communications channels, user density, computing power, and so on. All these variables should be optimized, while keeping energy consumption as small as possible. As is noted in [68], referring to 5G systems, in most such scenarios it is very difficult (if not impossible) to develop exact mathematical predictive and behavioral models.

On the other hand, AI and ML are capable of improving network efficiency and latency, by learning features from massive data, rather than pre-established fixed rules. Bearing in mind that next-generation wireless services will tend to evolve into complex systems and the requirements will vary in different applications and networks [69], the characteristics of AI and ML algorithms can build self-aware networks.

Further ahead, this can lead to the development of self-evolutionary features of the *network of networks*, with the ability, among others, to gather proper resources to ensure maintenance of KPIs (i.e. resilience) locally, while keeping homogeneity with the network as a whole.

For instance, AI algorithms can be applied to solve various kinds of problems, including sensing, mining, prediction, and reasoning [70]. Moreover, AI enables sensing the variations in network traffic, resources utilization, user demand, and possible threats, also enabling smart coordination of BSs, UEs, and various network entities [70]–[78].

Therefore, it is rather easy to see how disruptive the massive deployment of AI is going to be, with respect to the concept of network itself, equally involving the SW and protocols end, as well as the HW and infrastructural levels. Eventually, it is also clear how the SI is expected to be transversal and influential with respect to the other PSs discussed below, motivating its placement at the center of Fig. 1.

B. SEAMLESS COVERAGE (SC)

The target of global coverage is driven by the increasing trend towards ubiquity of services. To this end, the literature includes studies focused on the integration of 5G with satellites [79],[80], of 5G with UAVs [81],[82], along with space-air-ground integrated networks [83],[84]. Due to intrinsic limitations in terms of radio spectrum, geographical area coverage and operation costs, 5G terrestrial infrastructure cannot reach the desired KPIs of quality, reliability and of services available at any time and any place.

Nonetheless, if the target is to provide truly ubiquitous wireless communication services globally, it is necessary to take further steps, embracing the development of a space-air-ground-sea integrated network, to achieve worldwide connectivity, and to ensure seamless accessibility, especially in remote areas [85]. This challenge lays entirely on the shoulders of 6G, and will integrate underwater communication networks, as well, to support broad-sea and deep-sea activities.

Given the heterogeneity of the space-air-ground-sea integrated network, each employed technology exhibits pros and cons, in terms of coverage, reliability, throughput, transmission delay, etc. Via well-structured inter-networking protocols, different network segments could cooperate, when overlapped to a certain extent, to ensure and reinforce seamless services access and enhance their provision.

In this context, e.g., satellite-based communications could complement ground-based networks to bring services to those areas with poor or no terrestrial network coverage at all, like open seas and remote areas, as well as to disaster areas. Also, reasoning in terms of backup and redundant services, the complementary properties of satellite links, characterized by broad coverage, and of optical fiber-based backbones, able to handle high data rates, could be regarded as alternatives to wireless-based backhaul [67]. UAV communications can be exploited to relieve part of the terrestrial network load, as well as to improve service capacities in congested areas.

Considering additional functionalities, synergy of satellites and UAVs in connection with remote sensing technologies, could empower data acquisition for purposes of monitoring the network itself, leading to a more efficient management of the resources as a whole, and, consequently, to more effective strategies for planning and decision making [86].

Eventually, given the diverse nature of the space-air-ground-sea integrated network elements, it has to have a layered architecture, based on dynamic collaboration of multi-dimensional heterogeneous resources of the system, for resourcing data transmission, processing, sensing, caching, and so on [87]. To this end, a SDN control architecture seems to be particularly suitable.

C. SPECTRUM DIVERSITY (SD)

Driven by a massive trend toward integration of diverse solutions, similar in concept to what has just been reported on the PS of SC, 6G will entail the diversification of utilized frequency spectra, as already is being pursued in 5G. Having said this, an all spectra scenario is forecasted in [67], based on the continuity across sub-6 GHz frequencies, mm-Waves and sub-THz (from 30 GHz to 300 GHz), the THz range (above 300 GHz), and optical frequencies, as well. Of course, such a heterogeneity of spectra gives rise to a plethora of pros and cons that must be carefully and thoroughly evaluated.

Taking sub-6 GHz frequencies for granted, given their commonplace use, mm-Wave and THz channels exhibit comparable characteristics, like wide bandwidth and pronounced directivity (pros), along with, on the side of cons, significant path loss, blockage effects (foliage), atmospheric absorption and marked scattering. In particular, THz bands are affected by more severe cons, compared to mm-Waves [88].

On a different level, wireless channels in the optical domain show peculiar characteristics, such as material-dependent complex scattering properties, non-linear photoelectric characteristics, background noise effects, and so on. Optical non-guided communications can be further divided into the categories of LOS links, when the Tx and Rx ends see each other, and NLOS, when obstacles are standing between them [89]. In general, optical wireless links are not affected by multipath fading and Doppler effects.

D. ENHANCED SECURITY (ES)

In summary of the above, it is clear that the high-integration of technologies and the ubiquity of services driven by 6G, also bearing in mind the centrality of AI, will trigger non-trivial risks and concerns in terms of security and trust. The massive increase of sensing functionalities and of mobile/wearable devices will build around the core of human-centric services and communications, raising significant security and privacy issues at various levels.

AI itself is a source of security and privacy problems, including data security, AI model and algorithm security, software system vulnerabilities, along with improper utilization of AI technologies. Training of AI models requires the collection of huge amounts of data, very likely containing users' sensitive information, among which are identity and location [67]. Proliferation of miniaturized and wearable IoT devices poses security concerns, as well. Such items, by their nature, are based on frequent interconnections and interactions, requiring efficient authentication mechanisms and strategies. In this frame, traditional encryption/decryption techniques are cumbersome, as they require computing resources not at hand when dealing with limited computational capability, storage capacity and power availability, typical of IoT devices. Similar considerations apply to UAV networks, motivating the development of lightweight encryption protocols [90],[91].

Given such needs, multiple techniques and technologies can lead to the development of efficient, agile and secure protections. For instance, PLS can enhance security of wireless connections, while meeting stringent requirements in terms of latency, reliability and throughput, so critical in the 6G scenario. Also, QTs can come to aid, e.g. through QKD systems, generating keys based on the uncertainty and irreproducibility of quantum states, and implementing the key distribution according to random approaches [92],[93].

Blockchain-based solutions are also seen as promising to improve 6G data security and privacy [94]. Differently from traditional centralized authentication methods, decentralized data structures, typical of blockchain, exhibit improved anti-corruption and recovery abilities, along with high anonymity. In fact, AI and ML, when practically deployable thanks to the increased peak data rates to be achieved by 6G, will contribute to shaping security and privacy of operations [95],[96].

Eventually, a recently emerging technology regarded as pivotal to empower the PS of ES, is that of FL, here reported as last item certainly not because of secondary importance. In a nutshell, FL is an AI-based collaborative approach, which makes possible training high-quality AI models, through averaging and aggregating together local information, made available by a set of learning edge clients, [97].

Diversely from classical AI models training, the remarkable advantage of FL is that of making unnecessary the access to local data (at the edge), thus offering significant room for improving security and privacy [98],[99]. Simply to mention a relevant application scenario, FL applied to IoT networks would enable training of ANNs with the edges nodes sharing just parameters, instead of raw data, therefore improving significantly data security, as well as, also relevantly, latency of communications, as the amount of information to be transferred is much smaller [100].

III. THE HARDWARE-SOFTWARE DIVIDE

Looking at the past half-a-century and more, semiconductor technologies paved the way for the evolution of wide market sectors, like telecommunications and computer science. Electronics relentlessly pursued trends like miniaturization, integration and functional diversification, while decreasing power consumption and area occupation. All this has been effectively governed by the Moore's law [101], in conjunction to the *More than Moore* trend [102], the latter focused on non-standard silicon technologies.

Across such a large timespan, HW-SW systems evolved capitalizing on a steady conceptual and factual segregation among the material (HW) and immaterial (SW) parts. This pivotal aspect is addressed in [6] as the *HW-SW divide*, grouping all the asymmetries ascribable to the fact that HW is physical while SW is sot. The latter ones, in fact, contributed to creating an ideal groove among HW and SW, with most part of features like self-adaptivity and resilience, laying on the ground of SW. To this end, the HW-SW co-design approach [104], which was successful for decades and is still today with 5G, falls within the boundaries of the HW-SW divide.

The main point, stressed in [6] and also highlighted here, is that the unbalance of HW and SW, despite working pretty well up to date, does not seem the be the most effective strategy to make the 6G scenario, sketched in the previous section, turn into reality. Bearing this in mind, unprecedented design and development strategies must be architected, to overcome the HW-SW divide limitations. The authors already suggested in [7] that pursuing a trend to the increase of HW-SW *separation* and *symmetry* could be a key in solving the problem.

Deeper insight of these concepts is provided below. In particular, a graphical explanation of what increasing HW-SW separation means, is shown in Fig. 2.

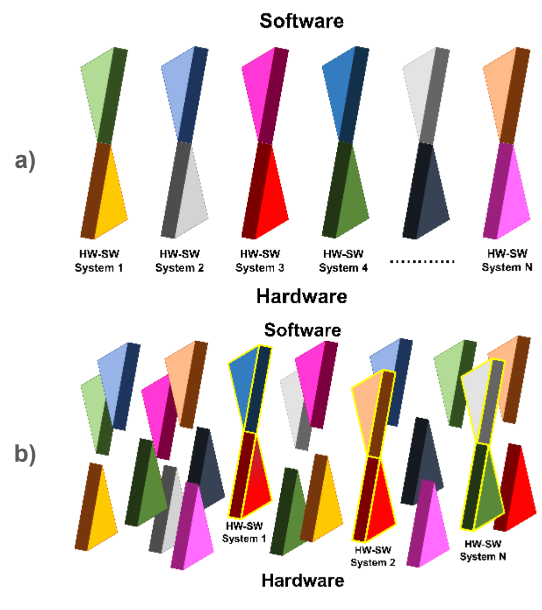

FIGURE 2. a) Schematic of HW-SW systems conceived according to the classical co-design approach. b) Envisioned context with increased separation (i.e. beyond co-design) between HW and SW. In this scenario, HW-SW systems can aggregate dynamically, depending on real-time needs, implementing diverse (including not a-priori forecast) functionalities.

The context in Fig. 2a is that of HW-SW systems as they have always been, and are still conceived today, in the 5G era, that is, static verticals, with the HW and SW parts mutually optimized, according to co-design development. Differently,

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the scenario envisioned as more suitable for 6G, relies on increased separation between HW and SW, stepping beyond the co-design approach, as reported in Fig. 2b. In this case, HW and SW modules can dynamically combine together, implementing functions and functionalities in an opportunistic way, i.e. according to real-time needs, also covering items that were not necessarily a-priori scheduled. In other terms, increased separation of HW and SW would trigger full self-evolutionary network capabilities, especially at the edge, as solicited by the capillary employment of AI mentioned above.

HW should also acquire additional symmetry against SW, concerning reconfigurability and flexibility of the functions implemented, self-adaptivity and self-recovery capacities, as indicated in Fig. 3.

