Introduction to the Special Section: Convergence of Automation Technology, Biomedical Engineering, and Health Informatics Toward the Healthcare 4.0

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***Abstract*—Industry 4.0 is spilling out from manufacturing to healthcare. In this article, we provide a brief history and key enabling technologies of Industry 4.0, and its revolution in healthcare—Healthcare 4.0—and its reshaping of the landscape of the entire healthcare value chain. We discuss the shift in the system design paradigm from open, small, and single loop to closed, large, and multiple loops. We provide the example of a Caregiving Home, and discuss emerging research topics and challenges, including healthcare big data, automated medical production, healthcare robotics, and human–robot symbiosis. Relevant papers published in this special section are also presented.**

***Index Terms*—Caregiving Home, convergence, Healthcare 4.0, healthcare robotics, human–robot symbiosis, Industry 4.0.**

I. INTRODUCTION

THE FOURTH REVOLUTION of industry (Industry 4.0) is reshaping all the segments of industries. Pulled by grand social challenges, automation technologies are dramatically "spilling out" from traditional scenarios, such as factories and workshops, to everyday life. The traditional research areas of biomedical engineering and health informatics for the aging population have gained unprecedented interest from the automation industry. The research landscape in both academia and industry is significantly reshaped with the cross-disciplinary synergy of expertise and the deep convergence of automation technology, biomedical engineering, and health informatics. This trend has been driving the rapid development of health engineering, an emerging interdisciplinary field for the predictive, preventive, precise, and personalized medicine. More powerful tools from process or factory automation, such as distributed control systems and robotics, are penetrating into biomedicine and healthcare applications [1], [2]. For example, research activities related to robotics for biomedicine and healthcare have been largely intensified in the recent years [3], [4].

The goal of this special section is threefold: 1) to review the advancement in the convergence of automation technology, biomedical engineering, and health informatics; 2) to identify the gap between the state-of-the-art of research and industrial demands; and 3) to envision the directions for future research. The application scenarios can cover single or multiple scenarios of health engineering, such as primary care, preventive care, predictive technologies, hospitalization, home care, and occupational health. We focus on the cross-disciplinary approaches, solutions, and initiatives rather than single disciplinary ones.

II. IMPACT OF INDUSTRY 4.0 TO HEALTHCARE

A. Industry 4.0 Basics and Key Technologies

Industry 4.0 (also sometimes spelled as Industrie 4.0) is a vision for a new industrial revolution put forward by the Communication Promoters Group of the Industry–Science Research Alliance to further enhance Germsany's manufacturing industry [5]. Several other countries, such as China and India, followed by articulating similar visions. The current advances in the following areas trigger the Industry 4.0 vision.

Cyber-physical systems (CPS) refers to the area where systems incorporate computation and physical processes. The sophistication that is reached in harnessing machine control through computing provides unprecedented efficiency in the physical processes and gives levels of performance never reached before. As early as the 1970s, we started to design systems where we embedded the computing driven control into

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the hardware. However, the control was quite simple. The computing systems that are the focus in CPS are of a complexity at an unprecedented scale. They are expected to perform cognitive and communication tasks that go beyond a simple proportional-integral-derivative controller [6].

Internet of Things (IoT) is a concept that captures the increasing capabilities that we recently gained in connecting almost any device to any other device through Internet. This applies as well to components in a manufacturing process or in any cyber eco-system of medical and residential components as one would find in a smart home. This concept of IoT brought this vision of allowing components, such as workpieces, to communicate with transformation machines [7].

Internet of Services is a concept that captures the possibilities of web-based service economy. Service providers would use the Internet to provide a vast range of services tailored to each client and coupled to a specific manufactured component or system. It ties the products to services at a global level. Imagine a hearing device that allows audiology-service providers to access it and offer remote tuning to make it more appropriate for the environment of the user. One can register with an audiology service provider to make sure that at all times the device is tuned to suit its environment whether it is a restaurant, a construction field, or a quiet area [8].

Cloud computing is the concept of delivering as needed on a pay-for-use basis, over the Internet, of computing resources from applications to data storage or usage capacity. It provides users with tailored computing capabilities and capacity without major investments in infrastructure [9].

