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Transformation to advanced mechatronics systems within new industrial revolution: A novel framework in Automation of Everything (AoE)

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ABSTRACT The recent advances in cyber-physical domains, cloud, cloudlet and edge platforms along with the evolving Artificial Intelligence (AI) techniques, big data analytics and cutting-edge wireless communication technologies within the Industry 4.0 (4IR) are urging mechatronics designers, practitioners and educators to further review the ways in which mechatronics systems are perceived, designed, manufactured and advanced. Within this scope, we introduce the service-oriented cyber-physical advanced mechatronics systems (AMSs) along with current and future challenges. The objective in AMSs is to create remarkable intelligent autonomous products by 1) forging effective sensing, self-learning, Wisdom as a Service (WaaS), Information as a Service (InaaS), precise decision making and actuation using effective location-independent monitoring, control and management techniques with products, and 2) maintaining a competitive edge through better product performances via immediate and continuous learning, while the products are being used by customers and are being produced in factories within the cycle of Automation of Everything (AoE). With the advanced wireless communication techniques and improved battery technologies, AMSs are capable of getting independent and working with other massive AMSs to construct robust, customisable, energy-efficient, autonomous, intelligent and immersive platforms. In this regard, rather than providing technological details, this paper implements philosophical insights into 1) how mechatronics systems are being transformed into AMSs, 2) how robust AMSs can be developed by both exploiting the wisdom created within cyber-physical smart domains in the edge and cloud platforms, and incorporating all the stakeholders with diverse objectives into all phases of the product life-cycle, and 3) what essential common features AMSs should acquire to increase the efficacy of products and prolong their product life. Against this background, an AMS development framework is proposed in order to contextualize all the necessary phases of AMS development and direct all stakeholders to rivet high quality products and services within AoE.

INDEX TERMS Advanced Mechatronics Systems, Wisdom as a Service (WaaS), Information as a Service (InaaS), Industry 4.0 (4IR), cyber-physical domains, cloud and edge/fog platforms, Automation of Everything (AoE).

I. INTRODUCTION

MECHATRONICS can be defined as "the synergistic integration of mechanical engineering with electronics and electrical systems using intelligent computer control in the design and manufacture of industrial products, processes, and operations [1]" to develop robust, cheaper, more reliable, more flexible and customisable products. Mechatronics systems (MSs) has evolved drastically since its invention by a Japanese engineer (T. Mori, Yasakawa Electric Co.) in 1969 to indicate "mecha" from mechanical and "tronics" from electronics, in particular, with the incorporation of information technology (IT). Machine technology, such as machine tools, power generators aims at relieving physical stress and strain on human beings, whereas electronics tech-

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nology along with IT aims at relieving mental strain of human beings [2]. Machine technology along with electronics and IT can substitute for human element in both physical and mental effort within multidisciplinary engineering. In this manner, the main driving force in MSs is to integrate technologies from traditional multi-disciplinary fields in engineering and computer science to develop well-established autonomous systems in new products. The integration of mechanical systems and microelectronics opens new possibilities for mechanical design and automatic functions along with the knowledge-based systems with learning abilities [3]. Increasingly, microcontrollers are embedded in electromechanical devices, creating much more flexibility and control possibilities in system design [4].

Bradley et al. [5] analysed the relationship between the Internet of Things (IoT) and mechatronics, and concluded that "the future, though challenging, is still seen as requiring mechatronics thinking. We entirely agree with this conclusion, yet with a different way of thinking. Mechatronics thinking has led to cyber-physical systems (CPS) and consequently smart domains which has changed our life significantly in the cloud platform. In this study, we are exploring Advanced Mechatronics Systems (AMSs) with respect to interconnected CPS where AMSs are taking their places in the market replacing the stand-alone MSs by involving a wider scope of stakeholders. The aim in AMSs development is to create high-quality intelligent autonomous products and maintain a competitive edge through better product performance by forging effective sensing, self learning, self-optimization, self-configuration, self-diagnosis and precise autonomous decision making and actuation with no or less human intervention using effective location-independent monitoring, control and management applications with products. AMSs are exploiting the wisdom created by CPS in the edge platform and primarily in the cloud platform along with the abilities of these platforms. With the advanced wireless communication techniques and improved battery technologies, AMSs are capable of getting independent and working with other massive AMSs to construct robust, customisable, energy-efficient, autonomous, intelligent and immersive platforms. In this context, we focus on AMSs that integrate various components to achieve more synergistic products in the light of advanced electronics, computers, intelligent software techniques, Industry 4.0 (4IR), cyber-physical smart domains, cloud and edge computing. More explicitly, this paper provides philosophical insights into AMSs regarding their present, past and future aspects.

The way of doing business has drastically changed with the smart applications/devices, where one is communicating to another within smart domains using the smart cloud and edge platforms. Smart platforms provide Machine-to-Machine (M2M) communication between smart objects with distributed intelligence and decision making capacity through integration of several technologies, such as sensors, actuators, identification, tracking, and enhanced communication protocols [6]. Millions of sensors and devices are continuously producing data and exchanging important messages via complex networks supporting M2M communications and monitoring and controlling critical smartworld infrastructures [7]. By 2022, Taylor [8] foresees that M2M traffic flows are expected to constitute up to 45% of the whole Internet traffic. We envision that smart domains and platforms will be the fundamental building blocks for the creation of AMSs and this M2M traffic rate will rise over 60% by 2025 with the new cutting edge communication technologies, such as 5G. Ultra-low latency is identified as one of the major requirements of 5G [9] . The importance of this research is derived from the fact that we studied the ways through which the cloud, fog/edge and AMSs concepts can be used in the context of smarter life within the Automation of Everything (AoE). Additionally, the life-time optimization, expressly, continuous improvement of currently used products and the products meeting the market is disclosed in this study, along with location-independent control and monitoring abilities in AoE using the wisdom created in both cloud and edge platforms and the abilities of these platforms in order to compose better products. To clarify the novelty of this paper, the contributions are outlined as follows.

1) To the extend of our knowledge, this is the first attempt that explicitly studies AMSs by forging the features of the smart domains, platforms, communication technologies, 4IR and mechatronics in a new concept - Automation of Everything (AoE), to enable the implementation of next-generation automation systems through exponentially revolutionising industry.
2) For the first time, the essential features of an AMS along with an explicit definition are revealed within a framework proposed.
3) The ways of producing cheaper and more effective AMSs with no or less number of sensors are proposed using Wisdom as a Service (WaaS) and Information as a Service (InaaS).
4) The ways of life-time optimisation of products, evolving products and technology generations within reduced design and run-time changes, in particular, in order to increase the customer satisfaction, are proposed.
5) The ideal framework of present and future technological products is presented with respect to AMSs considering the concept of the crucial features and architectures of AMSs within AoE.
6) New insights and design guidelines are provided for the companies that either use or produce IT and would like to lead the market in the near future.
7) Future of AMSs are analysed with respect to the emerging communication technologies, particularly promising wireless communication technologies.

The remainder of this paper is organized as follows. Section I provides a comprehensive state-of-the-art literature on the evolution of MSs. 4IR and its main components are presented in Section II. The CPS and smart domains, cloud and edge platforms are analysed in Section III. Section IV intro-

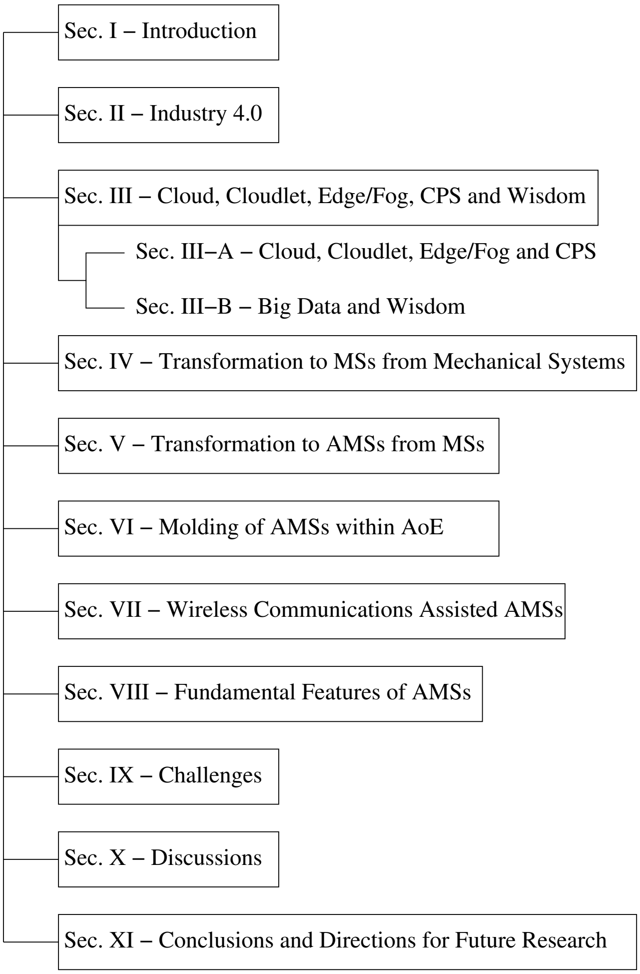

FIGURE 1: The structure overview of this paper.

duces the transformation to MSs whereas the AMSs concept and main components along with transformation phases are explored in Section V. The design and modelling of AMSs is addressed in Section VI along with a proposed architectural design (i.e., AoE) to shed light on how to develop AMSs in the context of the main components explained throughout the paper. The new cutting-edge communication technologies are disclosed in Section VII regarding their likely propulsion to the revolution of industry and AMSs. The essential features of AMSs within a proposed framework and challenges are revealed in Sections VIII and IX, respectively. Discussions are provided in Section X. Finally, Section XI draws conclusions and provides directions for potential future ideas. Readers are referred to Fig. 1 for an explicit structure overview of the paper.

II. INDUSTRY 4.0 (4IR)

Automation in industrial plants accelerated after the invention of PLC (i.e., programmable logic controllers) by General Motors in 1968 [10] along with the other controllers, such as PID (proportional-integral-derivative), SCADA (supervisory control and data acquisition) and DCSs (i.e., distributed control systems) by supporting enterprise resource planning (ERP) systems [11]. The industrial revolution after 4IR (i.e., the fourth industrial revolution) declared in Germany within a government high tech-project in 2011 has drastically changed the entire production cycle [12]. Computers and automation has come together in an entirely new way throughout smart automation, self-optimization, self-configuration, self-diagnosis/prognosis with robotics connected remotely to computer systems equipped with machine learning (ML) and artificial intelligence (AI) algorithms that can learn and control the robotics with very little input from human operators [13].

With the rapid development of electric and electronic technology, information technology and advanced manufacturing technology, the production mode of manufacturing enterprises is being transferred from digital to intelligent systems [14]. Within this industrial revolution, rather than applying a rigid mass production system, production automation is relying more and more of customisation of products with highly flexible (mass-) production which utilises relatively intelligent machines, that can adapt much more rapidly to product changes and unforeseen process events by maintaining a highly efficient production cycle [12]. 4IR aims to dramatically enhance the productivity of manufacturing technologies through the collection and analysis of real-time data [15]. In this context, MSs and IoT devices have evolved drastically in parallel with 4IR. The production of components needed for any system can be rapidly developed, which leads to efficient development of advanced products in the market with the help of the Industrial IoT (IIoT) [16]. In this manner, the immense growth of IoT devices comes right after this industrial revolution in 2011.