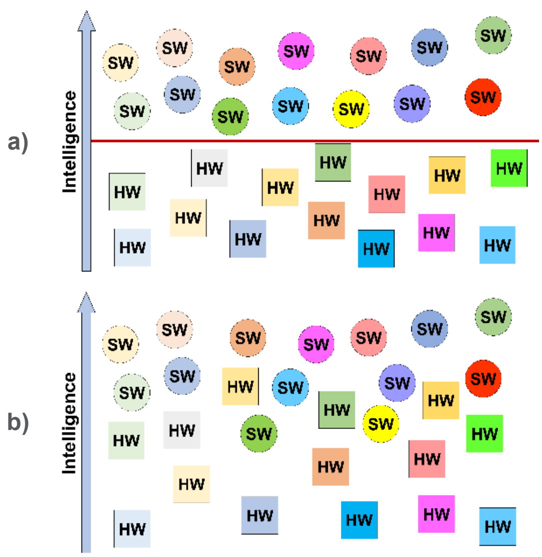

FIGURE 3. a) Schematic of the current pronounced asymmetry between HW and SW in terms of intelligence, intended as flexibility, adaptivity and, in general, self-referred capacities, like self-reconfigurability, self-healing, self-repair etc., as reported in Subsection 6.A. b) Envisioned context leveraging more symmetry between HW and SW, with the former acquiring part of the just mentioned characteristics typical of SW modules.

The scenario in Fig. 3a is the current one, upon which co-design-based HW-SW systems build. First, an ideal vertical axis is defined, where the term intelligence indicates items like flexibility, adaptivity, resilience, self-reconfigurability, self-repair/-healing, etc. In the existing scenario, such intelligence is so tightly an SW prerogative that a ceiling to HW intelligence can be set, as illustrated in Fig. 3a. What is predicted as necessary for proper development of 6G, is the context shown in Fig. 3b, where the ideal barrier between HW and SW is removed, and the HW can gain more intelligence, incorporating one or more of the features discussed above.

Recalling the previous section of the four main PSs of 6G, with specific reference to SI, it clearly emerges that they cannot be fully achieved simply by relying on the classical HW-SW systems development approaches, still in use today.

IV. THE WEAF MNECOSYSTEM

Bearing in mind the HW-SW divide previous discussion, reconceptualization of HW is here proposed, leveraging Micro/Nano technologies, embracing all their ramifications, in terms of devices, systems, electronics and materials.

Such a reformulation is built upon conceptual parallelism between HW-SW entities and the four classical elements in nature. The resulting scenario is addressed as the WEAF Mnecosystem, i.e. Water, Earth, Air, Fire Micro and Nano technologies Ecosystem, already introduced by the authors in [7],[103]. Its main features are just briefly recalled in this section, for the sake of consistency with the discussion that will be developed in the next pages.

Within the WEAF Mnecosystem, the classical concepts of HW and SW are addressed by the Earth and Air elements, respectively, while Water and Fire carry most of conceptual innovation. In particular, Water groups HW items, in the fields of sensors, transducers, actuators, materials, electronics, etc., implementing characteristics of self-adaptation, evolution and functional diversification, nearing them to fluidity of water. Fire, instead, has to do with HW dealing with energy, and in particular with its conversion, storage and transportation, elevating the concept of energy itself to an entity, virtually HW-independent, able to travel across the network edge, being available when and where needed, as heat does.

As discussed in [7],[103], Water-like HW is hinged around backbone trends, like functional adaptivity, self-evolution and ubiquity, triggered by the ease, typical of Micro/Nano technologies, of realizing orthogonal and redundant devices, within the same chip and in a monolithic fashion. Moreover, Water physical devices also implement interaction with features typical of SW, by means of the so-called trends of Evaporation and Condensation, i.e., Water-Air and Air-Water transition, respectively. In a nutshell, Evaporation (HW-SW upstream) has to do with incorporation into HW low-complexity devices, of self-reacting features, standardly realized by a system, the latter including sensors, interface electronics, computational capabilities and SW control routines. Instead, Condensation (SW-HW downstream) addresses full-in-HW implementation of logic circuits, computing low-/medium-complexity SW routines.

Similar characteristics apply to Fire-HW, despite, as stated above, the main applicative focus is that of energy to power tiny devices at the network edge.

Earth, eventually, despite representing standard HW, is an equally pivotal element of the ecosystem. It provides building block technologies that, combined together, give raise to devices and functionalities belonging to the other elements.

An explanatory example is that of a standard miniaturized inertial sensor, classified as Earth HW. When it is enriched in terms of functionalities (e.g. EH, actuation, etc.), and/or if redundancy is leveraged, the same sensor can transit into the Fire or Water domains, and in their interactions with Air.

Finally, a schematic visual representation of the WEAF Mnecosystem is provided in Fig. 4.

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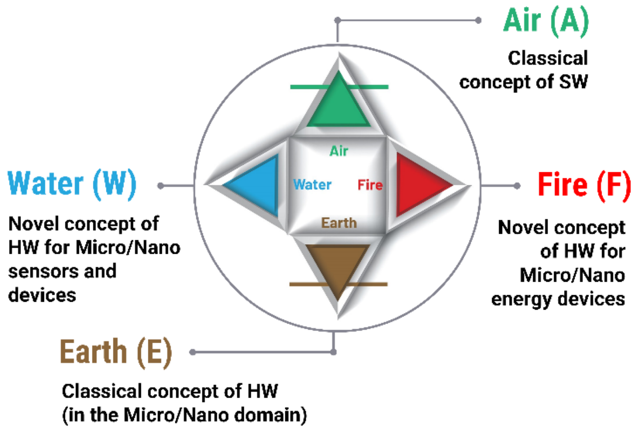

FIGURE 4. **Schematic visualization of the WEAF Mnecosystem.**

V. 6G AND MICRO/NANO TECHNOLOGIES MEETING AT THE NETWORK EDGE

The aim of this section is to build smooth connections between the high-level 6G scenario, along with the identified conceptual HW-SW systems limitations discussed above, and the Micro/Nano technologies (low-complexity) HW scenario, widely detailed in the following Section 6. In doing so, we also want to highlight specific needs, in terms of specifications and requirements for low-complexity HW components, not yet studied by the scientific community, nor to date reported in literature. The latter statement helps to better frame the effort in populating the currently empty WEAF Mnecosystem scenario, which will be developed in Section 6.

In fact, the upcoming review of existing MEMS/NEMS devices, systems, solutions and materials, has not to be intended as a plethora of ready-to-use HW components, able to support and empower the deployment of 6G. Differently, those items should be intended as reference examples of partially sketched and semi-developed technical and technology solutions, which should be further pushed and placed in reciprocal synergy, to reach the unprecedented characteristics of the WEAF Mnecosystem-related HW items, discussed in Section 4, targeting emerging needs and demands of 6G.

As emerged in the discussion developed up to this point, the 6G scenario is an amazingly intricated scenario. Said that, our aim here is to approach the discussion targeting a limited, yet intrinsically articulated portion of 6G. which is the network edge. In fact, we predict that, given the demands in term of HW to be listed in the following, the edge of 6G, and in particular the so-called edge intelligence, will be the first application frame in which Micro/Nano technologies will have the chance to play a prime role. Then, of course, such HW solutions will penetrate other more centralized layers of 6G infrastructure, despite probably according to more relaxed timing. This will require further discussion and prospects, falling well beyond the scopes of this work.

In this sense, the most rewarding target we would like to reach with our current contribution, would be that of providing some initial elements to stimulated such a frame of study across the scientific community.

Stepping now into the core of this section, dealing with 6G network edge means architecting and deploying capillary and ubiquitous HW infrastructure, capitalizing on very tiny, multi-functional and smart physical items.

Sticking to the HW frame of reference, we identify ten critical requirements of 6G network functionalities and operation, which are directly or indirectly related to the availability of low-complexity HW components with compliant characteristics. Such pivotal demands are sketched in Fig. 5, and discussed below.

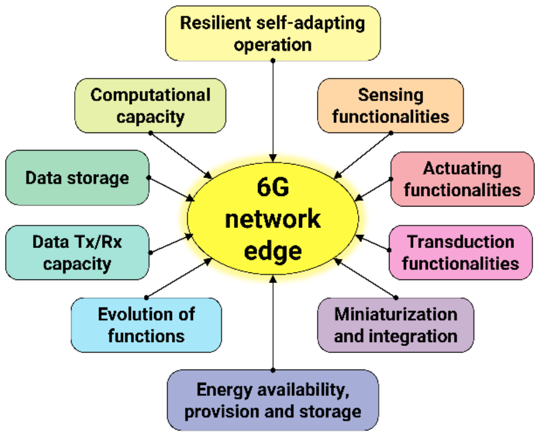

FIGURE 5. **Main directly and indirectly HW-related demands of 6G network edge.**

Given the sketched trends, Micro/Nano technologies can provide effective answers to all of them. This is going to be mentioned in the following list, also highlighting envisioned needs regarding physical MEMS/NEMS devices not already discussed in literature, yet feasibly achievable through working in synergy on further developments at technology, design and integration level.

1. **Resilient self-adapting operation**. 6G network edge will need the ability to tailor its functioning based on real-time local requirements and boundary conditions, also meaning to gather proper resources to counteract temporary impairments (resilience). This exerts non-trivial demands and challenges, in terms of HW components performances. To mention one among other relevant features, low-complexity HW components will need the ability to *react* autonomously to a changed surrounding scenario, without relying on a dedicated HW-SW sub-system, as not affordable in terms of complexity, costs, power demands and size of the tiniest HW infrastructure nodes at the edge. In addition, citing a practical case, one example can be that of HW units dealing with RF channels switching. Currently available solutions rely on redundant relays controlled by SW routines and activated in case of need. Conversely, Water-Air Evaporation-based solutions could employ micro-relays able to self-adapt against RF power levels,

making dedicated control circuitry and intelligence not needed anymore. This could be achieved via exploiting physical/mechanical properties of thin-films, like thermal expansion and temperature-driven self-actuation due to presence of intrinsic mechanical stress and its (thermally-induced) relaxation [103];