Artificial intelligence (AI) refers to the algorithms or systems developed and endowed with the intellectual processes characteristic of humans, such as the ability to reason, discover meaning, or learn from past experience. This emerging technology has currently been applied in diverse applications in advanced healthcare and medical systems, and it is on the rise solving a variety of problems for patients, hospitals, and the healthcare industry overall [10]. It approximates human cognition capability in the analysis of complex health or medical data for the prevention or treatment techniques, such as diagnosis processes, drug development, treatment protocol, personalized medicine, and patient monitoring and care [11], [12].

Although advanced statistics and machine learning provide the foundation for AI [13], revolutionary advances are currently underway in related subfields, such as natural language processing [14]. As a result, it has created tremendous excitement in many fields of science, including in medicine and public health. In addition, AI-based tools are already appearing in health or medical oriented applications that can be employed on wearable and networked smart devices [15]. This enables machines to sense, comprehend, learn, and act so they can perform administrative and clinical functions [16], [17]. Combining with life science, AI has the potential power to reshape the future of public health, community health, and healthcare delivery aiming to achieve a higher quality of life [18], [19].

B. Impact of Industry 4.0

The design of Industry 4.0 systems exhibits a list of characteristics that are given in [5]. They have to be modular, involve interoperable components and virtualization technology, encompass real-time capabilities, and are service oriented.

This Industry 4.0 vision had a huge impact on society in general and almost on all the sectors of the economy. Obviously, it had already impacted the manufacturing sector. New designs of smart distributed manufacturing ecosystems are put forward. This new revolution ignited by Industry 4.0 vision has the potential to raise global income levels and improve the quality of life for populations around the world. Moreover, its impact will very likely bring more prosperity to societies that are able to afford and access the digital world. Therefore, digital infrastructure is the prerequisite for benefitting from the opportunities created by Industry 4.0. In [20] and [21], we find that this revolution will be changing the relations between consumers, service, and product providers. Providers of service and goods need to work hand-in-hand with consumers to ensure their adaptability to smart product characteristics.

This revolution, while it started as a vision for innovation in manufacturing, is taking roots in all aspects of human life. For instance, providing healthcare and health services to a growing aging human population is one of them.

C. Healthcare 4.0: Spill-Out of Industry 4.0 From Manufacturing to Healthcare

As indicated above, the vision of Industry 4.0 spilled over other sectors of the economy. The health domain is one example of human activities affected by Industry 4.0. For example, the European strategy for empowering patients using the technological advances similar to those on which Industry 4.0 is based has been articulated for the period 2012–2020 [29]. It aims at addressing the problem that healthcare delivery systems in the members of the European Union are more and more faced with the challenges to deal with the growing demand for high quality services while the resources are getting scarcer. Using the technologies behind Industry 4.0 is perceived as a viable direction to reduce administrative costs, enable cross-institutional documentation of therapy activities, and to innovate by proposing new value-added services [30].

By analogy to Industry 4.0, “Healthcare 4.0” has been used to denote the trend that more and more technologies incubated in manufacturing industries driven by Industry 4.0 are being adopted in healthcare industries and services. Despite its broad acceptance as the vision for the future of manufacturing industries, the term of Industry 4.0 has not been intentionally and precisely defined so far due to the fuzzy meaning to be captured. We believe it is also difficult to give a strict definition for Healthcare 4.0 due to the same reason. But we still want to have a try to give an intentional definition for Healthcare 4.0 to unify the vision, the understanding, and communications in the future given the hyper importance of this concept.

An illustration of the concept of Healthcare 4.0 is given in Fig. 1. As an emerging revolution in healthcare industries and services powered by the technologies originated from manufacturing industries driven by Industry 4.0, Healthcare 4.0 is a continuous but disruptive process of transformation of the entire healthcare value chain ranging from medicine and medical equipment production, hospital care, nonhospital care, healthcare logistics, healthy living environment to financial and so-