Innovative ideas have been concretized with the help of rapid production of the desired customisable products within this industrial revolution. Gordon Moore, co-founder of Intel, states that the number of transistors per square inch on a chip doubles every 18 months while the price is halved [17]. Consequently, the technological replacement period has been considerably reduced owing to those similar improvements. One improvement has led to another and vice-versa. IoT, particularly IIoT has enabled 4IR as a new manufacturing paradigm [18]. More than 3 million industrial robots will be serving in factories across the world by 2020 [19]. 4IR and similar initiatives are embracing the concept of "edge in the factory" where the decision-making process moves from cloud to edge; analytical algorithms can help realize such concepts, since cloud based solutions are not optimal for meeting the low latency demands of manufacturing processes and devices, mainly because of the large volume of data produced at a rapid rate [20]. We envision that the wisdom-driven manufacturing by exploiting the big data using advanced AI analytics will lead to perpetual and exponential revolution of the industry, and consequently products and services by incorporating contemporary communication technologies, e.g. 5G and beyond, into the production will enable powerful interactions with the cloud platform. Having

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described the range of new technologies that are fusing physical, digital and biological worlds, 4IR revolution is about to alter the way people live, work, and relate to one another [21].

III. CLOUD, CLOUDLET, EDGE/FOG, CPS AND WISDOM

A. CLOUD, CLOUDLET, EDGE/FOG AND CPS

The cloud platform has the advantages for massive storage, heavy duty computation, global coordination and wide-area connectivity, while the edge will be useful for real time processing, rapid innovation, user-centric service and edge resource pooling [29]. The cloud is approaching to the edge as the massive network in a wider infrastructure along with the deployment of multiple virtual machines (VMs) in numerous cloudlets by leading providers [30], which facilitates the reduced latency requirement of AMSs. Experimental results demonstrate that cloudlets can decrease the response time by 51% and diminish energy dissipation by up to 42% in a mobile device compared to cloud offload [31]. The main cloud platform providers, including IBM, Amazon EC2, Alibaba, Microsoft Azure, Fiware and Google are serving an open public network connecting businesses and individuals all around the world under an umbrella with the Infrastructure as a Service (IaaS), the Platform as a Service (PaaS) and the Software as a Service (SaaS). However, the emerging IoT introduces new challenges, such as stringent latency, capacity constraints, resource-constrained devices, uninterrupted services with intermittent connectivity and enhanced security, which cannot be adequately addressed by the centralized cloud computing architecture [29]. Mobile devices that are connected to distant centralized cloud servers attempting to acquire sophisticated applications impose additional load on both Radio Access Networks (RANs) and backhaul networks, which results in high latency [32]. The edge (or fog) computing is an emergent architecture for computing, storage, control, and networking that distributes these services closer to end users [29] to enable a more independent processing and organization. Both edge and fog computing attempts to achieve the same goal, but through different approaches: the fog computing moves intelligence to the IoT gateways or to the local area network, whereas the edge computing pushes intelligence to the edge devices - at the bottom of the architecture hierarchy [33]. The segmentation of what tasks go to the fog/edge and what tasks go to the back-end cloud is application specific and can change dynamically based upon the state of the network, including processor loads, link bandwidths, storage capacities, faulty events, security threats [34] and per user requirements.

The term mobile-edge computing (MEC) is also often used to indicate the edge platform that is an instance of edge computing where the objective is to provide cloud-computing capabilities at the edge of the cellular network using the radio-access network along with other wireless technologies [35], which integrates the MEC servers and cloudlet infrastructures [36]. There are several platforms provided by the leading companies to be employed as an immediate edge computing platform and gateway (GW) for specific types of smart domains, such as Apple Homekit, CISCO Fog Computing IOx, Google NEST, IBM Node-RED Bluemix, Intel IoT platform, Microsoft nitrogen.io. A laptop, a smartphone or a single board computing device (SBCD), such as Raspberry PI can serve as an edge platform. Noting that today several studies have been focusing on making these edge platforms more intelligent and stronger, as discussed in [20], [31] and [37] on which we will be focusing in this paper, while conceptualising the guidelines in AMSs development. The devices used in these smart cyber-physical platforms and domains are termed as IoT, which is firstly proposed by MIT (Massachusetts Institute of Technology) in 1999 [38]. International Telecommunication Union (ITU) suggested the term "Internet of Things" for official and common use among researchers, industries and end-users. IoT is internet-oriented (middleware), things oriented (sensors, actuators) and semantic-oriented (knowledge). Noting that "Internet of Everything" (IoE) and "Internet of Anything" (IoA) are also being used instead of IoT [1].

One of the first instantiations of a "thing" connected to the Internet was a modified soda machine at the Carnegie Mellon University in 1982, which could report its beverage inventory as well as the temperature of the beverages stored [17]. It's predicted that by the year 2020 more than 50 billion devices would be connected around the world [40], [41]. The number of connected things will exceed 7 trillion by 2025 which makes 1000 devices per person and an estimated value of 36 trillion of dollars [24]. We can safely conclude that the way of doing business regarding CPS stimulates a new industrial revolution despite many challenges, where the most critical ones are discussed in Section IX.

Amongst all 4IR technologies, IoT is set to have the most impact on industries in the future, as most devices will soon be able to collect or process data [21]. IoT with resource constraint characteristics is composed of physical objects embedded with electronics, software, and sensors, which allows objects to be sensed and controlled remotely across the existing network infrastructure, facilitates direct integration between the physical world and computer communication networks, and significantly contributes to enhanced efficiency, accuracy, and economic benefits [42]. These objects use new idiosyncratic protocols, such as the message queuing telemetry transport (MQTT) to overcome the compatibility issues of high latency networks with limited bandwidth often used for M2M communications [17] and other resource constraint issues. The IoT term is used as an umbrella keyword for covering various aspects related to the extension of the Internet and the Web into the physical realm, by means of the widespread deployment of spatially distributed devices with embedded identification, sensing and/or actuation capabilities [43]. IoT envisions a future in which digital and physical entities can be linked, by means of appropriate information and communication technologies such as Radio Frequency Identifier (RFID), Near Field Communication (NFC), Wifi or

[1]Readers can find the evolution of the IoT technologies in [39] and [27].

TABLE 1: Smart domains and their applications.

Main domains	Sub-domains	Applications	Benefits	Examples
Smart city	-public services -homes -buildings -health -transportation -parking spaces -environment -people -families -children -pets etc.	-public transportation (smart bicycle) -water management & power supply and energy management -waste management -urban mobility -emergency response -e-governance -environment monitoring (e.g.,people, flood, fire) [22] -disaster management [23] -intelligent parking spaces (creating congestion for looking for parking spaces) -intelligent street lighting -smart healthcare -entertainment [24] -smart mobility, smart economy, smart governance, smart people [25] -smart education [25]	-help to increase the environmental sustainability [24] -provides smart solutions to enjoy the personal stay [24] -reduced pollution (electrical vehicles, measurement of air quality) -reduced illegal actions (e.g., illegal dumping) -increased quality of life (e.g., better living environment, smart living, water quality sensors)	-88 smart city worldwide (e.g., Singapore, Barcelona, San Diego, Amsterdam, Dubai [25])
Smart building	-skyscrapers -big shopping malls -big buildings -buildings connected to each other	-environmental monitoring [22] -intelligent lifts, heating, cooling, room usage -smart door locks, smart switches, and smart lights [7] -functional spaces (Edge: space utilization: no dedicated desks/rooms) -efficient energy utilization (low greenhouse gas emission) -visual management (cameras, smartphone applications) -seamless communication/network connectivity -security integration (fire, e.g., 9/11: World Trade Centre) -prediction (prognosis) of potential failures,detection/fixing problems) -green buildings	-reduced operating cost -positive experience for everybody (customers, employees, visitors) -making buildings more energy-efficient [24]	-Edge building in Amsterdam (green, no dedicated rooms/offices)
Smart home	-houses -homes -summer villas -backyard -pool -garage -nursery room -living room	-intelligent heating -lighting adjusted for the time of day -intelligent appliances -security/fire/gas alarm using intelligent sensors (connected to police/fire department) -activation of IoT devices using voice -wireless home automation (connected IoT devices) -controlling appliances remotely using smartphone controllers -sequence of events specific to your needs in a variety -while leaving home (closing curtains, stopping tv/music/heating) -when coming home (opening curtains, heating home, turning on your favourite channel -before going sleep (turn off tv, all lights) -before/after waking up (turning on tv, preparation of coffee) -entertainment [24] -elderly and disabled assistance [24]	-cost reduction (e.g., energy efficiency (electricity, gas)) -comfortable, easier, happier and functional daily life -time saving	-Apple Homekit,//-starting a washing machine from workplace -adjusting the temperature of the home -turning on your lights when you are holiday -triggering the lights when a motion is detected
Smart health	-hospitals -ambulances -patients -healthy individuals -insurance companies -national and international health services	-smart hospital services [24] -automatic monitoring of personal health -wearable IoT devices, -intelligent ambulance services -intelligent hospitals (efficient diagnosis/prognosis) -telemedicine, visualisation of remote treatment [22] -integrated health records/integrated health units -strong data analytics -community health monitoring [26] -child Health Care [26] - drug administration [26]	-cost reduction -health monitoring -improved health services -quick response -better preventive health services -improved health and social care [24]	-automatic monitoring of personal health using implants or wearable devices
Smart transportation	-highways -city transportation -traffic management [24]	-intelligent traffic sensors (e.g., jam detection) -choosing better routes not jammed (loading new routes) -intelligent traffic lights -vehicles talks to other systems (traffic management systems, weather systems) -real-time intelligent traffic monitoring (counting of cars) -real-time intelligent monitoring (diagnosis/prognosis) of problems in vehicles and communicating with service provider automatically, -guiding the driver accordingly -systems package providing driver information and support, and including monitoring features, such as driver alertness and pre-collision detection -autonomous vehicles [27] -smart traffic [27], driving behaviour detection [21] -intelligent transportation and logistics [27] -vehicle positioning, scheduling and navigation [22] -road planning and route optimization [22], intelligent bike sharing	-delays can be reduced, 20% -reducing greenhouse gas emissions, 20% -self-driving cars could save %500 billion each year in US by reducing the 94% of accidents caused by human errors [28] -drones and advanced transportation systems will deliver goods and services to new markets around the world [21].	-Toyota Intelligent Transport System -Intel Intelligent transportation system
Smart energy / Smart grid	-wind turbines -power generation plants -cities, energy users	-power generation, distribution, storage and management [24] -smart grid and household metering [27], [22] -safe, secure, self-healing [7] -renewable energy	-increased efficiency in the electricity transmission-distribution- control chain [24] and significant cost reduction	-smart meter reading -smart appliances -energy demand forecasting
Smart industry/ Smart factory	-plants -manufacturing -logistics	-monitoring industrial plants [24] -luggage management [24] -boarding operations [24] -real-time vehicle diagnostics [24] -warehouse and inventory management [24] -intelligent product supply chain [22] -energy saving and low carbon economy [22]	-cost reduction (e.g., energy efficiency(electricity, gas)) -smart manufacturing -customisable products -low cost SCADA systems [27]	-the healthcare industry using robotics to help perform surgery (e.g., da Vinci Robot), as well as to transport and manufacture medication [21].
Smart shopping	-markets -shopping malls	-mobile tickets [24] -fast payment [24] -online shopping	-increased customer satisfaction -cost reduction	-Amazon Go, "just walk out technology"
Smart agriculture	-livestock breeding -farms/fish farms -irrigation	-animal tracking [24] and intelligent feeding -farm registering and management [24] -product diversification -intelligent irrigation [24] -real-time access and information sharing of agricultural resources [22] -intelligent management of products circulation and management [22] -Intelligent transport (RFID, GPS, GIS) [22]	-increasing agricultural productivity with climate-smart agriculture -reorient agricultural systems to ensure food security -better agricultural strategies -cheaper products	-smart agriculture kits for various purposes