2. **Sensing functionalities**. In light of previous point 1), physical sensors will have to realize diverse and orthogonal functions, sometimes leveraging redundant duplication of heterogeneous sensors within the same physical chip, while, in other circumstances, exploiting the use of a unique HW component in different ways. These features can be fully supported by Micro/Nano technologies, despite to date just poorly covered by the scientific literature;
3. **Actuating functionalities**. Linked to the previous point, actuators will also need to be able to diversify their functions and functioning ways, like it happens with sensors. In addition, mixed sensing and actuating functionalities implemented by a unique physical device are envisaged as well as compliant with 6G network edge emerging demands. Also in this context, the state of the art is still limited;
4. **Transduction functionalities**. In fact, the transduction between different physical domain is an inherent feature of sensors and actuators. Nonetheless, physical devices whose functioning is centered around their transduction (instead of sensing/actuating) capacities are forecasted as pivotal, as well. This is the case, e.g., of RF-MEMS/-NEMS and of EH-MEMS/-NEMS, which are already widely discussed in literature. Nevertheless, what is still missing is their hybridization, targeting, among the others, the possibility to have a unique piece of HW realizing its function and harvesting, at the same time, the energy needed for operating;
5. **Miniaturization and integration**. The backbone linking all the previous points, as well as those still to be covered, is a relentless need for size reduction of physical devices at the edge, with a parallel increase of functionalities. Said that, Micro/Nano technologies offer significant room for pushing miniaturization, integration and hybridization of functions within a unique piece of HW;
6. **Energy availability, provision and storage**. As already stated across the lines, the aspect of energy for operation will be crucial at the edge of 6G. The scientific research is already quite mature for what concerns transducers for converting environmental energy (e.g. EH), transfer it from one point to another (e.g. WPT) and store it (e.g. miniaturized batteries). All this will be better framed in the upcoming Section 6. From a different perspective, what is still missing is putting together and harmonize all these technology tiles, aiming at the concept of EADO. Also in this context, the state of the art is rich of contribution on the single branches mentioned above, yet it is still partially developed for what concerns inclusive HW platform solutions, featuring diversified energy converters, optimized extraction, storage and adaptive operation strategies, tailored on real-time power availability;
7. **Evolution of functions**. Recalling the previous point 1), self-adaptation of 6G will not be uniquely related to counteracting adverse local conditions. In fact, massive employment of AI will lead to services and functionalities able to evolve, there including features not necessarily planned at deployment stage. As it is easy to imagine, such an augmented concept of flexibility cannot be unique prerogative of SW, especially at the network edge, where large and redundant HW-SW infrastructural resource are not available, nor fully accessible;
8. **Data Tx/Rx capacity**. Differently from previous generations, 6G will bring to the disruptive reversal from centralized (cloud) to distributed (fog/edge) capacities. Yet, this does not mean that data Tx/Rx across the network periphery and core will regress to the background. Edge HW infrastructure nodes will have to be equipped with high-performance, ultra-low power RF transceivers (transmitters/receivers). When dealing with RF passive components needed to build such systems, MEMS/NEMS solutions will certainly provide remarkable value;
9. **Data storage**. Putting together the trends to distribution of resources, exploitation of AI, along with self-adapting evolution of operation and functions, the availability of local data storage capacities, relying on miniaturized, ultra-low power consumption and very-low access latency HW, will turn to be crucial. To this end, further and more synergic developments of already existing Micro/Nano technology-based solutions, could make the difference, as also stressed in the next point;
10. **Computational capacity**. In close connection to the previous point, there will be significantly increasing demands in terms of resident high-efficiency edge computation capacities. This frame provided, a couple of emerging cutting edge research streams appear to be particularly relevant. The first is that of CIM, aiming to merge computation and data storage within physically very-close and, even better, monolithic (i.e. *atomic*) HW items, thus drastically reducing latency and power consumption. On the other hand, the next frontier of soft computing, moving away from classical "0-1" digital levels of information, to analogue (virtually infinite) states, mimicking human brain functioning, seems also to be a cornerstone to 6G. As before, these still partially covered research areas, appear to be particularly well-overlapped to what Micro/Nano technologies can offer.

Recalling all the listed points, the most relevant needs triggered by future 6G at the edge and weighting over the shoulders of low-complexity HW components, were

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addressed. If such demands result to be still partially covered by the scientific research, from a different perspective, Micro/Nano technologies seem able to properly meet them.

Bearing this in mind, the following section will review a comprehensive set of research items in literature, regarded by the authors as valuable pillars for further development, in view of the targets stressed up to here.

VI. SURVEY OF MICRO/NANO TECHNOLOGIES RESEARCH LINES FITTING THE WEAF MNECOSYSTEM

Capitalizing on the discussion previously developed, this section brings in more technical elements, having for hub Microtechnologies and Nanotechnologies. The aim is to start scattering few items over the empty scenario of the WEAF Mnecosystem. This is done by reporting selected research topics, available in the current state of the art, fitting the HW conceptual reformulation mentioned above.

In order to provide the reader with simplified access to this review, each research area or set of devices identified as relevant, is reported in a dedicated subsection. Per each of them, the WEAF Mnecosystem element/s involved is/are indicated, as in the following:

A. ***Devices with self-repair and self-healing properties – Water-Air upstream***
B. ***Monolithic orthogonally multi-functional devices – Water***
C. ***Logic circuits and memories based on MEMS/NEMS – Air-Water downstream***
D. ***Multi-source Energy Harvesting (EH) converters and platforms – Fire***
E. ***Miscellanea – Earth***
1) *RF-MEMS*
2) *Metasurfaces and Metamaterials*
3) *Flexible electronics*
4) *Heterostructures-based semiconductors*
5) *Devices fusion through packaging and integration*
6) *Additive Manufacturing (AM)*
7) *Photonic devices*
8) *Quantum Technologies (QTs).*

The subsequent material is arranged according to the just reported rationale.

A. DEVICES WITH SELF-REPAIR AND SELF-HEALING PROPERTIES – WATER-AIR UPSTREAM

An increasingly relevant research area is that of components, devices and systems displaying the ability to autonomously restore their functionality, in response to sudden malfunctioning conditions, as well as after physiological degradation due to long-term operation.

The abilities to self-detect an occurring problem and to consequently deploy self-repair/self-healing strategies, seem at first sight intrinsic prerogatives of SW-based systems. Though, significant efforts of the research community are oriented to the physical (HW) implementation of such features, according to a sort of built-in self-reacting capacity of devices and materials, as broadly reported in [105].

Prior to entering into technical details, the mentioned work builds comprehensive taxonomy of autonomous features. In particular, having in mind a general systems, *self-repair* is identified as a top-down process, acting at macro level within the systems, and taking place through the replacement of a faulty component. Oppositely, *self-healing* is a bottom-up process, involving the system at localized (micro) level, leveraging rehabilitation of a faulty component. Beside the latter features, various other capabilities are defined and discussed in [105], like, e.g., self-protection, self-inspection, self-management and self-awareness.

In general terms, a comprehensive scheme of the relationships existing between types of damage and potential healing solutions is reported in Fig. 6.

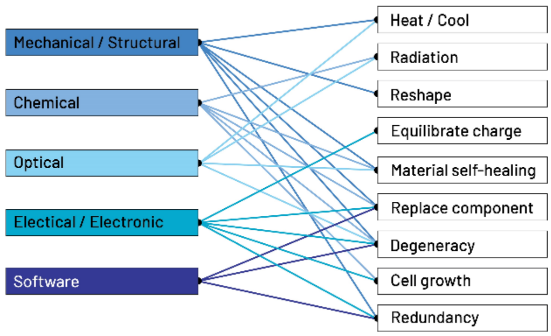


FIGURE 6. Scheme of the main existing links between types of damage and potential healing solutions [105].

In fact, HW-SW systems intrinsically allow multiple measures to account for failure occurrence, performance drifts and malfunctioning conditions. In simple terms, a certain level of HW redundancy combined with ad-hoc SW algorithms, often inspired by natural phenomena, like DNA or embryonics [106]–[108], leads to the implementation of self-healing items.

However, in light of the discussion developed here, the survey is going to be mainly concentrated around intrinsic properties of materials and HW devices, leaving the strategies at system/sub-system level uncovered.

Having said this, the discussion is hinged around *self-healing/-repairing materials* and *mechanisms*, with specific attention to the fields of Micro and Nanotechnologies.

1) SELF-HEALING AND SELF-REPAIRING MATERIALS

The first mentioned example exploits CNTs dispersed within an insulating fluid [109], used in the context of ICs. When malfunctioning occurs because of open circuit condition, the presence of an electric field triggers the aggregation of CNTs, which reestablishes the electrical interconnection between the two isolated terminals. The noteworthy aspect of this solution is that self-healing process starts autonomously (self-reacting feature), as soon as the open circuit condition occurs, since it necessarily happens when a voltage drop is present across the two banks of the gap. In a similar fashion, self-repair characteristics are observed with respect to the presence of CNTs within fillers based on resins and polymers [110].

Other technical solutions capitalize on the presence of micro-capsules, filled with proper liquid healing agents, scattered within other materials. When necessary, such capsules break, releasing their content that restores a certain property of the material, e.g. structural or electrical, that was undergoing degradation. The work in [111] discusses the electrical treeing in insulating materials subjected to prolonged high-voltage drops. The resulting cracks typically initiate from materials imperfections, like voids, and lead after certain time to dielectric breakdown (irreversible failure). The issue is counteracted by adding micro-capsules within the polymer-based dielectric, as shown in Fig. 7.

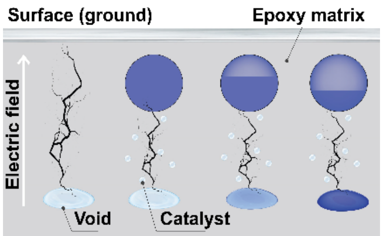


FIGURE 7. Schematic of the electrical treeing self-healing based on micro-capsules containing healing agent discussed in [111].

The sustained hypothesis is that treeing itself releases the healing agent, when cracks reach and break one or more micro-capsules. The released monomer fills the cracks and heat, due to normal operation of the dielectric, triggers the polymerization that completes the healing process. Other contributions discuss micro-capsules-based self-healing in diverse fields, e.g. in cementitious materials [112], with different triggering mechanisms, like ultrasonic waves [113].

The research community is also investigating materials with self-healing properties based on vascular-type ramifications, inspired by human body and plants. Diversely from the case of micro-capsules, in this circumstance a factual network of micro-channels is conceived and realized ab-initio within the material. This way, when restoration of a certain property is needed, healing agents are pumped through the vascular network, mimicking blood, lymph and sap [114]–[116].

Aside the articulated structures like those discussed above, materials with intrinsic self-healing properties are also reported in literature. The work in [117] discusses restoration of the mechanical resonant properties of cubic silicon carbide and germanium thin-films. Such 3D layers are intentionally altered by ultrasonic excitation and temperature cycling stress, and then recovered by means of heating.

Finally, a comprehensive review of innovative materials with self-healing characteristics with focus on high electrical stress applications is provided in [118].

2) SELF-HEALING AND SELF-REPAIRING MECHANISMS

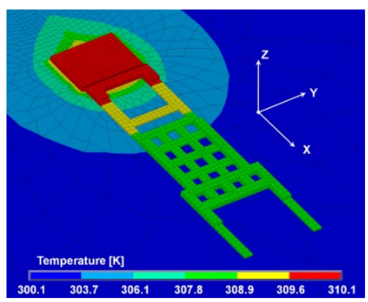
As stressed already, the least sophisticated, yet sound and effective self-repairing solution is redundancy. Nevertheless, apart from simply commuting from a failed to a fresh identical device or component, solutions to make the failing item intrinsically healable/repairable can also be pursued.