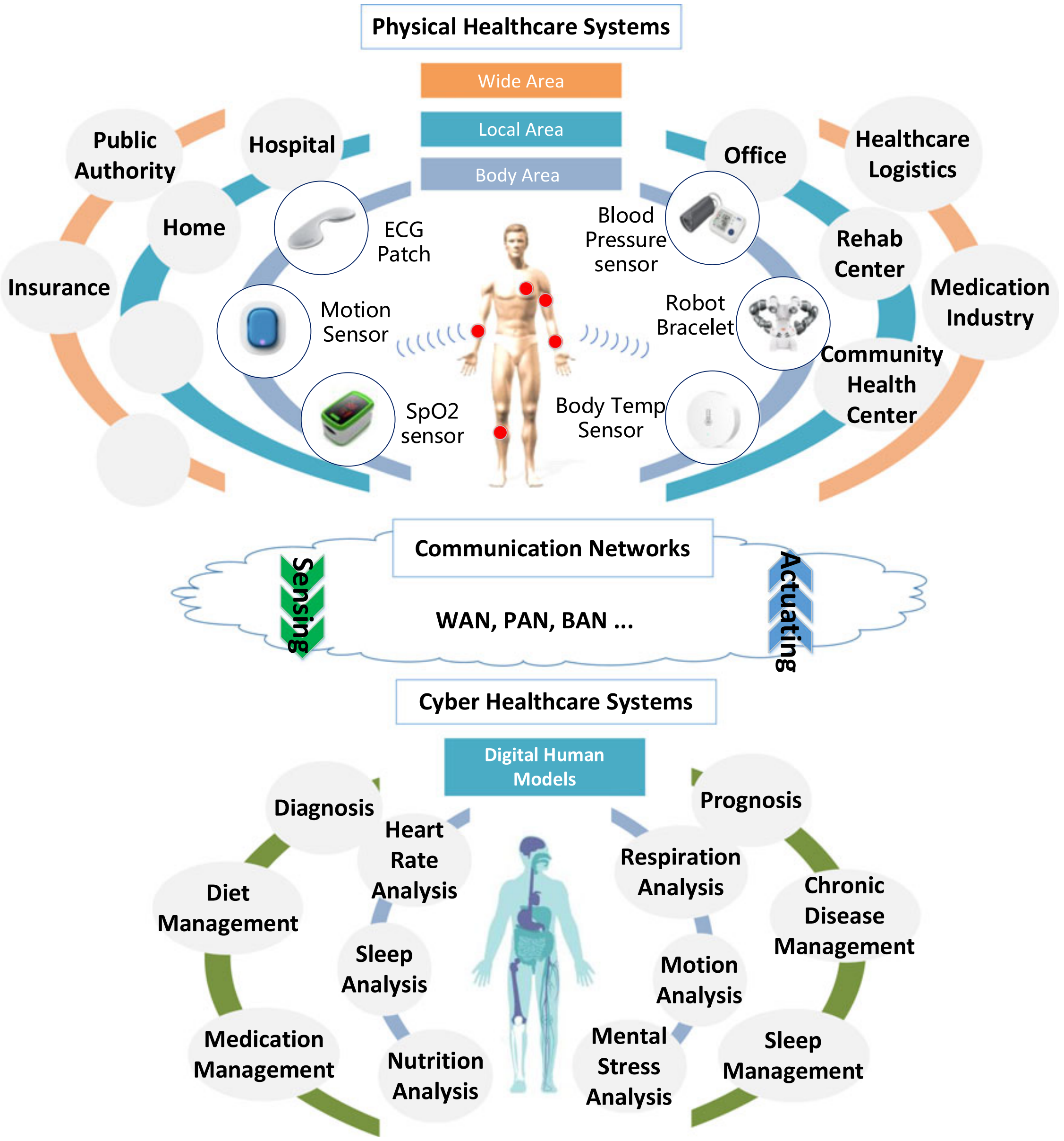


Fig. 1. Illustration of the concept of Healthcare 4.0.