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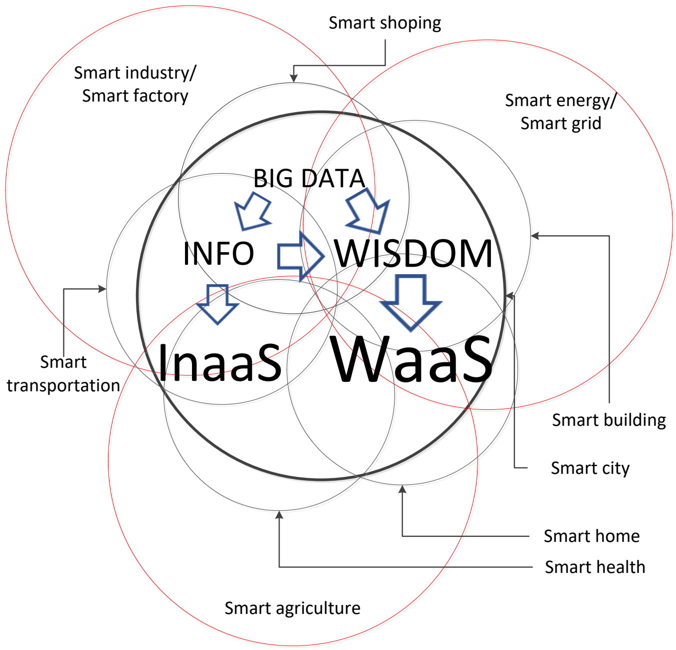

FIGURE 2: Interaction of smart domains and formation of WaaS and InaaS.

Bluetooth [17], to enable a whole new class of applications and services [43]. IoT devices create a voluminous amount of data, continuously, but can cope with only a limited number of computational queries [44] [2].

The idea of smart objects are the building blocks of IoT incorporating intelligence into everyday objects by which everyday objects turn into smart objects [24] with embedded electronics using ubiquitous services [46], [27], CPS [47] and Wireless Sensor Networks (WSN) [48], [39], [22], M2M communications [49] and cloud and edge platforms to 1) sense and collect information from the environment, 2) communicate, interact and control the physical world to be interconnected to each other to exchange data and information [24], and 3) finally automate and facilitate our daily-life using multi-functional hybrid products.

The GW architecture supports edge computing and GWs are mainly used to manage the traffic between the edge and the cloud platforms, as desired. The GW structure aims to process data at the edge computing platform instead of doing everything in the cloud platform [50]. In addition, the role of the GW is to allow Internet access for end devices that are not able to implement the full Internet protocol stack [50]. Moreover, virtualization feature of GW assists in making software updates, handling functionalities and managing features, for instance, supporting a new protocol on the fly [50].

B. BIG DATA AND WISDOM

Recent advances in cyber-physical domains and platforms, big data and data analytics have enabled the development of an open architecture with intelligent sharing and services [51] along with the Web of Things (WoTs) that facilitates services offered at Open Systems Interconnection model (OSI)'s application layer [52]. One of the recent prominent trends is to integrate all smart domains in a combined architecture of the cloud platform [6] to create bigger synergies even though it involves many challenges, some of which are discussed in Section IX. With an increased digital consumption the world is creating massive amounts of data on a daily basis. IDC (a technology research firm) estimates that data have been constantly growing twice as much for every other year [51]. According to Domo's Data Never Sleeps 6.0 report, by 2020 there are 2.5 quintillion bytes (1 million terabytes) of data created each day and it is estimated that 1.7MB of data will be created each second by every single person on earth [53].

Cloud platforms accommodate a large volume of big data in high dimensions that is generated exponentially in different formats and from different sources and likely input for all other smart systems as a wisdom using the intelligent big data analytics. A revolutionary networking model called Information Centric Networking (ICN) has recently attracted the attention of the research community working on data dissemination, mainly wisdom sharing among various smart domains [54]. Some of the main smart domains are smart home, smart building, smart city, smart transportation, smart health, smart shopping, smart industry, smart factory and manufacturing, smart logistics and retail, smart agriculture, smart energy and smart grid, as recorded in Table 1 along with their applications. The connected devices in these smart domains not only talk to each other within their domains, but also they interact with various other devices from diverse smart domains. For example, security, fire or gas alarm using intelligent sensors in smart home domain may trigger an action for the police or fire department in smart city domain. More explicitly, there is no strict boundaries between these smart domains; an output of the smart devices may become the input for other smart devices within their domains and for other domains, as illustrated in Fig 2, in which the smart city is located in the centre for signifying people-focused cyber-physical insights, since more than 60% of the population will be living in urban environment by 2030 [25]. Cities with heavy populations escalate burden on energy, water, buildings, public places, transportation and many other things [25]. The proliferation of devices with communicating-actuating capabilities is bringing closer the vision of an IoT, where the sensing and actuation functions seamlessly blend into these devices. More functional and novel devices are made possible through the access of rich new information sources [27]. The privacy and protection of individuals are vitally important due to huge volume of data recorded from the actions/activities of these individuals. Zhang et al. demonstrated that 20% of the big image data was found sensitive and maintained in the edge platform whereas 80% of was found insensitive and encrypted, then subsampled and stored in the cloud platform [55]. Research estimates that 90% of the data generated by the endpoints

[2]Readers can find more information about the interplay between the IoT, cloud and edge/fog in [29], [45]

will be in stored and processed locally rather than processing in the cloud [56]. The sanitisation process of the big data should be performed meticulously before sharing in order to preserve the security and privacy of individuals. More and more sensors and devices are being interconnected via IoT techniques, and these devices generate massive amount of data, which demand further processing and provide intelligence to both service providers and users [7]. Therefore, explosive growth of data from terabytes to petabytes has triggered interest in a new interdisciplinary form of scientific inquiry referred to as "data science" and "data analytics" [17]. With the help of the competent and scalable data analytics, the business processes can be accelerated and the overall decision making process may be substantially improved. The business intelligence landscape is currently dominated by the big data and all the business models are rapidly adopting the big data analytics solutions, and consequently, exponentially increasing the big data created in the cloud and edge platforms as a Data-as-a-Service (DaaS) can be transformed into Information-as-a-Service (InaaS); InaaS can be transformed into Knowledge-as-a-Service (KaaS) using Big Data analytics, and finally KaaS can be transformed into Wisdom-as-a-Service (WaaS), where Wisdom is an insight to know what's true or right for making correct judgements and decisions, and taking actions, accordingly [51][3]. These transformations can be readily observed from Fig. 8. The WaaS standards and service platforms are expected to be fine-tuned continuously as a core infrastructure for intelligence industry and smart city to support the development of various intelligent IT applications and it is anticipated that this will bring a huge economic value for intelligence IT industry by realizing the pay-as-you-go manner [57].

IV. TRANSFORMATION TO MECHATRONICS SYSTEMS FROM MECHANICAL SYSTEMS

Mechatronics does not indicate any new revolutionary technology [4], [58]. It is a philosophical approach in which mechanics, electronics and IT are forged in a synergistic way to produce enhanced products and systems. This process was eased using semiconductors. Semiconductor technology within conductivity modification using modified doped silicon with electrically neutral n-type silicon and p-type silicon has changed the understanding of MSs drastically regarding digital electronics, digital memory, amplification and switching. A semiconductor is able to transfer the current to trigger desired activation easily as a transistor in order to improve the conductivity performance by simply applying small positive voltage to the gate that is insulated from the semiconductor by an oxide layer and connects two n-types modified silicon through a p-type modified silicon (i.e., NPN) as forming a conducting channel rather than using a moving mechanical switch as shown in Fig 5, which does not only makes the response time quicker, but also makes the development of mechanisms simpler in a way of transforming mechanic functions into electronics and software. Furthermore, semiconductor technology made it easier to embed billions of micro-transistors or electronic mechanisms into a processor. In this sense, transistor has truly revolutionized human existence by impacting practically everything in our everyday lives [4]. Intel's Stratix 10 contains over 30 billion transistors [4]. A typical car has more than 100 embedded processors for engine control, emissions control, sound system etc.

More elements of MSs, such as microprocessors and microcomputers with faster speeds, larger memories, and more functionalities are being released by the help of the advanced transistors. Integrated sensors and microcomputers with less cost and space, higher precision, and fewer disturbances through digital transmission lead to smart sensors [3]. Integrated actuators and microcomputers develop to smart actuators to carry out the desired outputs, such as position, angle, force or torque [3]. Semiconductor sensors and actuators called microelectromechanical (MEM) devices have been changing the mechatronics systems drastically in 21^{st} century by merging silicon based microelectronics with micromachining technology [4]. Miniaturisation of components and consequently devices using MEM technology is imperative for ergonomic and functional use. This technology is being effectively used in almost every field such as automotive, electronics, medicine, communications and defense, (e.g., airbag, intelligent tyres, disk drive heads).

Analysis of the characteristics and behavioural patterns of biological systems has been an active study discipline since the creation of human kind in order to find solutions for complex problems that cannot be readily explained. This analysis using analogies has largely been applied to real world problems. More explicitly, biological systems have evolved to find just-good enough solutions to survive in complex, dynamically changing, and uncertain environments [59]. Understanding and adapting the underlying principles of these solutions to engineering systems have the promise of enabling many new MSs that can operate in unstructured and uncertain environments robustly and efficiently. Nowadays, human-learning-inspired systems are able to learn and function successfully by exploring, observing, watching and exploiting with reinforcement learning without prior knowledge, in particular in the hybrid combination of reinforcement learning and deep-learning with limited prior knowledge using effective behavioural mappings, such as Markov Decision Process (MDP) by maximizing the reward. Biologically inspired (bio-inspired) design is not about blindly copying biological systems, but more on understanding the physical principles of their operation and adapting such principles to engineering systems with the available synthetic materials, manufacturing methods, computation, and power sources [59].

[3]Readers can find monitoring and control, the big data and business analytics as well as information sharing and collaboration issues regarding cloud environment in [39].

[4]https://www.intel.co.uk/content/www/uk/en/products/programmable/fpga/stratix-10.html

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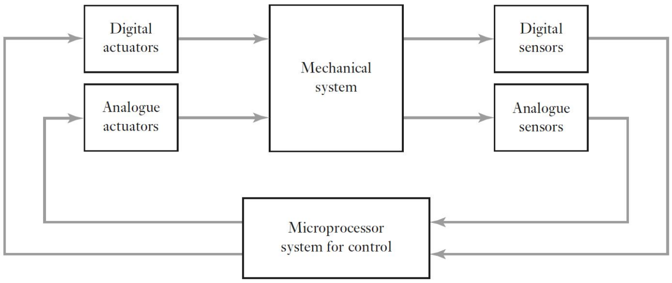

FIGURE 3: The basic elements of mechatronics systems [58]. The functions of mechatronics systems are composed of sensing, processing and actuating.