The first example is a self-repairing EH-MEMS exploiting thin-film with piezoelectric properties to convert mechanical vibrations into electricity. The device is the classical MEMS cantilevered structure with a sensing proof-mass [119]. The self-recovery feature pertains to the damage the piezoelectric layer could exhibit locally due to oscillations induced mechanical stress. The latter could lead to significant impedance changes of the generator. The metal electrodes sandwiching the piezoelectric layer are arranged according to a matrix of elements, rather than being continuous. Therefore, in case of failure, the element or elements containing the malfunctioning transducer material can be isolated. Moreover, additional inductance is inserted, to compensate the change of impedance and, in turn, to maintain stable the EH conversion performance. Of course, the mentioned approach is not able to counteract more critical failure conditions due to possible alterations of the cantilever structural material.

Another self-recovery mechanism is discussed for electrostatically actuated RF-MEMS micro-switches. Among the possible failure mechanisms there is stiction, which is the missed release of the electromechanical switch when the controlling signal is removed. Stiction can occur mainly because of two reasons, which are charge entrapment within insulating layers (due to DC/AC prolonged actuation) and micro-welding in correspondence with the input/output contacts (due to non-negligible RF power levels) [120]. It must be stressed that stiction due to entrapped charges can be recovered after waiting appropriate time for the charges to get dispersed. Differently, stiction due to micro-welding in most cases results to be a permanent failure condition.

The solutions proposed in [121],[122] both exploit the heat generated by a high-resistivity micro-heater embedded in the RF-MEMS micro-relay to counteract stiction. In particular, the design discussed in [121] demonstrates that the micro-heater activation speeds up the charge dispersion process and, in turn, the switch operation recovery. On the other hand, the concept proposed in [122] addresses micro-welding. The micro-heater is deployed under the metal anchoring area of a cantilever-type MEMS ohmic switch. First, the micro-relay is intentionally brought to micro-welding failure by driving large pulsed current between its terminals. Then, the micro-heater is activated by a pulsed voltage, as reported by the simulated 3D schematics shown in Fig. 8.

a)



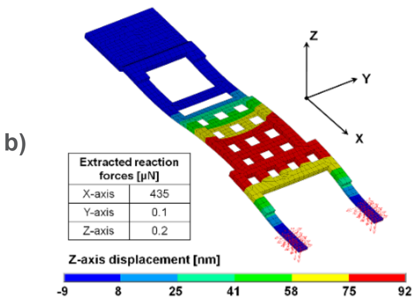


FIGURE 8. 3D schematics of the self-recovery anti-stiction design solution in [122]. a) Simulation of temperature distribution due to 2 mA current driven through the micro-heater. b) Corresponding shear force, due to thermal expansion, exerted by the MEMS membrane on the constrained contact fingers (i.e. where micro-welding occurs).

It is demonstrated that induced heating fluctuations cause cyclical deformations of the MEMS membrane (due to thermal expansion) that, in turn, apply shear forces on the contacts, large enough to break the micro-welding joints and restore the switch functionality.

Still referring to self-healing/-repairing mechanisms, a recently trending research area is investigating various polymers against shape-memory effects [123]. To better understand the potentialities of such materials, extensive thermomechanical characterization of a shape memory polymer is reported in [124]. The shape programming and subsequent self-repairing capability is depicted in Fig. 9.

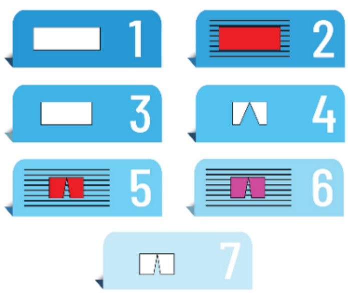


FIGURE 9. Shape programming and self-healing as reported in [124]. 1) Initial shape. 2) Shape programming with confinement and temperature above glass transition threshold. 3) Programmed shape. 4) Damage intentionally caused by impact. 5) Confinement and temperature above threshold to narrow the crack. 6) Cooling down while confinement is held. 7) Self-healed shape.

A practical exploitation of self-healing shape memory polymer materials is discussed in [125], where a capacitive pressure sensor with enhanced durability is obtained thanks to thermal cycling (70° C) in an oven. Such a treatment triggers the self-healing characteristics of the device, after degradation due to long-term nominal operation.

B. MONOLITHIC ORTHOGONALLY MULTI-FUNCTIONAL DEVICES – WATER

Recalling the main features of the Water-like novel HW conception, introduced in [7] and previously discussed in this work, the attention is now be focused on unique devices able to implement multiple sensing/transducing functionalities.

Given such premises, a contribution that is worth to be mentioned is discussed in [126]. The reported work exploits a MEMS processing technology platform, leveraging a set of fabrication steps both belonging to typical bulk and surface micromachining techniques. The manufacturing sequence, which is CMOS-compatible, allows integration of five orthogonal sensors, i.e., temperature, corrosion, relative humidity, gas and gas flow sensors, within a monolithic 3 x 3 mm^2 chip, as schematically reported in Fig. 10.

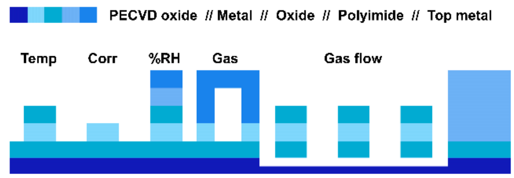


FIGURE 10. Schematic cross-section of the five different sensors integrated within a unique 3 x 3 mm^2 silicon chip, as reported in [126].

Other contributions exploiting similar approaches are also available in [127]–[129], demonstrating the wide functional flexibility offered by micro-fabrication technologies.

Another case study is the one reported in [130]. Here, a unique MEMS-based resonating element, implementing different and orthogonal sensing functions, is at stake. The device is the typical mass-spring system shown in Fig. 11, which exploits fixed and movable interdigitated finger electrodes, to transduce a mechanical displacement, induced by an acceleration, into a variation of capacitance.

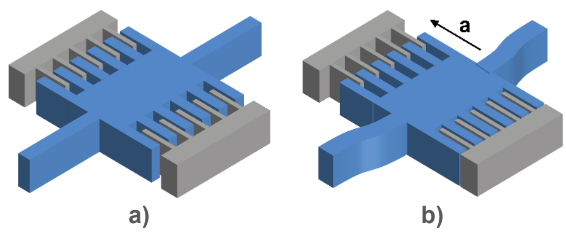


FIGURE 11. a) Schematic of a typical MEMS-based mass-spring capacitive inertial sensor. b) Deformed sensor when subjected to an acceleration *a*.

Despite the fact that this sensor architecture is well-known, the way it is used in [130] is rather innovative. In fact, a unique MEMS-based design concept is exploited as a building block to realize an environmental temperature sensor, an ambient pressure sensor, a classical accelerometer, and a gyroscope. The work is completed by the development of ad-hoc control electronics, able to drive the MEMS sensors in all the orthogonal sensing functionalities mentioned above.

Within the same frame of reference, a recent research trend is that pursuing integration of multitudes of diverse sensors on flexible and possibly low-cost substrates. The resulting complex devices, depending on their final use, are often indicated as *smart skin*, and they are of great interest within the contexts of robotics and wearables [131]–[133].

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C. LOGIC CIRCUITS AND MEMORIES BASED ON MEMS/NEMS – AIR-WATER DOWNSTREAM

Bearing in mind the Air-Water downstream (Condensation) characteristics, introduced in [7] and discussed above, Micro/Nano technologies-based implementations of logic gates/circuits and memory cells are now reviewed.

1) LOGIC GATES

First, it has to be stressed that most of MEMS/NEMS logic gates capitalize mechanically resonating structures, which transduce variations of such a periodic ringing into electrical magnitudes, as it is inherent to the multi-physical behavior of micro- and nano-structured devices. To this end, it must also be recalled that maintaining MEMS/NEMS structures in constant oscillation is effective from the point of view of power consumption, as their losses are typically very low (virtually zero).

In light of these considerations, the solution discussed in [134],[135] exploits an F-shaped MEMS bulk micromachined mechanical resonator, always kept oscillating. A set of vertical electrodes are deployed around the vibrating structure, with the purposes of driving mechanical resonance, applying input logic signals and reading the output logic state of the gate. In particular, depending on the ON/OFF voltages provided as inputs, the output state reflects in variations of the S21 transmission parameter in correspondence to the two main resonant frequencies of the device. The solution is discussed against the implementation of the AND and XOR (exclusive OR) gates, along with a half-adder. Thanks to the inherently very-low power consumption of electrostatic (capacitive) coupling, in which direct physical contact of electrodes never occurs, preventing electric currents flowing, the power consumption per operation is claimed to be in the order of femtojoules (fJ). Also relevantly, the solution can be easily cascaded, thus scaling up the computation capacity addressed by the micromechanical logic circuit.

A rather wide set of different realizations are reported in [136]. Among the discussed solutions, an example is sketched by the schematic in Fig. 12.

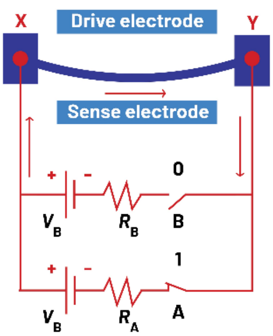

FIGURE 12. Thermoelectrically modulated AND logic gate based on a clamped-clamped MEMS resonating bar as reported in [137].

The solution features a MEMS clamped-clamped mechanically resonating bar. One driving and one sensing electrodes are deployed on both sides [137]. As visible in the schematic, the MEMS resonator is also connected to two branches in parallel, each provided with a switch. Depending on the ON/OFF state of the switches, an electric current is driven through the mechanical bar, thus heating the structure due to thermo-electromechanical coupling and displacing, in turn, the MEMS resonant frequency. Such a modulation carries the logic output of the gate that, in this case, is an AND.

Just to mention a different operation approach still based on MEMS micro-structures, the work in [138] discusses a variable capacitor realizing low power adiabatic logic gates with high states differentiation.

2) MEMORY CELLS

Entering now the field of memories, MEMS and NEMS technologies have been investigated since more than one decade to realize highly-integrated, non-volatile and ultra-low power consumption basic units.

To this end, the work in [139] shows a MEMS mechanical resonator that implements logic/memory functionalities. The “0” and “1” logic states differentiation leverages the typical non-linear hysteretic behavior of resonators, when the frequency of excitation is swept up and down, with respect to the fundamental resonance. A similar approach is reported in [140], despite in this case the mechanical resonator is fabricated in NEMS technology, pushing miniaturization ahead.

Another solution relies on electrostatically actuated NEMS nano-switches, both configured as cantilevers and clamped-clamped membranes. Leveraging the typical pull-in/pull-out behavior of such devices, the “0” and “1” logic states are inherent to hysteresis of actuation/release voltage thresholds.

Given this frame of reference, a significant contribution is discussed in [141], where NEMS nano-relays are fabricated exploiting a few steps of a CMOS technology. The schematic cross-sections in Fig. 13a and Fig. 13b sketch the “0” and “1” NEMS switch configurations, respectively.