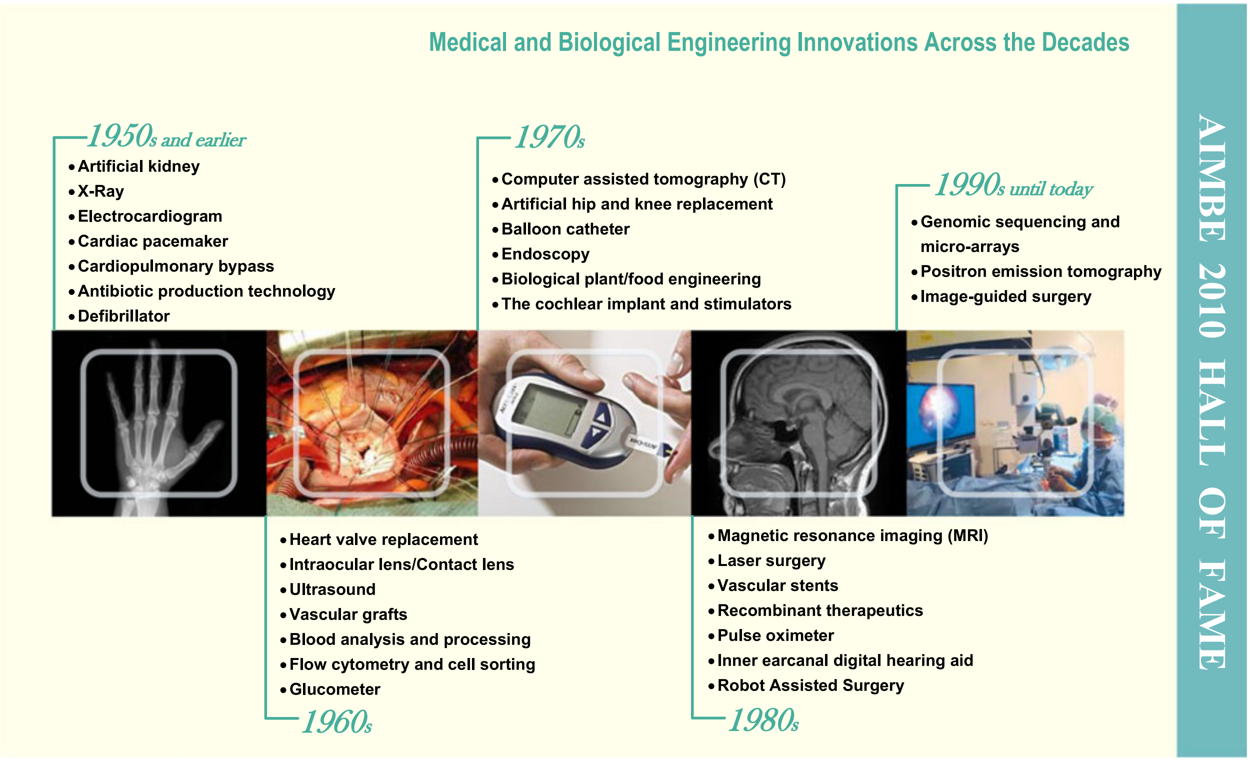
cial systems, where vast amount of cyber and physical systems are closely combined through the IoT, intelligent sensing, big data analytics, AI, cloud computing, automatic control, and autonomous execution and robotics to create not only digitalized healthcare products and technologies but also digitalized healthcare services and enterprises.

D. Correlation Between Industrial Technology Revolutions and Healthcare Technology Revolutions

In their Hall of Fame, the American Institute of Medical and Biological Engineering has selected a number of seminal advancements in both medical and biological engineering more than the past 100 years, as shown in Table I [22]. We further traced back the history of the clinical adoption of these modern healthcare technologies especially medical equipment. When we put these milestones with the history of industrial revolutions [23] together, we have observed interesting temporal correlation in between, as shown in Fig. 2. To systematically and positively explain this correlation is out of the scope of this article, but it is worth giving a hypothesis: The engineering capabilities introduced by industrial revolutions (Industry 1.0 to 4.0) are the foundation of the corresponding revolutions of healthcare technologies (Healthcare 1.0 to 4.0).