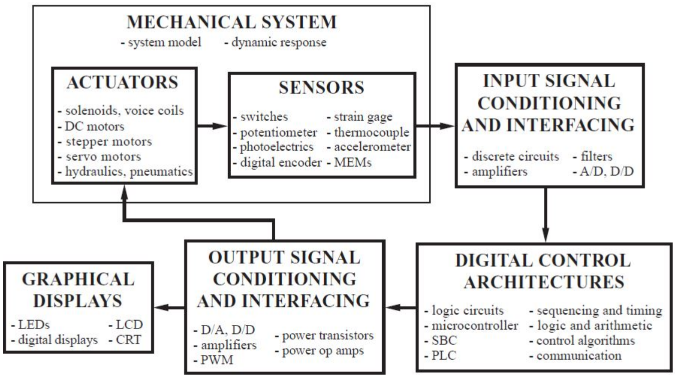

FIGURE 4: The intricate components of mechatronics systems [4].

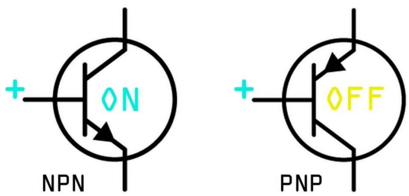

FIGURE 5: NPN and PNP types of bipolar junction transistors.

Bolton et al. [58] outlined the basic components of a MS as illustrated in Fig. 3. These components are detailed by Alciatore et al. [4] as described in Fig. 4. Engineering of MSs and products with advanced control systems is currently available in a substantial number of industrial smart products in many domains. All of these powerful and compelling systems are controlled by microcontrollers, on which intelligent software running along with external devices, such as sensors and actuators that might interface to the microcontrollers [5]. The philosophical insights of mechatronics have paved the way to the development of IoT devices.

V. TRANSFORMATION TO ADVANCED MECHATRONICS SYSTEMS FROM MECHATRONICS SYSTEMS

Current trends are placing new requirements on the technology used to support current product and service production [11]. The underlying precepts of the transfer of functionality from the mechanical domain to the electronics and information domains have been maintained with the mechatronics understanding [5], which made significant changes to the way of thinking in mechatronics. The sole understanding of MSs is not sufficient to address the rapid changing dynamics in the industry and the market. With the further development of technology and in response to increased customer diversity, and service and product quality requirements, the meaning of mechatronics has been broadened further to include intelligent information and communication technologies, such as knowledge-base, big data analytics, Data Mining (DM), AI, ML, Deep Learning (DL), WSN, cloud and edge platforms, cyber-physical domains, more importantly synergistic interconnection of various MSs/IoTs. The leading companies, such as Google ($3.9 billion), Amazon ($871 million), Apple ($786 million), Intel ($776 million) and Microsoft ($690 million) have been immensely investing on AI technologies since 2006 [60]. This indicates that we are moving into a new phase in which the way of doing business is significantly changing with mainly advancing AI, communication technologies and intertwined smart domains, and the components given in Figs. 3 and 4, which also discuss that MSs are not sufficient to establish desired AMSs in order to meet the needs of the stakeholders, in particular customers and companies. In this context, other new components are required to be incorporated into these elements to develop AMSs by which the new future will be shaped, enabling better ways of interacting, working and living. The main components of AMSs and their interrelation are illustrated in Fig. 6, in which the components incorporated are highlighted. AMSs, coping with rapidly changing dynamics, are replacing MSs with a new form with the aid of the cloud and edge platforms, CPS, IoE, 4IR, cutting-edge AI and communication technologies.

In the coming years, IoT is expected to bridge diverse technologies to enable new applications by connecting physical objects together in support of intelligent decision making [45]. Furthermore, the evolution of the industrial IoT and 4IR creates the possibility of connecting computer automated control systems for remote monitoring and rapid response to events requiring real-time handling [61]. M2M or Device to Device (D2D) along with Peer to Machine (P2M) and Peer to Peer (P2P), talking mechatronics devices within sharing knowledge, more importantly using service-oriented WaaS through the cloud platform within smart domains are replacing stand-alone mechatronics devices rapidly in order to enable enhanced responses to time-critical actuation and context-dependent data needed for AMSs to function in a more desired way. WaaS can make correct judgements, decisions, and actions to provide the right service for the right AMSs at the right time with the right content.

Bradley et al. [5] explores the relationship between IoT and mechatronics: IoT is forcing disciplines to further review the ways in which mechatronics systems and components are perceived, designed and manufactured. In this regard, for the future of mechatronics, recent years have seen a shift from systems based on the interconnection of physical

[5]Readers can access further information about the main components of MSs in [4] and [58].

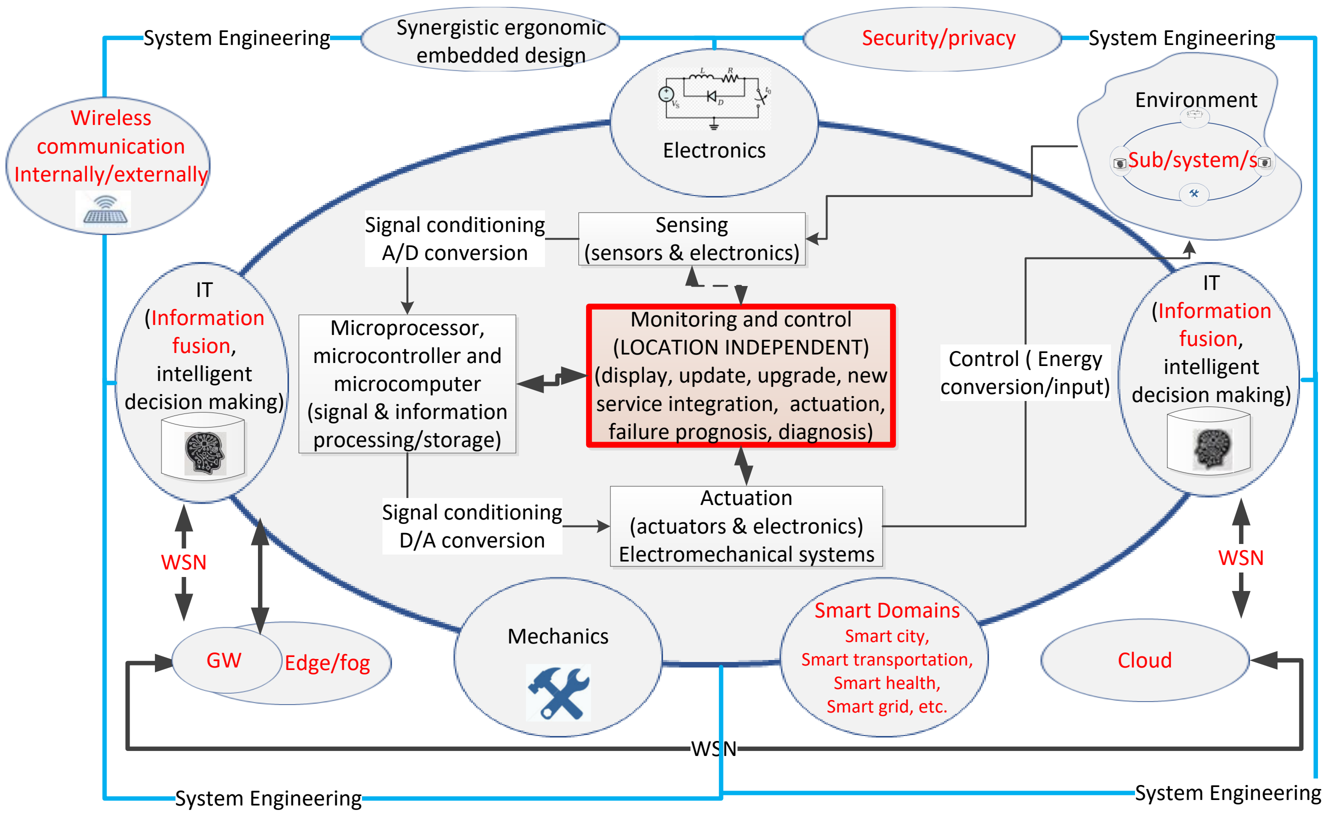

FIGURE 6: AMS framework and the main components of an AMS and their interaction with the environment and other AMSs.

components, in which transmitted data have been used to facilitate control of systems. Information is at the heart of these systems and serviced by smart objects [5] in a broader aspect covering several advanced systems at a time in a more complex synergistic understanding using the wisdom - i.e., WaaS, and InaaS created in the cloud and edge platforms in a pay-as-you-go model.

On one hand, the vastly and rapidly growing number of connected things is creating data at an exponential rate [56]. Contrarily, many resource-constrained devices will not be able to rely solely on their own limited resources to fulfil all their computing needs. The majority of AMSs may not have sufficient resources to process the big data with respect to advanced processing and monitoring tools that are already in the cloud platform, such as Amazon Web Services (AWS) IoT, Bluemix, and Microsoft Azure IoT Suite. The data collected by the sensors are in raw form and in large volume; these data need to be stored, processed, and analysed to extract interpretable information from it, which is accomplished by storage and data analytical tools provided by the cloud platform [62], where near to real-time operations can be performed. However, these are usually delay-tolerant applications. The outcome derived from raw data collected by the sensors can be used by any application [62] as a service, such as InaaS and WaaS. The cloud platform derives manifold advantages to store and process enormous data generated by heterogeneous devices, in particular, these devices have limited computation and storage capacity [6].

On the other hand, the cloud platform may not be suitable for scenarios involving real-time operations, low latency requirements, and high quality of service (QoS). Therefore, extending cloud computing and services to the edge platform where proximity to consumers supports for quick processing at the edge fulfilling low latency requirements is imperative, particularly for customer-centric applications, such as medical devices, connected cars, industrial robotics and vehicles in aviation. Against this background, a mobile smart phone with improved computing abilities may serve as an edge platform to provide local control and analytics applications to AMSs. The direct interaction of these devices with the cloud will be unrealistic and cost prohibitive, since such interactions often require resource-intensive processing and sophisticated protocols [29]. Sending all the data to the cloud will require prohibitively high network bandwidth, which is mostly infeasible with respect to network bandwidth constraints [29]. For instance, an autonomous vehicle can generate big data, which are estimated to be about one gigabyte per second [63]. Aircraft engines, such as in Boeing 787 generates about 1 Terabyte of sensor data every 24 hours and Industrial machines and their parts, such as gear system generates huge amount of vibration data every second [64]. Thus, sending all the data to the cloud will require prohibitively high network bandwidth [29]. Some functions are naturally more advantageous to be carried out in the edge while others

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in the cloud. Determining which functions should be carried out in the edge platform and how the edge should interact with the cloud will be the key aspects of the edge research and development [29]. More explicitly, the data required to be sent to the cloud platform, the data maintained in the edge platform and the data deleted to spare enough space for further processes should be determined during the development phase of AMSs based on the constraints, abilities and requirements using data-intensive applications and big data analytics for data processing under the supervision of data scientists.