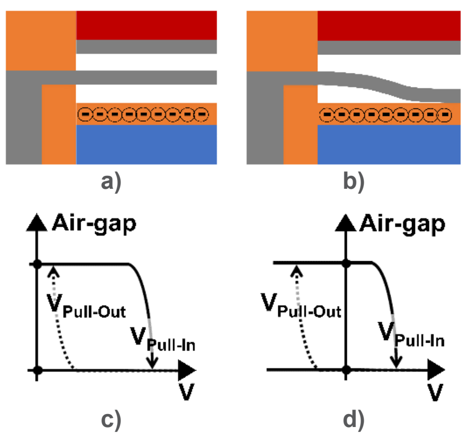

FIGURE 13. Schematic cross-section of the NEMS switch in [141] in the “0” (a) and “1” (b) state. c) Typical pull-in/pull-out hysteresis of switches driven by electrostatic (capacitive) coupling. d) Displaced hysteresis by means of the underneath layer with entrapped charges.

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The intrinsic limitation of electrostatic switches is that they are monostable. This means that just the rest position is stable, while the actuated configuration needs to be maintained by keeping the DC bias imposed. The typical hysteresis of such devices is shown in Fig. 13c. The advancement proposed in [141] is that of trapping a certain amount of charge within a layer accommodated underneath the NEMS membrane (see Fig. 13a and Fig. 13b). This way, the hysteretic characteristic of the switch is displaced to the left and centered around 0 V. Such a solution makes the device bistable, and external energy has to be applied only for programming the bit state, and not anymore to keep it.

Still based on NEMS nano-switches, other contributions explore the employment of thin-films with ferroelectric properties to achieve bi-stability of devices, and, in turn, non-volatility of the stored information [142], as well as the exploitation of CNT-based NEMS structures [143],[144].

Another class of devices, orthogonal with respect to what discussed up to here, is that of memristors, i.e., memory resistors. Memristors were discussed for the first time in 1971 [145], and depicted as the fourth still missing element, after resistors, capacitors and inductors, defining the relationship between charge and flux, as sketched in Fig. 14.

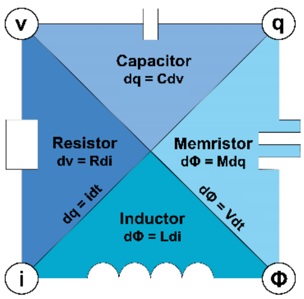

FIGURE 14. **Schematic representation of the relationship between voltage (v), current (i), charge (q) and flux (Φ), realized by resistors, capacitors, inductors and memristors.**

Despite theorized since half a century, memristors were experimentally demonstrated just about one decade ago [146],[147]. Among the various potential exploitations, non-linearities of the charge-flux relationship attract particular attention, as they enable mimicking synaptic plasticity of neuronal system, opening to human-inspired storage and elaboration of information [148]. To this purpose, the work reported in [149],[150] threw light on the possibility of stacking memristors according to 3D arrangements, resembling human brain *architecture*. Technological advancements of memristors are also discussed in literature. For instance, the work in [151] focuses on a three terminals device. The additional terminal enables better control and wider tunability of the memristor configurations.

D. MULTI-SOURCES ENERGY HARVESTING (EH) CONVERTERS AND PLATFORMS – FIRE

Moving away from Water-like and Water-Air interactions of HW and SW, the attention is now oriented to the Fire element within the frame of the WEAF Mnecosystem. As brief recap, Fire-like HW are miniaturized transducers and devices devoted to the conversion, storage and distribution of energy, to power pervasive sensing, actuating and small data elaboration, at the network edge.

Having said that, pivotal technologies that capitalize on Micro/Nano devices are EH, WPT and miniaturized energy storage units, as summarized in Fig. 15.

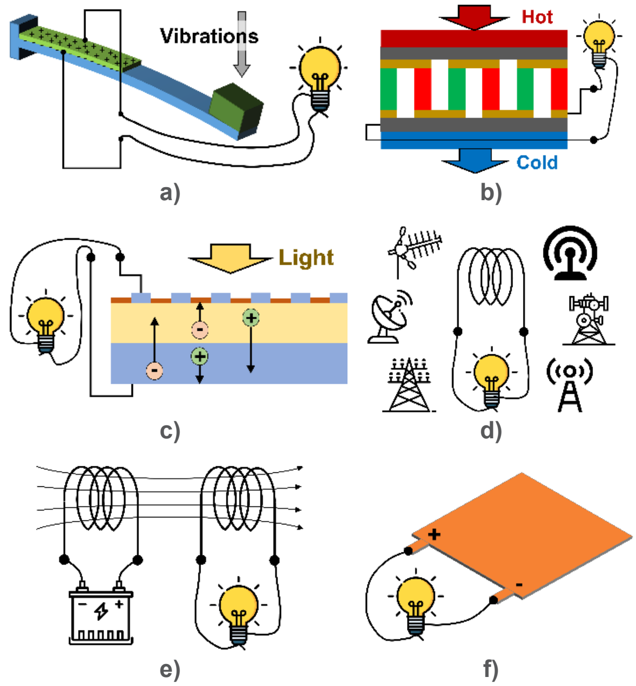

FIGURE 15. **Schematics of EH principles for the conversion of energy from: a) mechanical vibrations; b) heat and thermal gradients; c) light (indoor/outdoor); d) EM waves in the environment. e) Transfer of energy by WPT. f) Miniaturized thin-film batteries. [Some of the thumbnails used to compose the graphics are powered by Freepik.com].**

The scientific literature is rich of contributions discussing the just mentioned topics. In particular, EH is undoubtedly the most populated of items, as it has been investigated since longer. More details are reported in the following subsections.

1) ENERGY HARVESTERS

As shown in Fig. 15, EH has to do with the conversion into electricity of part of the energy available in the surrounding environment. The sources of energy can be classified as mechanical vibrations, heat and thermal gradients, light (solar and artificial), as well as EM radiation.

Concerning the latter one, a couple of additional considerations are due. First, EM waves scattered in the environment are not *natural* in the strict sense, as are mainly the consequence of human activities. However, they are so common that can be regarded as a source almost always and nearly everywhere available for EH purposes, as well as vibrations, heat and light are. Second, at a glance EH from EM sources and WPT could look like two different names indicating the same thing. In fact, they are radically different. As a matter of fact, EH aims at catching and converting part

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of the energy of EM waves scattered in the environment for other purposes, like for telecommunications, radio/television signals, mobile devices, radars, etc. Differently, the target of WPT is that of delivering energy wirelessly, *broadcasting* it from a source to a specific target located elsewhere.

As far as EHs in the field of mechanical vibrations conversion are concerned, the scientific literature is populated by many contributions. In particular, this is true when dealing with piezoelectric [152]–[154], electrostatic (capacitive) [155],[156], and magnetic transduction [157],[158]. In addition, the combination of multiple transduction techniques, along with the development of ad-hoc designs, are investigated with the target of extending operability of EHs over wider frequency ranges of vibrations [159]–[161].

Moving now the focus on EH devices that address heat and thermal gradients, the research community reported several contributions discussing the realization of miniaturized thermocouples in semiconductor technologies, opening up to significant miniaturization of the energy converters [162]–[164]. Moreover, as for other classes of micro- and nano-devices, *More than Moore* technologies are also analyzed against their exploitation in thermal EHs. To this end, e.g., CNTs are discussed in [165]–[167].

Besides, EHs addressing heat and thermal gradients are also implemented according to strategies orthogonal to the use of thermocouples. The work in [168] discusses a bi-layer structure, including piezoelectric material, which is subjected to mechanical buckling when exposed to an heat source.

When light as an energy source is at stake, it must be stressed that research and development around photovoltaic cells is mature. Nevertheless, in recent years, the increasing diffusion of pervasive low-power applications, mainly driven by the pivotal paradigms of IoT and IoE, are driving research advancements around miniaturization of light-based EHs [169]–[171]. Given such a context, indoor application scenarios are attracting particular interest [172].

Entering the field of EHs converting EM radiation dispersed in the environment, the scientific literature discusses several relevant works, both targeting optimization of antennas capturing radiation and of conversion circuits [173]–[176]. The work in [177] shows a miniaturized rectifying antenna (rectenna) monolithically structured above semiconductor-based diode (i.e. conversion electronics), characterized at 60 GHz. Also interestingly, the possibility of exploiting metasurfaces (discussed later) is becoming attracting for EM harvesting, providing significant room for miniaturization down to the millimeter range [178],[179].

2) WIRELESS POWER TRANSFER

As already pointed out, given the trending need in providing energy to remote sensing nodes (in the IoT scenario and beyond), powering strategies are of particular interest. To this end, WPT is certainly an attractive solution, especially in scenarios in which remote devices to be powered are difficult if not impossible to reach (implantable devices), like it is in medical and health monitoring applications [180],[181].

In a nutshell, in WPT systems, energy can be transmitted according to two different ways of linking the active (Tx) to the passive (Rx) coil, i.e., RF or inductive coupling, with a plethora of pros and cons of one against each other [182].

The significant room towards miniaturization of WPT devices is pushing research around the integration of Rx antenna with power extraction interface electronics and storage [183]. Besides, further aspects are being investigated, like, e.g., waveform design, to optimize power transmission performances [184], and the possibility of transmitting data over power, exploiting a unique RF link [185].

3) MINIATURIZED BATTERIES

Concluding the overview of Fire-like HW within the WEAF Mnecosystem, the remarkable opportunities offered by Micro/Nano technologies are of significant interest in the field of batteries miniaturization. In particular, as for the previous categories of devices mentioned, thin-films deposition techniques, typical of microelectronics, result to be significantly beneficial to the realization of tiny power units. To this end, the work in [186] discusses the realization of amorphous lithium-ion films by means of RF sputtering, with deposition of top and bottom metal electrodes within the same micro-fabrication process. Besides, the feasibility of microelectronic technologies for this type of devices is driving research around fabrication techniques and materials properties optimization for thin-film batteries [187],[188]. To this regard, among diverse solutions, the possibility to realize miniaturized batteries on flexible substrates, particularly suitable for applications in wearable devices, deserves to be reported [189].

4) MULTI-SOURCE PLATFORM

As just discussed, research and development on micro-/nano-level conversion, transfer and storage of energy is reasonably mature, despite some topics, like, e.g., WPT, are more recent than EH. Yet, the actual change of paradigm for the concept of energy, as meant by the Fire element within the WEAF Mnecosystem, needs further integration and diversification to be properly deployed. In fact, it is difficult to envisage energy as an HW-independent entity, flowing here and there at the network edge, when relying just on one or a couple of the items graphically summarized in previous Fig. 15. This is because energy available in the environment in a certain moment might not match the network demands at that specific time.

In light of this statement, it is a solid belief sustained by this work that a critical direction to pursue in future research is that of integrating as many of the principles and devices in Fig. 15 as possible, within the same HW platforms.

Given such a frame of reference, the scientific literature reports interesting investigations on the integration of diverse EH converters, from the points of view of design and architecture of interface electronics, necessary to optimize energy extraction [190]–[192]. To this end, two relevant aspects must be kept in mind.

First, depending on the class of device (e.g., EH, WPT), the addressed energy source (e.g., light, vibration, heat) and the EH transduction mechanism (e.g., piezoelectric, electrostatic), the electric output available to the extraction circuit can significantly vary in terms of impedance, frequency, voltage/current provided, etc. This makes simultaneous management of such diverse devices not a trivial task.

Also importantly, it should not be forgotten that interface circuitry itself needs power to extract energy from the converters and store it in a battery. Therefore, the need to keep power consumption of the entire module as low as possible, makes even more complex the design phase of the sub-system.