In the age of the first revolution (Industry 1.0 and Healthcare 1.0), some basic modern medical tools were invented and applied in clinics, such as flexible tube stethoscope (1840s), piston syringe (1850s), and portable clinical thermometer (1860s). These medical tools introduced in Healthcare 1.0 are passive devices without power supply, simpler than the active devices introduced later, but the production of these

TABLE I
AMERICAN INSTITUTE FOR MEDICAL AND BIOLOGICAL ENGINEERING'S HALL OF FAME [22]



Medical and Biological Engineering Innovations Across the Decades

1950s and earlier
- Artificial kidney
- X-Ray
- Electrocardiogram
- Cardiac pacemaker
- Cardiopulmonary bypass
- Antibiotic production technology
- Defibrillator

1960s
- Heart valve replacement
- Intraocular lens/Contact lens
- Ultrasound
- Vascular grafts
- Blood analysis and processing
- Flow cytometry and cell sorting
- Glucometer

1970s
- Computer assisted tomography (CT)
- Artificial hip and knee replacement
- Balloon catheter
- Endoscopy
- Biological plant/food engineering
- The cochlear implant and stimulators

1980s
- Magnetic resonance imaging (MRI)
- Laser surgery
- Vascular stents
- Recombinant therapeutics
- Pulse oximeter
- Inner earcanal digital hearing aid
- Robot Assisted Surgery

1990s until today
- Genomic sequencing and micro-arrays
- Positron emission tomography
- Image-guided surgery

AIMBE 2010 HALL OF FAME

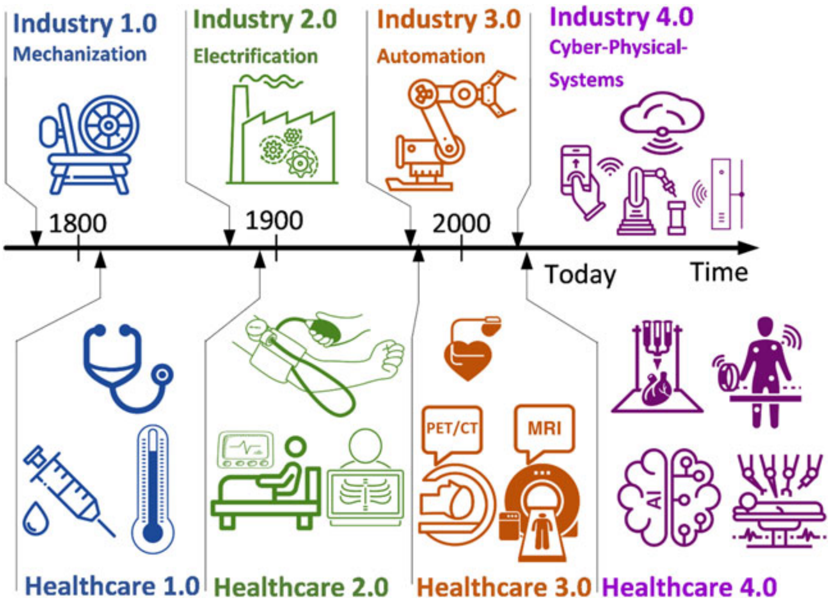


Fig. 2. Temporal correlation of the revolutions in industry and healthcare technologies. (Icons are created by Eucalyp, Laymik, Ben Davis, Mary Bowie, Artem Kovyazin, Bernar Novalyi, Linseed Studio, jhonythomang, Sergey Demushkin, Grant Fisher, Vectors Market, priyanka, Peter van Driel, Gan Khoon Lay, Jonathan Coutino, Bohdan Burmich, mungang kim, Becris, Sunny Gurmakh, and Delwar Hossain from Noun Project. https://thenounproject.com/).

tools needs sophisticated mechanical design and processing. The mechanical design and processing techniques developed through Industry 1.0 made it possible.

When it comes to the second revolution (Industry 2.0 and Healthcare 2.0), more complex medical equipment were invented and applied in clinics, such as X-ray imaging (1890s), sphygmomanometer (1890s), and electrocardiograph (1900s). These new medical technologies mostly employ complicated electrical and electronic engineering in addition to the mechanical engineering. The electrical power introduced by

Industry 2.0 brought medical equipment into the era of electrification.

Later on, in the age of the third revolution (Industry 3.0 and Healthcare 3.0), the advancement of microelectronics, computer science, automation, and biomedical engineering enabled the invention and adoption of more complex medical systems, such as brightness mode ultrasonography (1960s), implantable pacemaker (1970s), X-ray computed tomography (1970s), magnetic resonance imaging (1980s), artificial heart (1980s), Positron Emission Tomography (1980s), and many more [22]. All these medical systems need sophisticated design of mechanics, electronics, computer software, and control algorithms. High-precision processing and quality control is prerequisite to produce such systems. Without the advanced manufacturing technologies introduced by Industry 3.0, it is not possible to make them into reality.