An important feature of an intelligent system is the automatic supervision and fault diagnosis of its components [3] or one mechatronics system may be monitoring the health of other mechatronics systems. Advanced intelligent diagnosis/prognosis applications without human intervention are required in order not to face any malfunction, such as software failure in AMSs. Prognosis of pending faults are supposed to be carried out to be proactive using the circumstantial evidences and symptoms, such as noise, vibration, smell etc. Systematic error (i.e., inaccuracy), random error (i.e., imprecision) and blunders (engineering errors) should be minimized through effective self calibration abilities and careful design, and furthermore, approaching failures and system inconsistencies should be foresighted through effective and autonomous intelligent prognosis techniques to establish precise and consistent-robust AMS. Required maintenance processes should be triggered autonomously via the edge or cloud platform where the edge platform is not close to the people who may be concerned using remote abilities of the smart cloud platform based on the non-stop 24/7 service targeted for AMSs.

More sensors mean more information for better decision making but introduce more complexity and expense to the systems. Within the cloud, it is possible for AMSs to function with no or less number of sensors resulting in less complex AMSs. Information or wisdom already created in the cloud can be incorporated into AMSs as InaaS or WaaS. For instance, weather conditions, such as temperature, wind speed and humidity are already in the smart city domain and one can readily incorporate these parameters into AMSs rather than integrating additional sensors into the existing AMSs to measure these parameters separately. Similarly, smart vehicle systems should be using the information created by the sensors in smart transportation domain.

WSNs are required as AMSs get independent to function efficiently anywhere, anytime. In this manner, establishment of energy efficient AMS is an urgent need. Wireless sensor devices- i.e., wide range of intelligent and tiny wireless sensing devices, are resource constrained and operate on batteries, the communication overhead and power consumption are therefore important issues for WSNs design [22]. It is essential to design reliable and efficient communication protocols to remotely manage sensor devices without consuming significant resources [22] and they are opt to switch to sleep mode during their nonactivity period and wake up when required [62]. Furthermore, by transferring computation and communication overhead from nodes with limited battery supply to nodes with significant power resources, the system can extend the lifetime of the individual nodes [7] [6]. The sleep interval of sensors can be predicted and controlled depending upon their prior activities, data acquired and remaining battery level in which the sensors undergo automatic configuration, optimization, and healing mechanisms to save energy [62]. The modelling of AMSs for the sake of the functioning independently anywhere anytime is explored in Section VI along with an explicit architectural framework and various examples.

The low-cost SBCDs, such as Raspberry Pi, Arduino Uno, Intel Galileo, Intel Edison, Beagleboard, Libelium Waspmote in a light-weight, easy to use, customisable and highly-interoperable way are paving the way towards the development of AMSs. Their success lies in their small design and built-in general purpose input output (GPIO) pins, wireless components, such as built-in Wi-fi, Bluetooth and many other promising abilities. Moreover, many other devices, such as sensors, actuators, extension units compatible with those SBCDs, such as Google's Rainbow HAT are progressively attaining their places in the market, which contributes to the development of AMSs. We envision that those SBCDs with promising abilities will create an immensely growing market for building AMSs.

VI. MOLDING OF ADVANCED MECHATRONICS SYSTEMS WITHIN AUTOMATION OF EVERYTHING (AOE)

An explicit architectural scheme of AMSs that aims to establish a heterogeneous execution environment using a homogeneous computing model is presented in Fig. 7. Main components of this design are the platform of automated AMSs (poaAMSs) along with the intelligent edge platform, customers, vendors, the cloud platform and production plant, which support QoS in many aspects. AMSs can be mobile or location-dependent systems in this architecture which is a promising enabler of many real-life applications and systems.

AMSs in a dedicated location or on mobile are automated to work harmoniously forming the basis of an optimal environment that reacts to our needs and moods. They are able to communicate with each other directly to use any resource and/or information in virtual manner or to trigger any desired actuation in other AMSs. WaaSs and InaaSs along with the capabilities of the cloud and edge platforms open up possibilities for dynamic learning through autonomous feedback, feedforward, and cross-linking between all stakeholders during the product life-cycle. AMSs are designed to utilise available WaaSs and InaaSs in the first instance rather than embracing more sensors. The main reason for connecting to the edge platform from the cloud platform is to benefit from these services while maintaining the location-independent monitoring and controlling abilities. The required WaaS or InaaS may either be in the cloud or in the

[6]Readers can find the detailed analysis of the efficient use of WSN in [65].

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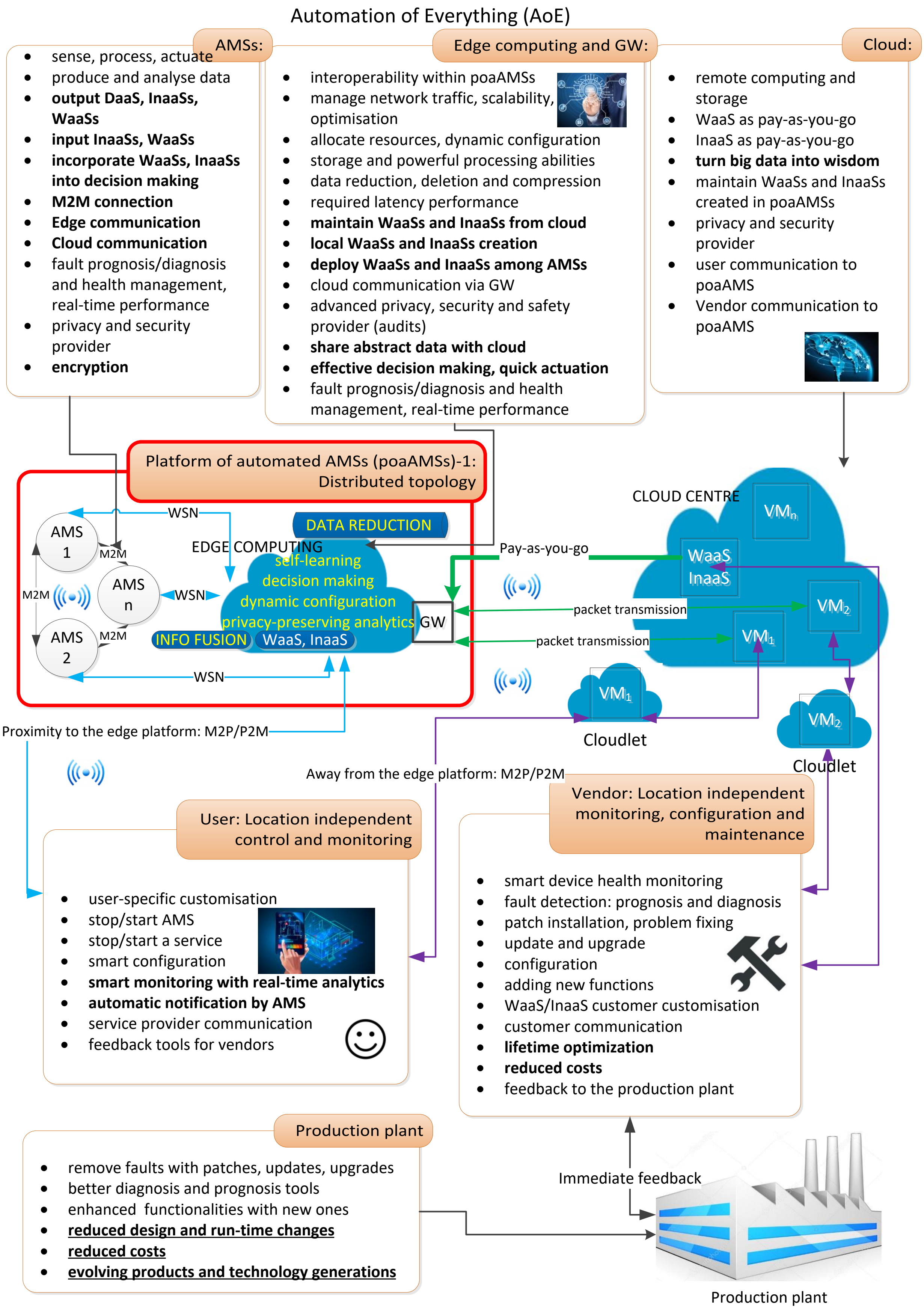

FIGURE 7: Framework of AoE: Service-oriented architecture of poaAMSs with the internal and external components and main functions, which we name it as Automation of Everything (AoE).

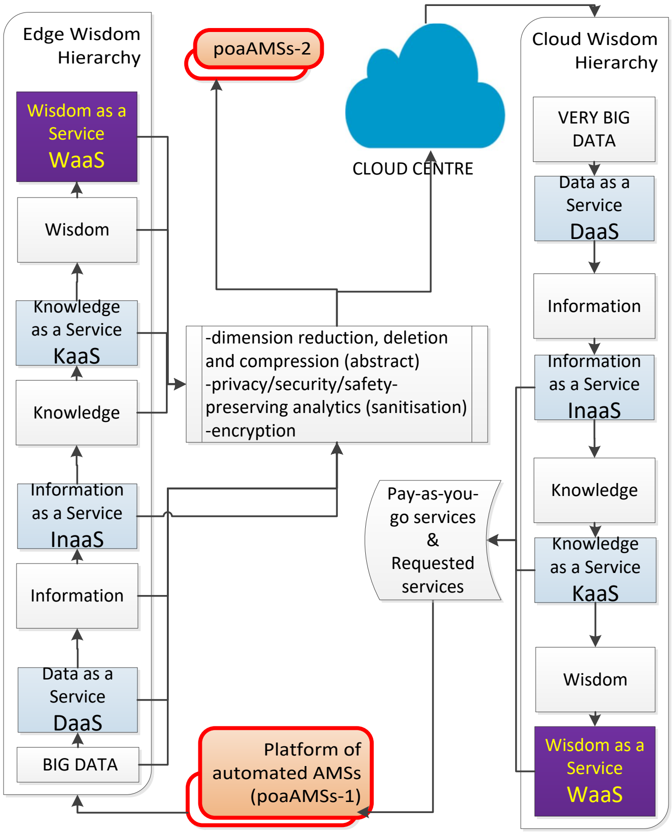

FIGURE 8: Framework of big data transformation between the main poaAMSs and other poaAMSs, and the cloud platform.

edge platform. More explicitly, WaaSs and InaaSs in the edge platform may be created by poaAMSs as depicted in Figure 8 or directly obtained from the cloud platform. The vendors have to buy these services in a pay-as-you-go model without on-demand access for minimizing latency if they are in the cloud platform and these services are opt to update the edge platform in intermittent manner for the most recent information or wisdom via GWs using resource scheduling functions. These services are ready-to-use if they are in the edge platform as illustrated in Figure 8. Strictly speaking, AMSs acquire these most recent updated services in the edge platform without demanding from the cloud, which enables real-time deadline requirements. A WaaS may be sufficient for an AMS to determine how to actuate, or it can be fused with other WaaSs, InaaSs and information gathering from local sensors on the AMS for real-time data collection and control purposes. Additionally, the vendors can create multi-purpose WaaSs unique to their products in the cloud platform, if there is no available WaaS. One way of doing this is to generate WaaSs by poaAMSs that are designed to use all sensors for their distinguishing purposes. These services can also be integrated into other AMSs that are designed to leverage these particular WaaSs in the cloud platform rather than to directly use sensors. Noting that using WaaSs is crucial, particularly for application scenarios requiring mass amount of information detection from numerous sources, which can be highly complex, costly and impractical.