As far as energy converters are concerned, most of the contributions reported in literature around multi-source EH platforms rely on commercial or lab-based prototypes realized in standard technologies, i.e., not based on semiconductor and/or Micro/Nano technologies [193],[194]. On the other hand, the option of integrating diverse EHs in silicon-based technologies is still partially covered by scientific publications, despite it is very likely to turn into an hot topic in the time to come. To this purpose, a remarkable example is discussed in [195], where optical and thermal EHs are monolithically realized within the same CMOS-compatible micro-fabrication process.

E. MISCELLANEA – EARTH

The previous discussion was an attempt to review and highlight state of the art research activities, topics and technologies envisioned as falling within the WEAF Mnecosystem. Given the intrinsic novelty of HW reconceptualization led by Water and Fire, the research items above are mainly centered around such elements. This does not mean that reported items cover all the possibilities available in literature. More reasonably, they are and must be interpreted as a limited set of examples, relevant to the purposes of this work, that would definitely benefit if extended, integrated and reshaped by the reader.

On a different perspective, the Earth element, related to the classical concept of HW, remained untouched up to this point, despite its role is of prime importance, as well. In fact, Earth is the source of consolidated or emerging technologies, which can trigger unprecedented solutions, breaking the boundary to Water, Water-Air and Fire elements, thus providing further momentum to the increase of HW abstraction in the 6G scenario.

Given this preamble, a brief list of research areas, technologies and devices falling into the Earth category, is developed in the following. Regardless of their TRL, all those categories are predicted to provide significant contribution in populating the WEAF Mnecosystem scenario.

1) RF-MEMS

Passive RF components in MEMS technology have been investigated for about two decades, showing remarkable characteristics in terms of large reconfigurability/tunability, frequency agility, low-loss, high-isolation, very-low power consumption, etc. [196]. Since several years, RF-MEMS technology started to be employed in mass-market applications [197], with 4G/5G smartphones first in line.

Among their typical features, RF-MEMS enable to scale up complexity of the RF passive device of interest, merging together diverse conditioning functions of RF signals, like switching, delay/phase shift, attenuation, coupling, and so on. Moreover, MEMS-based RF passives have been recently characterized in the (sub-)THz range [198],[199].

All the mentioned characteristics, confronted against 6G requirements discussed above, make RF-MEMS an interesting technology tile for future networks applications.

2) METASURFACES AND METAMATERIALS

Metamaterials, recently more commonly addressed as metasurfaces, are known in literature since years for realizing physical characteristics, e.g., optical, acoustic and electromagnetic, of materials that are not available, nor existing in nature [200].

The mentioned behavioral features, joined to the possibilities of miniaturization, triggered by their implementation in CMOS-compatible/-like technologies, the latter increasing their reconfigurability and tunability, as well, are making metasurfaces particularly attractive for smart antennas realizations [201],[202]. These devices, currently investigated in the frame of 5G, will certainly have an important role in 6G.

3) FLEXIBLE ELECTRONICS

The option to manufacture Micro/Nano devices on flexible substrates, e.g., sensors, actuators, antennas, along with transistors, electronic circuits and displays, has been investigated in literature since long [203]–[205]. Materials with flexible properties can come both from thinning down of silicon wafers, or from employment of natively flexible substrates, like polymer foils, with flattering opportunities in terms of low-cost and large-area (panel-like) manufacturing solutions.

Given these premises, flexible electronics are gathering interest in the field of IoT and wearable applications [206]–[208], while increasing room for their exploitation can be forecasted in 6G and future networks.

4) HETEROSTRUCTURES-BASED SEMICONDUCTORS

Falling into the riverbed of the *More than Moore* philosophy, stand semiconductor devices leveraging hybridization (i.e. hetero-structuring) of standard silicon-based processing steps, with materials other than silicon, like graphene, silicon carbide, gallium arsenide, silicon carbide, etc. [209]–[211]. Depending on the material/s employed, heterostructures transistors enable performances and characteristics that are unknown to classical all-in-silicon CMOS-like technologies. Among the most relevant, it is worth mentioning increased power handling [212] and higher electrons mobility, the latter making such devices suitable to work in high-frequency ranges, like mm-Waves and above [213],[214].

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Also relevantly, such hybrid devices can be manufactured with low-cost processes [215], and can be synergetic to flexible electronics techniques, mentioned in the previous point. To this end, it must be stressed that the option of structuring transistors according to a vertical, rather than classical planar, arrangement of layers and their interfaces, opens to the exploitation of novel deposition and patterning techniques, orthogonal with respect to those of classical CMOS processing. This is, for instance, what happens with the so-called FinFET transistors [216].

5) DEVICES FUSION THROUGH PACKAGING AND INTEGRATION

This field of technology would probably require a dedicated article as long as the current one to be properly reviewed and highlighted. In simple terms, it can be stated that the realization of diverse and complementary components within a unique fabrication technology, i.e. according to monolithic approach, is a viable option to pursue, as also previously stressed in this work.

However, when the all-in-one chip manufacturing regards physical objects typically realized with radically diverse and often incompatible technologies, like active CMOS electronics and MEMS/NEMS sensors, the monolithic option, despite still technically possible, can turn into a much less wise solution from other perspectives. In fact, aspects like excessive process complexity and the consequent low yield, diversity of area occupation and of footprint, incompatibility and interference of technology steps (e.g. in terms of thermal budget), poor reliability, high costs, and so on, suggest looking for different strategies.

Diversely, methods, techniques and technologies for encapsulation, shielding, protection and packaging of HW devices [217],[218], components and building blocks, offer nearly unimaginable enabling solutions for integration of physical items, within the so-called SiPs [219], also capitalizing on 3D (vertical) stacking of modules [220].

Advanced packaging makes possible waiving all the issues listed above, inherent to the heterogeneous manufacturing of pieces of HW, also easing electrical signals interfacing. In light of these considerations, the impact that such solutions can bring in the field of 6G can be easily sketched.

6) ADDITIVE MANUFACTURING

Away from the scattered field of semiconductors-driven micro-/nano-fabrication technologies and techniques, falls the emerging scenarios of AM and 3D printing. These terms unroll a widely scattered ground of technical solutions and materials employment, like powder or polymer based, electrically conductive and insulating, which provide developers with a remarkably extended set of degrees of freedom [221]–[225].

As already stressed for previous items, also AM carries valuable potential in light of the HW needs of 6G and future networks, especially at the edge. To this end, given the increasing trend to low-cost and large-surface manufacturing processes, various hybridizations of AM and 3D printing with one or more of the previously reviewed technologies, are likely to be ventured in the time to come.

7) PHOTONIC DEVICES

As it is verified substantially for most part of the items discussed up to here, optical devices significantly benefited from miniaturization and integration offered by Micro/Nano technologies. Since decades, objects like micro-mirrors, (split) ring resonators, couplers, switches, often coupled to optical fibers [226]–[230], exploited as sensors, actuators and transducers, have been widely investigated and reported in literature.

Given the emerging KETs of 6G, among which the exploitation of optical frequencies for communications, possibly including VLC, must certainly be mentioned, a pivotal role can easily be imagined for photonic devices, also breaking into the field of quantum phenomena, as reported in the following point.

8) QUANTUM TECHNOLOGIES

As last item, not certainly because of scarce relevance, the field of QTs must be reported. The scientific community is increasingly active in studying the exploitation of quantum phenomena in Micro/Nano technologies-based devices, aiming at practical applications in the fields of cryptography, telecommunications, computation, etc. Particular attention is devoted to photonic devices working in the quantum domain, as well as to miniaturized objects merging optical and RF signals [231]–[234].

VII. SUMMARY OF MICRO/NANO TECHNOLOGIES QUANTITATIVE PERFORMANCES

The extensive discussion developed in the previous section was mainly qualitative. This choice was driven by the need of harmonizing the concept of WEAF Mnecosystem with significant state of the art items that already today are compliant with the envisioned 6G future needs for HW.

The target of this final section is to cover the missing part of quantitative information around the studied literature. To this end, the following content is arranged in tables (from Table 2 to Table 8), reporting brief notes and, whenever available, numerical performances of several of the scientific works mentioned in the previous pages and, when needed, of additional works, as well.

Tables are arranged following the logical sequence of subsections reported in the previous pages, and are split according to the specific element of the WEAF Mnecosystem involved in the discussion. In details, Water-Air Evaporation is covered by Table 2, Water is discussed in Table 3, while Air-Water Condensation is reported in Table 4 and Table 5. Moreover, Table 6 and Table 7 deal with Fire, and finally Table 8 reports Earth-like examples. It must also be stressed that each table indicates the particular section/subsection of the paper where the corresponding entry is discussed, or to which it logically refers, in case of not-cited-before references. Eventually, progressive numbering of entries keeps constituency between subsequent tables.

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TABLE II
SUMMARY OF WEAF MNECOSYSTEM-COMPLIANT MICRO/NANO SOLUTION IN LITERATURE RELATED TO WATER-AIR EVAPORATION

No.	Sec./ Subsec.	Category	Description	WEAF overlap	Relevant features	Ref.
1	6.A.1	Self-healing material	CNTs as fillers to trigger self-healing EMI shielding properties	Water-Air Evaporation	Initial EMI shielding capacity of 30.7 dB (5% CNT in weight) in the X-band (8.2–12.4 GHz), recovers from 16.8 dB (damaged) to 29.8 dB after three times cut/healing (thermal) cycles	[110]
2	6.A.1	Self-healing material	Thin-film of semiconductor material with heat-triggered self-healing properties	Water-Air Evaporation	Resonant frequencies, modes shapes and Q-factor observed. Ultrasonic vibrations and 20-100 °C thermal cycles for accelerated aging and damage. Subsequent thermal treatment improves the resonant behavior	[117]
3	6.A.1	Self-healing material	Elastometer with large actuation strain	Water-Air Evaporation	When dielectric breakdown occurs, sparks locally burn the top and bottom conductors, turning them into insulators, thus eliminating the conducting path through the dielectric. The actuator recovers operability after multiple breakdown events	[235]
4	6.A.2	Self-healing mechanism	Cantilevered vibration EH-MEMS with piezoelectric conversion	Water-Air Evaporation	Array-based piezoelectric layer, with smaller capacitor where mechanical strain is larger. Capacitor/s where failure occurs is/are excluded according to anti-fuse approach. At 1 kHz vibrations and 1 kΩ load, the EH-MEMS generates 100 mV. Excluding the damaged capacitor, the output voltage drops to 87 mV, yet the device still works	[119]
5	6.A.2	Self-healing mechanism	Cantilevered RF-MEMS switch with active recovery device	Water-Air Evaporation	Cantilever-type RF-MEMS series ohmic switch with embedded serpentine-shaped micro-heater. The switch is intentionally brought to stiction (malfunctioning) due to micro-welding of contacts. The micro-heater is then activated with pulsed 2 mA current (1 s period; 50 % duty-cycle). After 30 s the switch recovers operability. Simulations show about 400 µN induced shear force due to pulsed heating	[122]
6	6.A.2	Self-healing mechanism	Pressure sensor based on shape memory polymer	Water-Air Evaporation	3D capacitive pressure sensor based on shape memory polymer, restoring its functionality when heated at 70 °C for 30 s. It is applied for in-shoe pressure measurements. Standard sensors are destroyed after 100 cycles (i.e. steps) at 410 kPa load. The shape memory sensor recovers its structural integrity with the heat normally present in the shoe and was tested up to 1000 cycles, with 0.0247 kPa^{-1} sensitivity	[125]