The above observation has confirmed the envisioned prospect of Healthcare 4.0 powered by the key technologies introduced by Industry 4.0, such as cyber physical systems [24], IoT and services [25], AI [26], big data [27], robotics [4], bio-three-dimensional (3-D) printing [28], connected wearable devices [29], etc., it is happening in the recent years rapidly.

E. Impact of Healthcare 4.0: A Leap Toward the 8-P Healthcare

After Healthcare 4.0, the entire healthcare segment have achieved significant progress toward the ultimate vision of 8-P Healthcare: preventive, predictive, participatory, patient-centered, personalized, precision, pre-emptive, and pervasive healthcare [25], [30], [31].

Pervasive and Preventive Healthcare: In Healthcare 4.0, much more smart and unobtrusive sensors will be deployed not only on human body but also in the ambient environments through the digitalization of living infrastructure especially before one becomes sick. The interoperability of medical devices to reach more accurate and complete data sets that facilitate better service or diagnoses is key aspect of the systems of Healthcare 4.0. Distributed and connected health records repositories and flows of real-time data from wearable devices to data analytics present us with more possibilities in the performance, scope, and quality of healthcare services and capabilities [32–36]. Intelligent actuators especially robots will also become more popular, which will significantly increase the effectiveness of telehealth and remote caring. Thus, unprecedented real-time and exhaustive information and comprehensive coverage of living scenarios can be provided to professionals for more pervasive and preventive healthcare.

Personalized and Precision Healthcare: Moreover, superior interoperability and collaboration crossing the boundaries of different organizations will be enabled by digitalization of enterprises. The above real-time data will be seamlessly fused and analyzed together with all genic data, personal healthcare records, and other historical data captured by various organizations. All these data can be precisely linked with the corresponding individual with guaranteed privacy preservation. Thus, the diagnosis and treatment will become more personalized and precise [28].

Patient Centered Healthcare: Once the barriers of information flow throughout the entire healthcare service flow is broken down, Healthcare 4.0 can provide patients with seamless integration of patient flows and holistic optimization and scheduling of healthcare process. For example, in Sweden, the university hospital of Karolinska Institute, host of The Nobel Assembly that awards the Nobel Prize in Physiology or Medicine, has built a new hospital which will apply the latest automation technologies to enable the patient-centered care process compared with the transitional doctor/equipment-centered care [37].

Among the 15 global challenges facing humanity, one is about how can scientific and technological breakthroughs be accelerated to improve the human condition. Improving human health management within physical, mental, emotional, and social contexts can be achieved using the technologies driving Industry 4.0. It would give the technical possibilities to patients from remote areas or developing world to have access to experts in advanced health facilities through the globe. However, ethical, legal, and political barriers might be obstacles that ought to be overcome in order to gain all the benefits from this possible health revolution. The deep cross-disciplinary convergence of computing, commination, automation, biomedical engineering, and health informatics is the key for future research in academia and industries.

F. Shift of Design Paradigm

A primary change made by Healthcare 4.0 to the conventional healthcare is the shift of system design paradigm from open loop to closed loop, from small loop to large loop, and from single loop to multiple loops [38–41].

Take the scenario of home care as example. Since the concept of Smart Home was first demonstrated by the house of Bill Gates in 1997, tons of single point devices and systems have been developed to provide condition monitoring, human activity monitoring, health status tracking, remote operation of home appliances, or several other needs. In general, there is a lack of synergy among the automation, biomedical engineering, and health informatics technologies. As a result, these systems are mostly open loop and isolated from each other. Therefore, the value proposition of existing Smart Homes is still mainly about user experience and showing off. In the era of Healthcare 4.0, we believe that the new generation concept of Caregiving Home will become a reality enabled by the smart sensing, broad data fusion, and multiloop intelligent execution [42], [43].