Communication of users and vendors with poaAMSs in the cloud platform is carried out using different VMs to effectively manage data traffic, authentication, privacy and security. VM interaction is provided to the cloud customers where the cloud is closest to the users, which is commonly called as cloudlet [66] in order to provide the best possible latency requirements. Several poaAMSs can be clustered to form an integrated ecosystem of poaAMSs if they are geographically available to be merged without the need for cloud network resources, as illustrated in Fig. 9. Moreover, a cluster of poaAMSs can also be established using various cloudlets and their virtualization and data replication abilities without generating additional data traffic for the main cloud centre in order to build bigger automated platforms with respect to the abilities of the cloud platform. For instance poaAMSs-4 in Fig. 9 can jointly work with poaAMSs-1, poaAMSs-2 and poaAMSs-3 using two cloudlets. It has been discovered that service providers could analyse sensitive information such as user activities, even with encrypted devices [67]. Private information of users must never be sent to the VMs, which are assigned for other particular tasks such as the VMs reserved for vendors to remotely monitor and to access real-time health information of AMSs. Sensitive data should only be stored on authorized VMs to ensure anticipated security and privacy. Furthermore, sensitive data that are forwarded to the cloud should be encrypted to meet security and privacy requirements. This would prevent third party to potentially sniff on the network for the packets of crucial data, which might compromise the security and privacy. The customer uses VM_1 whereas the vendor uses VM_2 in our design in Fig. 7. A VM instance is created for each AMS or each edge platform, and vendors can use different VMs while several vendors can contribute to poaAMSs. The GW is the interface between poaAMSs and cloud platforms to manage the necessary authentication, and to protect poaAMSs from malicious eaves-droppers and network attacks. Additionally, in a binary decision between edge and cloud with respect to the proximity to the poaAMSs, the customer can establish a communication with the resources directly where s/he is in the dedicated location of poaAMSs.

Users are authorised to perform specific operations whereas vendors are authorised for other specific operations. The main authorised jobs unique to the customer and vendors are depicted in Fig. 7. Automatic notifications and other required information for customers are sent to VM_1, where the costumer can monitor and control the services of poaAMSs via this particular VM. One can accomplish these tasks while being away from poaAMSs, since the cloud allows efficient real-time data collection and analysis by offering a comprehensive selection of resources, remote data management, easy access, and economic benefits [68]. However, attaining low latency is particularly difficult when cloud services are involved, as the cloud could be far away from devices [30], [20] even though the cloud platform is closer to users with the extension of the cloud centre using

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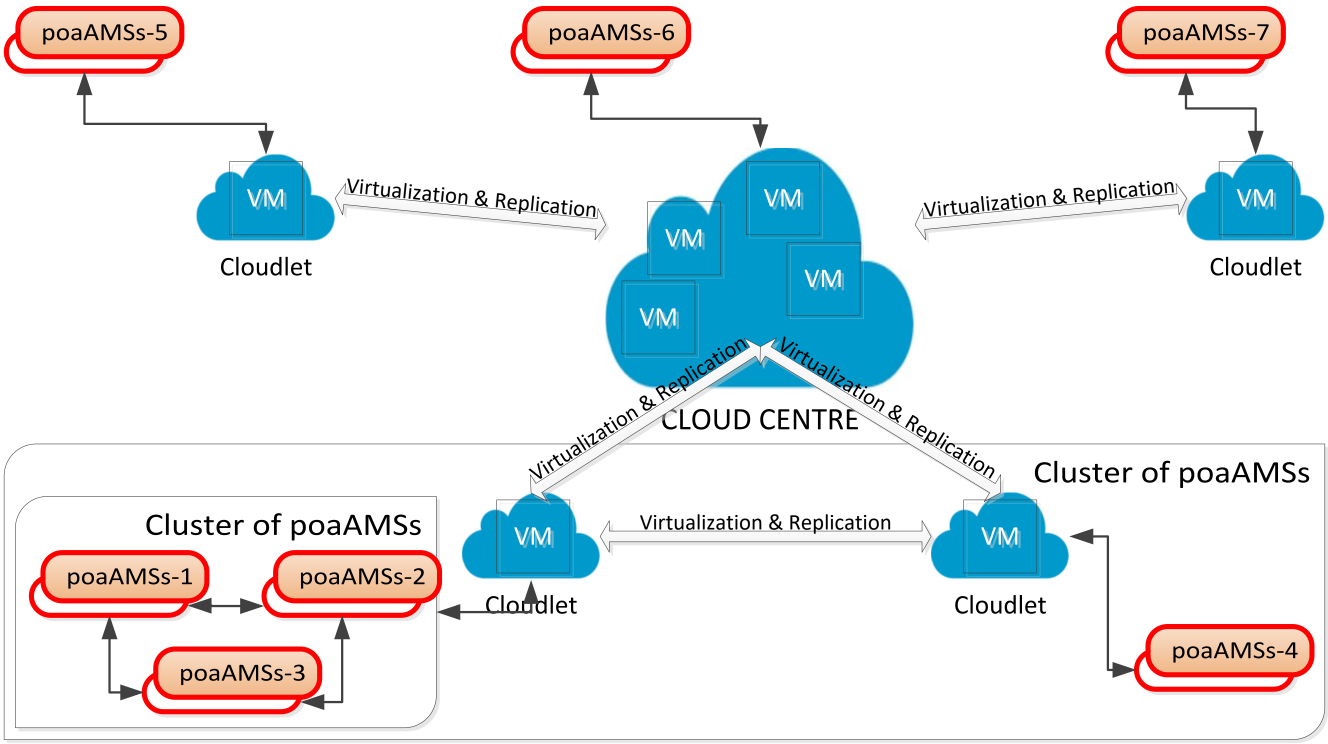

FIGURE 9: Communication between the cloud platform and the poaAMSs.

cloudlets and virtualization of resources.

AMSs are connected to each other in a distributed computing environment, such as M2M to perform their tasks in smarter ways mainly using the edge platform, particularly for satisfying very low latency requirements, where a specific output of one AMS can be relayed as an input to other AMSs in order to commence a desired actuation. Additionally, AMSs autonomously learn about the individual behaviour, and adjust their responses accordingly using intelligent techniques. For instance, if an AMS-based clock is adjusted to 6am from its usual 8am, the AMS-based coffee machine learns this behavior and prepares the coffee according to this time adjustment. Similarly, all other waking up sequence of events (e.g., turning on tv) created by other AMSs are automatically adjusted based on this time alteration. The more intelligence in the edge as explored in [20], particularly for the poaAMSs, the better performance can be attained from our proposed architecture, which is illustrated in Fig. 7.

A large volume of data is created in poaAMSs and processed near the data source to enable knowledge generation to occur at the data source using data analytics, real-time data processing, data caching, and computation offloading in the edge platform. Most of this data is deleted in an intermittent manner by intelligent data reduction tools after establishing WaaSs and InaaSs using advanced self learning and decision making techniques to guarantee that available memory is not exceeded. Each update for WaaSs and InaaSs may make the previous data obsolete. Useful data are transformed into abstract forms, WaaSs or InaaSs to reduce the data traffic load either for the notification of the customer or for vendors to be able to evaluate how their systems are functioning. The useful data in abstract form or as WaaSs or InaaSs are stored in the cloud platform by transmitting packages from the edge platform in aggregated and compressed forms to diminish bandwidth requirements, transmission delay and packet loss, which enables efficient streaming data collection, storing, processing and transmitting. The cloud servers in the far end environment can provide more computing power and more long-term data storage, such as massive parallel data processing, big data mining, big data management, ML [7], [69]. This, in turn, has led to an aggregation of data that is now being employed to optimise all steps of the processes to ensure higher quality goods are manufactured at lower cost [5]. These abstract data forms are particularly analysed by the advanced big data tools to monitor the health of the AMSs. Detected problems are fixed and lifetime optimization of AMSs are carried out based on these results for both the products that are being used by the customers, and the products that are being produced in the factory. Most importantly, new products meeting the market are progressively improved in 4IR in order not to cause any similar faults by learning from the experiences of the products currently used by the existing customers.

Assume that a customer is using an intelligent autonomous blind system working based on the changing daylight and weather conditions along with user preferences. It needs various sensors to be able to detect the current weather and daylight conditions to work as desired. If it is working stand-

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alone with all these sensors, we can call this system as a MS. More explicitly, assuming that there is an ongoing issue with the system and the customer is ringing the vendor to fix this problem, where this system can be referred to as a MS. If the customer is just able to control this system from home, not from his way to the house or workplace, this can also be determined as a MS. So, what makes a system an AMS? 1) the system obtains the service, i.e., wisdom, as a WaaS from the smart city domain in the cloud platform about how much it is supposed to open or close the windows without knowing the current outdoor conditions, 2) The user can monitor and control the system using location-independent abilities on the edge and cloud platforms, 3) a pending problem with the system is predicted by the vendor using intelligent prognosis embedded in the system using cloud platform; some of the problems might be fixed in cyber-physical platforms online and some of them can be fixed by engineers on the site, in particular hardware problems, 4) patches, updates or upgrades for the system are performed by the vendor in the cloud platform. AMSs may still have sensors to obtain the required information that is not or can not be created in the smart domains. In a similar way, a surgeon can operate a patient from another location using location-independent monitoring and operating abilities of AMSs, e.g. with the help of an advanced da Vinci Robot. A pilot can direct an airplane to land in any location under an emergency situation using location-independent control abilities. MSs or other electronic devices can be converted into AMSs by incorporating the properties mentioned here, particularly as illustrated in Fig. 7, more detailed in Section VIII along with Fig. 10.

VII. WIRELESS COMMUNICATIONS ASSISTED AMSS

The world's Internet population is growing significantly year-over-year, where Internet access reached 47% of world population totaling up to 3.8 billion people in 2017 [53]. Moreover, more than half of the world's web traffic is gleaned from smartphones, and it's anticipated that about 6.1 billion people will have access to a smartphone by 2020 [53], which will demand advanced wireless communication techniques in the following years in order to meet the increased capacity. In the last decade, wireless communication and networking techniques used in the applications of mechatronics have immensely grown due to the necessity of mobility, which enables an AMS/poaAMSs to move around independently and to communicate wirelessly. Some of these techniques can be observed in the applications of exploration using mobile robots [70]- [71], underwater systems [72], surgery [73], intelligent buildings [74], pedestrian localization [75], tracking systems [76], [17], micromedical robots for capsule endoscope [77], [78], localization for pipeline inspection [79], robotic milling [80], remote pain monitoring systems [81], stroke rehabilitation systems [82] and intelligent transportation systems [83].

In the context of wireless mechatronics systems, mobile robots can be exploited for cooperative information gathering, simultaneous localization, map building (SLAM) and exploration of a fully or partially known environment [70]-[71]. However, Takahashi et al. [70] observed a serious communication delay due to the nature of communication method between mesh network and mobile robot. Adopting 5G technology into such systems can significantly reduce the end-to-end delay. Considering huge amount of data and its processing in IIoT applications involving with the cloud, the vision of 5G (one thousand times throughput improvement, 100 billion device connections and close to zero end-to-end latency) [84], [85] overlaps with the principles of advanced mechatronics systems and 4IR considering that industrial robots require rapid decisions without any communication delay[7].