TABLE III
SUMMARY OF WEAF MNECOSYSTEM-COMPLIANT MICRO/NANO SOLUTION IN LITERATURE RELATED TO WATER

No.	Sec./ Subsec.	Category	Description	WEAF overlap	Relevant features	Ref.
7	6.B	Multi-functional device	Monolithic multi-sensors device	Water	Five sensors (temperature; corrosion; relative humidity; gas; gas flow) monolithically realized in a 3 x 3 mm^2 silicon chip. The MEMS process is CMOS compatible. Signal conditioning circuitry is designed in the same MEMS sensors chip. The whole demonstrator system is 10 x 10 mm^2	[126]
8	6.B	Multi-functional device	Monolithic in-package multi-sensors device	Water	Five sensors (electric field; accelerometer; humidity; temperature; pressure) monolithically realized in a 10 x 10 mm^2 silicon chip. The MEMS process is based on surface and bulk micromachining steps on SOI wafer. The electric field sensor and accelerometer are in a vacuum thanks to hermetic packaging with TSVs for signal redistribution. The other sensors are exposed. The five sensors combine capacitive, piezoelectric and resistive transductions	[129]
9	6.B	Multi-functional device	Unique transducer with multiple functionalities	Water	Classical dual-mass interdigitated capacitive inertial sensor design, working as environmental temperature sensor, ambient pressure sensor, accelerometer and gyroscope. The device (2.5 mm^2) is realized in a 0.18 µm CMOS MEMS/ASIC technology	[130]
10	6.B	Multi-functional device	Monolithic multi-sensors device on flexible substrate	Water	Multi-sensors platform that senses at the same time pressure, temperature, strain and humidity under various deformations. Deposition and patterning of metal layers, polyimide and PDMS are performed on a silicon substrate according to a CMOS compatible process. Finally, the wafer is back-etched down to 20 µm thickness, making the multi-sensors device flexible	[131]
11	6.B	Self-powered sensor	Smart-skin MEMS flow sensor	Water (Fire)	The sensor is realized in MEMS technology and features a 2D array of 20 (5 by 4) 2.7 mm tall hair-cell flow sensors deployed on a 30 x 40 mm^2 area. Piezoelectric transduction is used both for sensing flow and powering the sensor. Each individual sensor is sensitive to flow velocities as low as 8.24 µm/s. The whole array of sensors detects the location and distance of the underwater stimulus with an error below 1 %	[133]

TABLE IV
SUMMARY OF WEAF MNECOSYSTEM-COMPLIANT MICRO/NANO SOLUTION IN LITERATURE RELATED TO AIR-WATER CONDENSATION (CONTINUES IN THE NEXT TABLE)

No.	Sec./ Subsec.	Category	Description	WEAF overlap	Relevant features	Ref.
12	6.C.1	Logic circuit	XOR, AND, half-adder	Air-Water Condensation	Three-point anchored F-shaped MEMS resonating structure. The longer beams (400 µm long) are arched, while the shorter beams (120 µm long) are straight. The transduction mechanism is electrostatic and the device is provided with a couple of electrodes to excite mechanical resonance, plus two couples of electrodes, for logic inputs and outputs. The two arched bars resonate at 69.76 kHz and 86.25 kHz, respectively. The "0" or "1" inputs do not affect resonant frequencies but their amplitude, observed in terms of S21 (transmission) parameter. The same device can realize XOR and AND (2 inputs; 1 output) basic gates, as well as a half-adder (2 inputs; 2 outputs). Power consumption of logic operations is in the femto-Joule (fJ) range	[134]
13	6.C.1	Logic circuit	XOR	Air-Water Condensation	NEMS cantilever (4 µm long) with embedded diodes. It exploits anisotropic properties of piezoelectric material to obtain cancellation of vibration motion when input signals are imposed. Operation time is around 0.2 ms, while power consumption per operation is as low as 10^{-18} J	[236]
14	6.C.1	Logic circuit	NOR/OR, NAND/AND	Air-Water Condensation	Clamped-clamped electrostatically actuated MEMS bar exploiting bi-stability of hysteretic behavior of non-linear resonator to realize logic functions. The time per operation is around 0.2 ms while the power consumption is around 10^{-17} J	[237]
15	6.C.1	Logic circuit	Reversible gate operating as AND, OR, NOT, FANOUT	Air-Water Condensation	Multiple clamped-clamped electrostatically actuated MEMS bars (20 µm long) implementing diverse logic functions by means of the resonant frequency shift. The time per operation is around 0.2 µs while the power consumption is around 10^{-17} J	[238]
16	6.C.1	Logic circuit	AND, OR, XOR, multi-bit gates	Air-Water Condensation	Piezoelectrically driven clamped-clamped MEMS membrane (260 µm long; 84 µm wide) exploited as parametric resonator. The device mixes different inputs whose logic state resides in the signals' frequency, generating oscillation states that carry the output logic information. The time per operation is around 0.83 s. Power consumption is around 10^{-14} J	[239]
17	6.C.1	Logic circuit	XOR, AND, NOR, OR, NOT	Air-Water Condensation	Cantilevered NEMS structure (10 µm long) electrostatically controlled, facing two opposite drive electrodes plus one sense electrode. The device exploits resonance frequency tuning, depending on logic inputs, to carry the output logic information. The time per operation is around 200 µs. Power consumption is around 10^{-15} J	[240]
18	6.C.1	Logic circuit	NOR, NOT, XNOR, XOR, AND	Air-Water Condensation	Clamped-clamped MEMS bar (15 µm long) kept in oscillation via electrostatic actuation. The logic operation is performed through electro-thermal actuation, resulting in a shift of the resonant frequency that carries the logic output. The time per operation is around 35 µs. Power consumption is around 10^{-9} J	[241]
19	6.C.1	Logic circuit	OR, XOR, NOT, cascaded NOR	Air-Water Condensation	Clamped-clamped electrostatically actuated MEMS bar (600 µm long) with multiple electrodes for the application of logic inputs. The output information is carried by the activation/deactivation of second mode of vibration. The time per operation is around 35 ms, while the power consumption is around 10^{-13} J	[242]

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TABLE V
SUMMARY OF WEAF MNECOSYSTEM-COMPLIANT MICRO/NANO SOLUTION IN LITERATURE RELATED TO AIR-WATER CONDENSATION

No.	Sec./ Subsec.	Category	Description	WEAF overlap	Relevant features	Ref.
20	6.C.2	Memory / Logic circuit	Memory cell and OR/AND gate (MEMS)	Air-Water Condensation	MEMS mechanical resonator based on central suspended mass and interdigitated fingers, and counter-electrodes, for electrostatic excitation. The “0” and “1” information is stored in the amplitude of resonance, exploiting hysteresis. The device area is about 1 x 1.4 mm^2 and operation frequency is around 8.6 kHz	[139]
21	6.C.2	Memory	Memory cell (NEMS)	Air-Water Condensation	CMOS compatible NEMS cantilever and clamped-clamped bars electrostatically driven to keep their mechanical resonance. Hysteresis of resonance is exploited to dynamically keep the “0” or “1” information. Target storage density per area in the order of 140 $Mbit/m^2$	[140]
22	6.C.2	Memory	Memory cell (NEMS)	Air-Water Condensation	CMOS compatible NEMS cantilevers and clamped-clamped membranes (300 nm and 1000 nm long, respectively; 30 nm thick). The nano-devices implement electrostatically driven switches and they store the information within the ON/OFF input/output state. Electrostatic switches have a typical hysteretic behavior of ON/OFF state, i.e. pull-in/pull-out threshold, despite they are monostable (OFF state stable; ON state unstable, needing energy to be maintained). In this solution, proper amount of electric charge is injected in a thin-film insulator beneath the NEMS membranes. The built-in potential shifts the pull-in/pull-out characteristics, centering the middle point of hysteresis at 0 V bias. This makes the memory cells bistable, requiring energy only to shift the “0” or “1” stored information, not for keeping it	[141]
23	6.C.2	Memory	Memory cell (NEMS)	Air-Water Condensation	NEMS electrostatically driven switches using thin-films with ferroelectric properties (instead of injected charge like in [141]) to center the pull-in/pull-out hysteresis around 0 V bias axis, making the memory cell bistable	[142]
24	6.C.2	Memory	Memory cell (NEMS)	Air-Water Condensation	Preliminary studies on the realization of CNT-based NEMS suspended bars to be electrostatically driven like classical switches. Atomistic simulations are performed to optimize the NEMS structure in such a way that van der Waals forces are large enough to keep the switch ON state stable	[143] [144]
25	6.C.2	Memory	Memory cell (Memristor)	Air-Water Condensation	Neuromorphic system based on CMOS-compatible neurons and memristor synapses. The latter ones are able to mimic human-brain functions, like spike-timing dependent plasticity, enabling high connectivity and density for efficient computing	[148]
26	6.C.2	Memory	Memory cell (Memristor)	Air-Water Condensation	3D memory architecture based on silver-doped methyl-silsesquioxane arranged according to crossbar array configuration. The material is planar and easily patternable with lithographic techniques. Silver-doping provides resistive switching characteristics. Crossbar arrays can be as small as 100 nm	[149]
27	6.C.2	Memory	Memory cell (Memristor)	Air-Water Condensation	Thin-film memristor based on metal oxides, with an additional third electrode (i.e. gate controlled), enabling accurate and continuous setting of conductance over 3 orders of magnitude with 5 V gate voltage	[151]

TABLE VI
SUMMARY OF WEAF MNECOSYSTEM-COMPLIANT MICRO/NANO SOLUTION IN LITERATURE RELATED TO FIRE (CONTINUES IN THE NEXT TABLE)