An example of the shift of design paradigm in the scenario of Caregiving Home is illustrated in Fig. 3. The Caregiving Home seamlessly integrates all the smart devices in the home environment by heterogeneous but interoperable communication networks, collects exhaustively detailed data about human health and condition of infrastructure through various smart sensors [25]. It also performs broad data fusion, analytics, and decision making aided by AI [44–46]. Moreover, eventually it closes the loop by intelligent execution through all kinds of actuators, such as home automation devices, medical equipment, and home service or nursing robots. By shifting to such closed, large, and multiple loop design, the Caregiving Home systems will be able to take care of people. This will be revolutionary

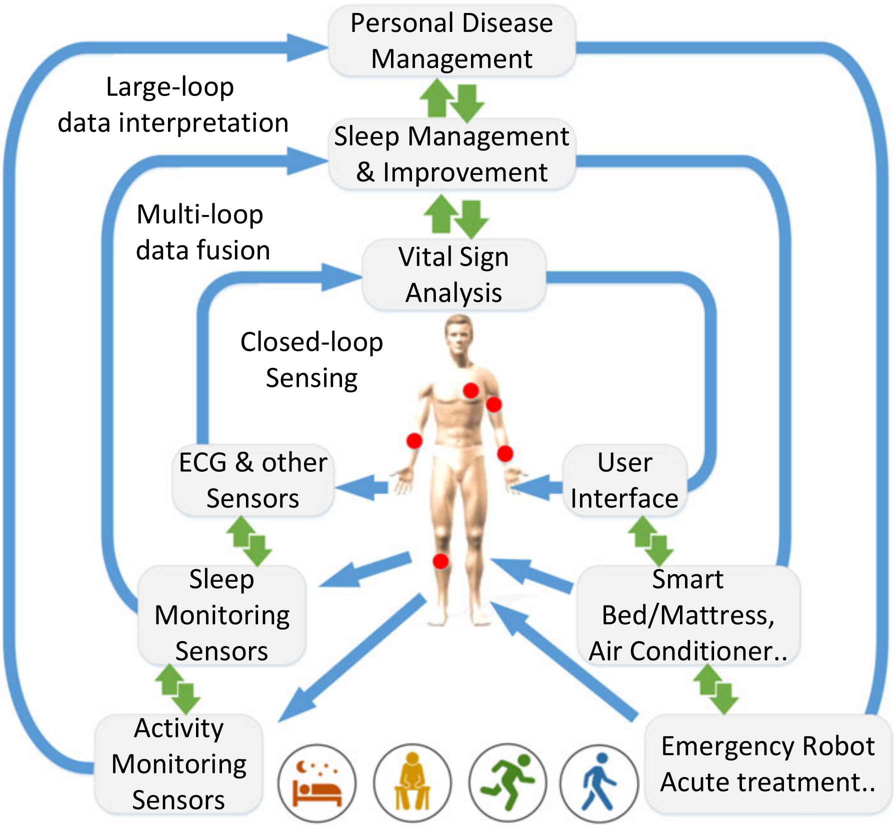


Fig. 3. The Healthcare 4.0 design paradigm shift: from open loop to closed loop; from single loop to multiple loops; and from small loop to large loop in the scenario of Caregiving Home.

impact the society given the serious challenge of population aging [47–50].

III. EMERGING RESEARCH TOPICS AND CHALLENGES

Given the general impact of Healthcare 4.0 as abovementioned, we will discuss some of the emerging research topics and challenges pushed by the convergence of automation, biomedical engineering, and health informatics.

A. Automated Medical Production

As a subsegment of advanced manufacturing, the production of medicine and medical equipment will be largely impact by Healthcare 4.0. Productivity, reliability, resource efficiency, process precision and quality, and cost effectiveness will be improved by the adoption of advance automation and robotics technologies. As a good example of this impact, the paper "Detection and Automation Technologies for the Mass Production of Droplet Biomicrofluidics" by Wang reviews the latest progresses of the adoption of automation technologies in the production of droplet biomicrofluidics, which is an important technology for many industrial and clinical applications, such as biosensors, regenerative medicine, and drug delivery. The review has concluded that with the advances in parallel droplet generation, highly sensitive detection, and robust closed-loop regulation, the productivity and reliability of droplet biomicrofluidics will be significantly improved to meet the industrial and clinical needs.