Remote individual health monitoring is also another crucial application of wireless mechatronics within smart health domains. Yang et al. [81] proposed a wearable device with a biosensing facial mask to track and monitor pain intensity of a patient via facial surface electromyogram, where the wearable devices perform as wireless sensor nodes that are integrated into an IoT platform. However, managing real time wireless communication between sensor nodes, cloud server and web application can be challenging mainly due to the GW limitations. In such scenarios, heterogeneous communication networks[8] [89], [90], [91] play a significant role in achieving the required capacity increase. Another appealing application of heterogeneous wireless MS can be found in [92], where aerial and ground vehicles are coupled with multiple robotic platforms each of which are characterized by different dynamics and unique sensing abilities.

One compelling application of wireless mechatronics is the robotic milling with the aid of wireless force sensing in order to increase the accuracy of robotic milling, while conserving its adaptability [80], where wireless polyvinyldene flouride sensors are utilized for real time force measurement. Cen et al. [80] concerned with the high transmission speed constraint between external PC and robot controller. High data rates can indeed be compensated by a 5G ecosystem encompassing a heterogeneous communication landscape, while incorporating communication networking and IT resources with edge/fog/cloud-enabled services [86], [87], [88], such as software and virtualization.

The popularity of mobile devices and thus the immense growth of data traffic has led to breakthroughs in small-cell ultra-dense, massive-MIMO, millimeter-wave (and/or terahertz) communications and networks constituting the

[7]Motivated readers are referred to [84], [86], [87], [88] for a better understanding of the underlying technology behind 5G in order to reduce the end-to-end delay to near zero.

[8]Heterogeneous networks (HetNets) refer to network architectures deployed with distinct network devices, which are equipped with diverse transmission power requirements and different data processing capabilities, different radio access technology (RATs) support, and are provided for a variety of backhaul links. For example, a HetNet may be collectively deployed with multi-RAT networking and scheduling along with cellular-based networks (potentially 5G) with high transmission power macro eNBs and low transmission power pico eNBs.

underlying technology of 5G, which promise to attain gigabit wireless access for next-generation systems and networks [93], [94]. High-data rate, low latency and highly reliable communications provided by 5G can enable computing services at the remote cloud server. However, propagation delay is an inherent constraint of the cloud computing due to vast distance between end user and the cloud server. For this particular reason, still cloud computing is not favourable for emerging time-critical AMSs applications even with 5G technology. It is commonly known that cloud computing is insufficient to satisfy the millisecond-scale latency requirements of 5G. Solely relying on the data exchange between end users and remote clouds may create data tsunami and demolish the backhaul networks [94], [95]. Therefore, it is vitally important to support cloud computing with MEC in order to move traffic, computing and networking tasks towards the network edges. Noting that the use of edge or fog computing aligns with MEC and these terminologies are often used interchangeably [93], particularly where the mobility measures take place. With 5G integrated fog computing/MEC, we envision that AMSs will further advance the WaaS, the InaaS, the poaAMSs, the production process, the customer (user) feedback and the vendor interventions, such as location-independent monitoring, configuration and maintenance. It is also speculated in a recent study by Tariq et al. [96] that sixth-generation (6G) will be empowered by artificial intelligence (AI) and anticipated that AI will be collaboratively operating with distributed training at the network edges, which is yet to be solved. In summary, the contribution and the advances of wireless communication techniques for the development of AMSs and 4IR is essential. For example, radio frequency communication related impairments within a very sophisticated communication network composed of thousands of AMSs devices are the inherent communication challenges to tackle with. Therefore, AMSs have to support ultra-reliable low-latency communication (URLLC) and conduct AI-assisted operations at the edges, potentially through 5G-and-beyond (6G), and time-critical applications, such as remote surgery will require less than 1ms delay, but the upcoming 5G systems are not yet capable [96]. We anticipate that real-time transmission of massive amount of data under 1ms delay requirements may be realized upon the release of 5G-and-beyond (6G).

VIII. FUNDAMENTAL FEATURES OF AMSS

The framework criteria for the design and the development of AMSs are presented in Fig. 10. Based on this figure, essential features of AMSs distinguishing them from MSs and concerns in addressing the high-level challenges in the life-cycle of AMSs are disclosed as follows:

1. A mechatronics engineer along with a data engineer and a communication engineer should be in the middle of the development/integration process as a coordinator and designer to establish an efficient collaboration within the philosophy of integrated product development between multi-disciplinary fields for both reducing time over-runs, over-cost, unreliability and failures, and consequently to build robust AMSs.

2. AMSs incorporate various components as described in Figs. 6, 7 and 8 into a harmonized working environment.

3. Wisdom for AMSs is attained from the cloud. For example, the information of daily lighting conditions can be set as InaaS and the wisdom of when to turn on/off the lights can be set as WaaS for operating the security lights in any home security system, which can be readily acquired from the smart city domain. This use of WaaS reduces the complexity of having excessive number of sensors, such as photoresistors.

4. Emerging wireless communication technologies are essential for implementing AMSs to avoid latency for time-critical applications of AMS, and to support huge amount of data processing and transmission, which is also speculated for the contribution of 5G-and-beyond (6G) into the artificial intelligence assisted distributed training at the network edges in [96].

5. When users are at smart domain ecosystems, an edge environment is used for monitoring and control. Implementation of edge for local use provides reduced latency and increased security. The edge also enables connectivity amongst AMSs in a dedicated smart domain ecosystem.

6. A location-independent monitoring interface is another requirement in AMSs using the cloud platform. This allows users to monitor their system from anywhere and anytime, and a rapid action can be taken by the vendor if any fault is present in the system. Additionally, a location-independent control in order to update and upgrade the systems or to stop/start any services in poaAMSs should be performed via the cloud platform to; i) remove faults, ii) provide better functional performance, and iii) customise products that are being actively used by the customers. Engineers, alerted through the cloud, can assess and fix errors via updates to provide lifetime optimisation. Additionally, incorporating the production plant into this cycle within AoE ecosystem can effectively help new products to meet the market with less error-prone components by learning from the experiences of the products currently being used by the existing customers. This interface is primarily needed to establish the communication between the user/technician and the system to provide visual feedback about the internal activities (e.g., fault detection), to modify the system with new parameters, and to reset the system if required. In this context, lifetime optimization of current and emerging AMSs will be provided, which will result in longer life-cycle for AMSs and better functioning abilities. There are leading companies that freely provide these services on the cloud platform to which AMSs in poaAMSs can be linked using easy-to-use interfaces such as i) Google with the AndroidThings Console [9] by which easy and secure deployment of updates, upgrades can be concurrently performed for many devices and informative analytics can be employed to understand how well AMSs are performing,

[9]https://developer.android.com/things/console

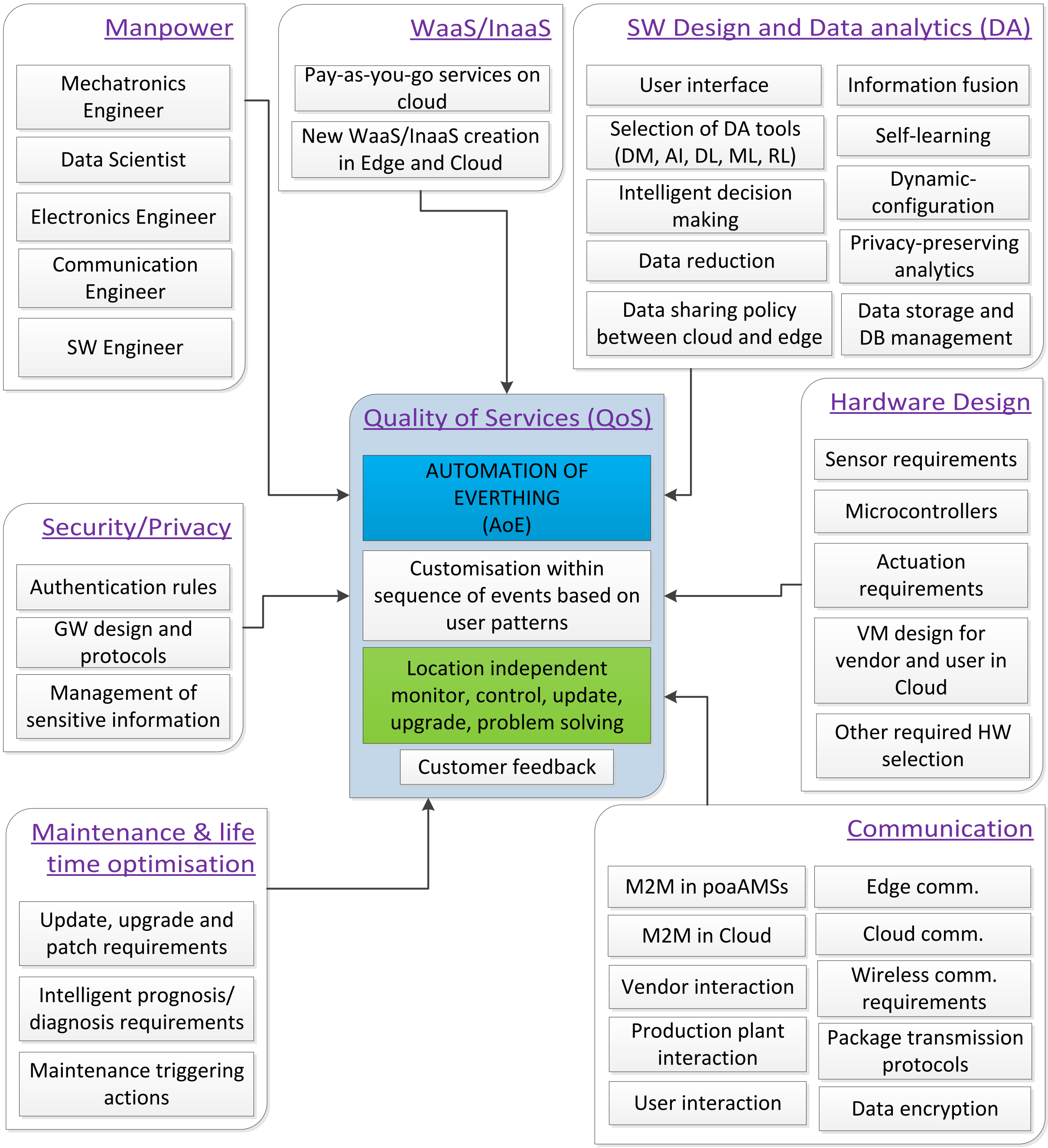

FIGURE 10: Framework criteria for the design and the development of AMSs.

and ii) Wia Platform with location-independent actuation services [10] including several other options can trigger any desired actions on/from mobile devices, which can be used as a cloud platform for building effective AMS with remote actuation abilities away from the poaAMSs ecosystem and communicating them online anytime anywhere.

7. A location-independent new service incorporation that is already in the cloud platform in any domain or on the AMSs to i) adapt to dynamically changing environmental parameters, ii) provide better functional performance, and iii) customise products that are being actively used by customers, mainly based on changing customer preferences.

8. AMS should serve with no interruption within autonomous prognosis and diagnosis decision making using internal sensors, and proactive required alarms should be triggered accordingly for maintenance, spare part replacement or need of battery change via cloud or edge.

9. AMSs need to use advanced information fusion techniques and data analytics for better decision making and better traffic management between the edge and cloud platforms.