No.	Sec./ Subsec.	Category	Description	WEAF overlap	Relevant features	Ref.
28	6.D.1	EH-MEMS	Vibrations, Piezoelectric	Fire	Silicon proof-mass suspended by flared-U shaped beams, obtained by MEMS bulk-micromachining technique. The whole device, i.e. MEMS mass-spring system plus surrounding frame, is 4 x 4 mm^2, while the proof-mass thickness is 300 µm. PZT is exploited for piezoelectric transduction. The EH-MEMS generates around 10 nW with vibration of 0.07 g at 30 Hz, scoring normalized volumetric power density around 2.6×10^{-2} $\mu W/mm^3/g^2/Hz$	[152]
29	6.D.1	EH-MEMS	Vibrations, Piezoelectric	Fire	Toggle-type EH-MEMS realized with bulk micromachining of SOI wafer and aluminum nitride for energy transduction. The device provides around 400 nW with 1.3 g acceleration at 1.6 kHz, with 1 MΩ load. Its volume is 1.94 mm^3 and the normalized power density is 240 $\mu W/g^2/cm^3$	[154]
30	6.D.1	EH-MEMS	Vibrations, Capacitive	Fire	Surface micromachined EH-MEMS, featuring metal suspended oscillating plates suspended with serpentine-shaped anchoring structures. The device generates 2.5 µW at 500 Hz when subjected to 15 V DC bias and accelerations above 5 g	[243]
31	6.D.1	EH-MEMS	Vibrations, Magnetic	Fire	Hybrid realization of a magnetic EH, with the proof-mass and flexible folded suspension fabricated in MEMS technology, while the stacked coils are implemented on standard flexible material. The whole in-package device has volume of 13 x 13 x 11.5 mm^3. The EH generates 208 mV and 10.5 µW, when undergoes 1 g acceleration at 143 Hz	[157]
32	6.D.1	EH-MEMS	Vibrations, Magnetic	Fire	Magnetic EH-MEMS, exploiting a double mass-spring system, with nested mechanical resonators, and non-linear springs, to broaden the frequency range of vibrations across which efficient power conversion is achieved. Continuous EH spectrum is demonstrated with 3 dB bandwidth of 65 Hz. The power output is 127 µW with 37.5 Ω load. The achieved normalized power density is 1064 $\mu W/cm^3/g^2$	[159]
33	6.D.1	EH-MEMS	Thermal	Fire	CMOS compatible thermoelectric EH-MEMS, exploiting phosphorous and boron heavily doped poly-crystalline thin-films, arranged in such a way to realize thermopiles. Top and bottom cavities are deployed to concentrate heat on proper terminations. Single device of 1 cm^2 generates 16.7 V and 1.3 µW with optimal resistive load, when subjected to 5 K temperature drop	[244]
34	6.D.1	EH-NEMS	Thermal	Fire	Textile (wearable) thermoelectric EH based on CNTs. The work estimates various configurations, among which the one related to a 44 mm long fiber generates 55 µV when subjected to 1 K temperature difference	[166]
35	6.D.1	EH-MEMS	Light	Fire	Exploitation of light-induced thermal energy leveraging piezoelectric and pyroelectric properties of PVDF. Over a 8 cm^2 area exposed to illumination, with temperature variation of 5.7 °C, the PVDF foil generates 413 nW, with 4.3 V and 96 nA	[169]

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TABLE VII
SUMMARY OF WEAF MNECOSYSTEM-COMPLIANT MICRO/NANO SOLUTION IN LITERATURE RELATED TO FIRE

No.	Sec./ Subsec.	Category	Description	WEAF overlap	Relevant features	Ref.
36	6.D.1	EH-MEMS	EM	Fire	Bow-tie rectifying antenna (rectenna) monolithically integrated with a metal-insulator-metal diode, within a MEMS fabrication process, yielding a 4.5 x 4.5 mm^2 device. The EH is designed for the V-band (40-75 GHz) and was experimentally characterized at 60 GHz. The device delivers 250 µW from an impinging mm-Wave signal with -20 dBm power, leading to a voltage responsivity above 5 V/W	[177]
37	6.D.2	EH-MEMS	WPT	Fire	Implantable WPT system, with Tx and Rx circuitry realized in 0.35 µm CMOS technology. Silicon chips are smaller than 2 x 2 mm^2, while coils diameter ranges between 9.5 mm and 4 cm. The WPT system works at 13.56 MHz. Maximum received power and efficiency are 102 mW and 92.6 %. In dynamic (transient) conditions, the overshoot/undershoot are about 110 mV, while the settling time is below 130 µs	[183]
38	6.D.3	EH-MEMS	Battery	Fire	Miniaturized lithium-ion battery entirely realized in a microelectronic fabrication technology, capitalizing on amorphous thin-films. The battery is composed of a multilayer of lithium-doped vanadium oxide, lithium phosphorus oxynitride, and silicon, as cathode, electrolyte, and anode, respectively. The battery is realized both on glass and polyimide substrates. Its areas is around 2 x 2 cm^2. Measured charge and discharge peaks are around 4.2 V and 1.5 V. The initial area discharge capacity is 8.0 $\mu Ah/cm^2$ and 5.4 $\mu Ah/cm^2$, for glass and polyimide substrate, respectively	[186]
39	6.D.3	Multi-EH source	Extraction and storage system	Fire	Integrated modular multi-source system, collecting energy generated by two EH converters. Electronic circuitry is designed and realized in 0.18 µm CMOS technology, exploiting 900 pF metal-insulator-metal capacitance for storage. Expected results show maximum power point tracking efficiency of 90 %, charge pump efficiency of 70 %, as well as E2E efficiency of 55 % at regulated output voltage of 1.5 V	[190]
40	6.D.4	Multi-EH-MEMS source	Monolithic EHs	Fire	Multi-source EH-MEMS monolithically realized in a CMOS-compatible technology platform. The device features thermoelectric EH (thermopile) and a miniaturized solar cell. Proper selectively patterned insulating layers and openings allow optimal operation of both converters. Concerning thermal EH, maximum output voltage factor and power factor are 0.316 $V/cm^{-2}/K^{-1}$ and 6.34×10^{-3} $\mu W/cm^{-2}/K^{-2}$, respectively. Differently, when the multi-EH is operated as solar cell, measured efficiencies are 4.11 % and 0.5 %, respectively	[195]

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TABLE VIII
SUMMARY OF WEAF MNECOSYSTEM-COMPLIANT MICRO/NANO SOLUTION IN LITERATURE RELATED TO EARTH

No.	Sec./ Subsec.	Category	Description	WEAF overlap	Relevant features	Ref.
41	6.E.1	RF-MEMS	Ohmic series micro-relay	Earth	Electrostatic series switch realized in a surface micromachining RF-MEMS technology. The simulated pull-in voltage is around 20 V, despite the presence of residual stress within the MEMS suspended membrane increases it to around 50 V. When OPEN, isolation (S21 parameter) is better than -20 dB up to 30 GHz. When CLOSE, insertion loss (S21 parameter) is better than -1 dB up to 40 GHz	[245]
42	6.E.1	RF-MEMS	Packaged shunt micro-relay	Earth	Electrostatic shunt RF-MEMS switch packaged within a rectangular microstrip waveguide. The design accounts for reduction of the equivalent parallel switch inductance, thus enabling low-losses in the sub-THz range. Measured insertion loss (S21 with CLOSE switch) is better than -2 dB in the 220-280 GHz range, while isolation (S21 with OPEN switch) is around -16 dB in the 240-320 GHz range. The switch actuation voltage is around 30 V	[199]
43	6.E.2	Metasurfaces	Planar antenna for beamforming	Earth	Planar lens antenna featuring a linear array of Tx/Rx elements for spatial beamforming and multibeam massive-MIMO. The lens is formed by two-layer ultra-thin metamaterial surfaces, separated by air and fed by substrate-integrated waveguide-fed stacked patch antenna. The antenna reaches scanning coverage of ±27° with gain tolerance of 3.7 dB, maximum gain of 24.2 dBi with aperture efficiency of 24.5 %, in the 26.6-29 GHz frequency range	[246]
44	6.E.3	Flexible electronics	Transistors	Earth	Realization of thin-film transistors and electronics on flexible substates by means of inkjet printing and spin-coating. Silver interconnects with dimensions of 100 x 10-20 μm^2 are realized. Gate dielectric layer obtained by vapor polymerization of Parylene. By optimizing ink formulation and thermal annealing of organic semiconductors, p-type characteristics with mobility above 1 cm^2/Vs are achieved	[247]
45	6.E.4	Heterostructures	TFET	Earth	Review of various TFET realizations, with ultra-low quiescent current (around pA), high ON current (I_{ON}) and low OFF current (I_{OFF}). The work lists I_{ON}/I_{OFF} as large as 10^8 and 10^{12}	[248]
46	6.E.5	SiP	3D integration	Earth	Advanced fan-out wafer-level packaging solutions for hetero-integrated wafer-level SiP and 3D heterogeneous integration package. Such technologies enable integration of various functional dies, like, logics, memories, power ICs, RF active chips and passive components	[220]
47	6.E.6	AM	RF passives	Earth	Discussion of AM technologies for the realization of RF passive components and antennas. For instance, the review reports 3D-printed microstrip lines with performances similar to traditional copper tape (insertion loss below -5 dB up to 30 GHz), as well as microstrip antennas	[222]
48	6.E.7	Optical MEMS	Mirror	Earth	MEMS-based micro-mirror realized by bulk micromachining of SOI wafers, exploiting PZT for piezoelectric actuation. Dimensions of the intrinsic mirror, torsion suspending structures and actuators are 400 x 400 μm^2, 20 x 200 μm^2 and 600 x 1000 μm^2, respectively, while the thickness of the entire device is 5.3 µm. The micro-mirror exhibits a 3.58 degrees rotation when a 1 V peak-to-peak bias is applied at 10.4 kHz resonance	[226]
49	6.E.8	QTs	RF signal switching	Earth	Real-time RF signal switching technique based on polarization-dependent four-wave mixing in a highly-non-linear optical fiber. The discussed solution allows manipulation of multidimensional RF signals over tens of GHz, as well as frequency hopping and phase switching of GHz RF signal	[233]

VIII. DISCUSSION AND CONCLUSIONS

Future communication networks and application paradigms, with 6G, Super-IoT and TI first in line, are deploying demanding challenges that HW-SW systems will have to address, looking at the symbolic and practical deadline of 2030.

To date, while 5G is being unrolled, visions and prospects by eminent scientists sketch for 6G KPIs a 100 to 1000 times increase in comparison to what 5G will ever achieve. Also importantly, 6G network infrastructure is expected to implement self-adaptive, highly resilient and evolutionary features, thanks to the massive employment of AI, both at service and operation level.

In light of the just sketched scenario, this work states that classical approaches in the development of HW-SW systems, exploited for decades and still in use today with 5G, are not appropriate to face future challenges of 6G.

Building upon such a proposition, simplified analysis of what the 6G will be, in terms of high-level KPIs and KETs, was developed at first. Then, the concept of HW-SW divide, gathering all the identified limitations of current development approaches in the context of 6G, was analyzed in details.

The envisioned measure to bridge this gap builds around a conceptual reformulation of HW, increasing its level of abstraction, thus making it closer, for some features, to SW. This point was addressed by the introduction of the WEAF Mnecosystem scenario, i.e. an analogy between current and future features of HW, empowered by the exploitation of Micro/Nano technologies, and ideally linked to the four classical elements in nature (Water; Earth; Air; Fire).

Thereafter, a broad review of current state of the art in Micro/Nano technologies, systems (MEMS and NEMS), electronics and materials, was developed, both concerning their working principles and target performances.

The main target of the survey was to trigger the process of filling the currently empty space of the WEAF Mnecosystem, with classified sets of Micro/Nano technologies solutions, able to empower the above mentioned reconceptualization of HW, in view of 6G challenges.

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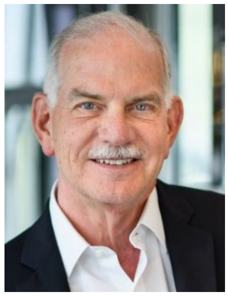

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