[10]https://www.wia.io/

10. AMSs should have an open architecture with intelligent sharing and services, and should be able to integrate with other systems easily to share data and wisdom in the AoE ecosystem.

11. AMSs should prioritise the user privacy and security where there is a trade-off between various options using appropriate authentication protocols and data encryption tools in order to preserve the sensitive information on behalf of the user.

12. AMSs in AoE should have the customising features that can learn from user patterns and behave accordingly in a sequence of triggering events without requiring user intervention in order to increase QoS perpetually.

IX. CHALLENGES

The emerging AMSs pose new challenges, some of which cannot be adequately addressed by current state-of-the-art cyber-security solutions, cloud and host computing models alone, which exacerbates the current situation. To unleash AMSs potential, these challenges raising concerns must be addressed well in terms of both technical infrastructure and the management of data, and human factors, such as privacy and security. The main challenges are presented as follows:

1. Lack of cross-functional interdisciplinary knowledge or experienced mechatronics/system engineers along with data scientists: AMSs with various intertwined systems are related to the notion of getting interdisciplinary interactions between several engineering disciplines to work together harmoniously and requires knowledge of different skills between various expertises, which do not simultaneously exist in companies and hampers the development of AMSs rapidly. Cooperation of various disciplines in different expertises and cultures makes the processes difficult since one discipline may not be well aware of the capabilities of other disciplines, which reduces the reasonable imagination, such as unpredictability impact of a design change or design/integration conflicts across disciplines, difficulty predicting about how advanced mechatronics product act until physical prototypes exist and difficulty in getting the desired product to the market fast.

2. Insufficient modelling tools and methods: Engineering tools for design, deployment, management, operation, security, and migration are currently the greatest bottleneck [11]. Insufficient functionalities of current design tools to communicate seamlessly across disciplines, to design/explore/model/outline all the components, to identify system-level problems early and consequently to make up a robust product is evident.

3. Heterogeneity and incompatible protocols: Electronical products established by various manufacturers (e.g., Amazon, Google, Samsung, Cisco, Nuimo, Lifx, Sonos, Philips (Hue), Mixtile etc.) may not be compatible with each other with respect to dedicated protocols and electronics design, which makes the integration of new devices a challenging task. Simple technology standards are not adequate for the integration and interoperability with many other different devices. Different devices from variety of manufacturers are mostly based on distinct protocols [7]. In this respect, making system components interoperable, so that devices from different manufacturers operating in different application domains can work together, is essential [23]. Innovative directions are required by governments, national and international leading organization to guide for agreed upon standards.

4. System integration: The edge computing is a heterogeneous platform incorporating various technologies, protocols, platforms, network topologies, and servers, which requires skillful and qualified engineers from various discipline, such as data, computer, electronics and communication engineers. Therefore, it will be difficult to program and manage resources for diverse applications running on varying and heterogeneous platforms at distinct locations [7].

5. Cybersecurity: Cybersecurity (e.g., protection of industrial know how, data security) remains an ongoing problem despite progress in secure communications and storage of data [97]. There are still competing standards, insufficient security, complex communications, and proliferating numbers of poorly tested devices [39]. Based on this background, security is one of the crucial issues that needs to be addressed to enable an efficient and reliable communication [45]. Secure communications and data storage require the use of strong cryptographic techniques which are often computationally expensive [5]. Remotely managed control systems require reliable, scalable, and sustainable solutions for increased usability, management, and rapid response. Those systems play a significant role in AMSs and cannot be hijacking-prone. Malwares to attack industrial automation, to gain control over devices or corporate espionage to steal sensitive data from competitors have to be avoided.

6. Legal issues: The legal challenges, in particular, the privacy of people using cyber-physical domains have yet to be solved [98] [11]. The responsibilities of vendors giving the cloud services such as Google, Amazon, Microsoft against the customers are not well defined within the national and international laws of electronic commerce.

7. Privacy: Only authorized entities should be able to use services [23]. The cryptographic mechanisms impose some overhead in terms of processing and amount of data transmitted [99]. Furthermore, lack of standards, secure authentication and authorization policies are yet to be discussed. What happens if a smartphone operating as an edge platform is hacked by a cyber attacker; cameras that are meant for surveillance may turn into cameras that are violating our privacy.

8. Technical difficulties: Pinpointing the problem might be difficult throughout within heterogeneity. What happens when a smartphone acting as an edge or GW is not functioning (broken, out of charge); more connection to other systems or devices and smart environments requires more

[11] The motivated readers are referred to [98] for the analysis of privacy and security legislations regarding IoT and cloud use.

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data sharing and there is a lack of technical expertise to manage AMSs and fix emerging problems quickly.

9. Hardware (HW) and Software (SW) compatibility: The integration of HW and SW in AMSs is not a sequential, rather parallel process, one effects and changes the design and integration process of the other significantly. The leading SW companies are not able to produce their operating systems or SWs compatible with the CBCDs emerging in the market quickly. For instance, it has been 8 months since the Raspberry Pi 3 B+ was marketed and still Android Things operating system is not able to work on this model. The companies developing HW (e,g., SBCDs) should collaborate with the leading SW companies to make their products compatible with many other products in order to accelerate the sustainability of the products in the market.

10. Egde, cloud and IoT related problems: As an emerging field of study, edge computing is still in its infancy and faces many challenges in its implementation and standardisation [100]. IoT devices have vulnerabilities due to lack of transport encryption, insecure Web interfaces, inadequate software protection, and insufficient authorisation [39]. The variety of standards and technologies in these elements and the way they should interoperate is a main challenge that can impede the development of IoT applications [45] and the development of AMSs that need to communicate with those devices.

11. Big data management challenge: Managing huge amount of data created in the cloud that consist of highly-valued information merged with unnecessary and erroneous data is also a challenging task [38]. A recent research by IBM shows that 1% of data collected by organizations is used for analysis [101] in which required WaaS and InaaS can not be revealed sufficiently. Therefore, it can be safely concluded that the big data need more powerful data analytics. Big data that need to be processed and stored is an important characteristic of the hyper-world, so how to effectively manage, mine, and utilize the big data as WaaS and InaaS in order to create successful AMSs, improve the ability and quality of AMSs are the immediate concerns.

X. DISCUSSIONS

In future mobile networks, such as 5G emerging smart services are expected to support billions of smart devices with unique characteristics and traffic patterns [102] to achieve a flexible and efficient communication, consequently an excellent synergy. WaaS will be the core architecture of IT applications in the coming age of the hyper-world [57]. It is worth noting that industrial companies are re-evaluating the way they do business and feeling the increasing pressure to adapt to the changing environment with cyber-physical systems by recognising the benefit of connecting devices and services to the Internet in which too many smart ideas to be explored and exploited and excessive room is available for IT experts and creative people. Transforming the systems and products into more intelligent, more autonomous AMSs is necessary for leading companies to produce quality products with increased customisable functionalities and maintain a competitive edge through better product performance in order to meet the market dynamics, in particular, changing consumer habituation and demands. Therefore, companies need more mechatronics engineers along with more data scientists to develop robust AMSs by exploiting system engineering design throughout modelling, simulation, analysing, refining, prototyping, validating, deployment and life-cycle improvement of AMSs with respect to the underlying disparate engineering disciplines. In this context, we envision that new companies highly expertised in designing and developing AMSs and next generation of CPSs will emerge to help other companies develop their own AMSs.

High-level topics concerning today's production of goods and services include sustainability, flexibility, efficiency, and competitiveness [11]. The new consistent revolution will rise over the use of the created wisdom. The increasing volumes of information created in cloud IoT analytics is being turned into wisdom using data mining, AI (e.g., reinforcement learning), ML/deep learning, pattern recognition, vision/image/speech processing etc. This, in turn, has led to an aggregation of data that is now being employed to optimise all steps of the process to ensure higher quality goods, which can be manufactured at lower cost [5]. To the extent of our knowledge, optimisation of all steps of the production process has not been disseminated in the literature, which can be extracted from the framework of AoE discussed and proposed in our study. Regarding exponentially increasing smart applications in increasing smart domains, WaaS is expected be the core architecture of IT applications in the coming era of the hyper-world. It is also anticipated to bring huge economic value for intelligent IT industry by realizing the pay-as-you-go model [51].

With 4IR, the prevalence of robotics in society will be one of the most notable changes. Robots are already utilized in manufacturing facilities across the world. However, the use of robotics is not limited to manufacturing. Recent developments include service robots to help people with vision problems, low-cost robots to assist with grocery shopping, and autonomous robots that can inspect the structural health of nuclear plants and underground mines [21]. The healthcare industry is already using robotics to help perform surgery (e.g., da Vinci Robot), as well as to transport and manufacture medication [21]. More customisable robust products using advanced intelligent machines within 4IR will be developed using more intelligent embedded software techniques with the help of the framework criteria of AMSs and AoE proposed in our study. Consequently, more advanced miniaturized and interconnected AMSs will emerge in the market in the following years, particularly, using AI, MEMS, nano technologies and emerging cutting-edge communication technologies within the AoE. To prevent chaos in the hyper-connected world, businesses need to make every effort to reduce the complexity of the connected systems, enhance the security and standardization of applications, and to ensure the safety and privacy of users anytime, anywhere and on any device [39]. By focusing on user interaction and configurability, on lifetime optimisation, on intelligent analysis of created big data, on location-independent monitoring and control, on data security and reduced system complexity using WaaS, the overall appeal of the final product is grown regarding the design of AMSs within the AoE ecosystem that is proposed in this treatise.

XI. CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

Mechatronics thinking has led to CPS and consequently smart domains which are now transforming MSs into AMSs in smart platforms. The need for a high product diversification based on the continuously changing market and customer demands within customisations, reduced production quantities, reduced concept-to-market lead times and lifetime optimisation of products has resulted in a shift in the approaches adopted for manufacturing, particularly through the availability of smart domains. Against this background, in this study, we analysed the transformation from MSs into AMSs with respect to the recent advances in 4IR, cyber-physical smart domains and platforms, communication technologies, and an architectural design is proposed along with the fundamental features of AMS. By adopting the approaches proposed in this study, 1) companies will be able to track and monitor the performance of their smart products in real time and will be able to fix their problems, most of which on-line, 2) the efficacy of smart products will increase through effective product lifecycle management, 3) the structure of these products will be less complex, consequently less error-prone, 4) the customisation will be easier, 5) the cost will decrease significantly with less number of sensors within less complex structures using WaaSs and InaaSs, 6) customer satisfaction will increase within smoothly working environment with 24/7 seamlessly working products.

The user driven development of new and innovative AMSs will be rapidly replacing the current products in the market. AMSs within the distributed cloud approaching to the edges and 4IR will have a great impact on the economy by transforming many enterprises from digital businesses into intelligent businesses and facilitating new business models, improving efficiency and increasing employee and customer engagement within AoE. We envision that the invention of efficient and robust models in AMSs will further advance the future research and innovative products based on the concepts of AMSs presented in this treatise in a perpetual revolution of the industry. Additionally, the transformation of the big data created both on the edge and cloud platforms into wisdom to establish more services as WaaS and InaaS will be immensely focused on along with the overcoming challenges mentioned in Section IX, which will foster the development of more functional successor models of AMSs and consequently the technological advances of AMSs ought to make our life better and simpler.

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