B. Healthcare Big Data

Making use of the tremendous volume of patient related data to improve healthcare and health services is essential to a meaningful progress in quality care. The big data in healthcare is also coming from the huge volume of data gathered from wearable devices [51], [52]. A high volume of details on patients is being collected daily. They include a wealth of knowledge on diseases, their progress, and their cures. Combining the use and the analysis of variety of structured and unstructured data from multiple sources plays an important role in diagnosing patient conditions, matching treatments with outcomes, and predicting possible complication to patients' health. For instance, it has the potential to take evidence-based medicine to a higher level and to expand its scope from local to global reach. It would provide this practice of medicine with information systems that provide decision support to doctors at the time of making decisions. Therefore, predicting, modeling, and analysis of health related big data is one of the key technological foundations for a true health revolution.

The paper "Chronic Diseases and Health Monitoring Big Data: A Survey" by Lin *et al.* gives an extensive review on the latest progresses in medical big data on chronic diseases and health monitoring covering the full cycle of medical big data processing from data preprocessing, tools and algorithms, data visualization, and security issues. This review also tries to fill the gap between common big data technologies and the specific needs of medical big data.

C. Healthcare Robotics

Through technological innovation, robotics has drastically reshaped the landscape of healthcare both in its structure and its operation for the last decade [44], [53–59]. Healthcare robotics becomes one of the fastest growing field of robotics penetrating the fields of traditional medical treatment and healthcare with the most advanced robot technology, including surgical robots [60–62], catheter robotics [63–66], medication management robots [67], hygiene robots [68], and companion robots [69–72].

Surgical robots become increasingly precise today. By leveraging magnified 3-D high-definition vision system and highly flexible wristed instruments, surgical robots are able to precisely bend and rotate far greater than the human hand can do. With the help of surgical robots, the surgeon is able to carry out minimally invasive surgery and conduct more precise operations than ever with smaller incisions and faster healing.

Catheter robots are devices that enable surgeons to perform medical procedures within a patient's blood vessels without the need of open surgery. Considering the procedure is time-consuming and delicate, surgeons need accurate, flexible, and effective catheters. From technical point of view, it is challenging to precisely manipulate and accurately position the catheter tip at the target tissue and meanwhile provide a stable contact force for a specific duration to the region of interest. To address these issues, technological innovation of advanced catheter tip is highly required for the future steerable catheter robots where hybrid integration technology can be leveraged to integrate flexible sensing [73], [74] and actuating [75–77] functional units into the catheter.

When it comes to medication management or other healthcare workflow, robotics for medication and pharmacy automation eases the work of medical professionals, nursing staffs throughout the whole healthcare spectrum, and relieves them from monotonous and repetitive daily tasks.

It is believed that with the integration of advanced sensing, actuation, and embedded computing, AI technology, etc., future healthcare robotics can find its applications in a wider range and more sophisticated medical and healthcare treatment scenarios.

D. Human–Robot-Symbiosis

With rapid advances in robotic technology, a variety of advanced robots have been developed within the last few decades. These robots enter into people workspaces or living spaces, operating side by side with humans or assisting humans with specific tasks, e.g., social robots, assistive robots, etc.

With such a context, enhanced robot interactions toward the human–robot symbiosis are highly required, in particular, the capabilities of natural, safe, and effective human–robots interactions [78]. Integrated with dedicated sensors and advanced control algorithms, active-safety strategy allows the robot constantly monitoring its surroundings and dynamically changing the behavior of manipulator in potentially risky situations: intentional and unintentional human–robot contacts or collisions. Increasingly sophisticated sensing technology, such as large-area multisensory conformable sensor skin or haptic device, which can be bend and mounted onto the surface of the moving parts of the robot [79], has the potential to play a vital role in the active-safety for the future collaborative human–robot interaction [80], [81].

In addition, the emerging assistive robotics has been gaining increased attentions both from industry and academia, which can sense, process sensory information, and perform tasks that benefit people with disabilities and seniors. These assistive robots have many exciting and powerful uses, such as second-body assistive robots. With enhanced function and strength, these devices allow paralyzed people to walk and improve the day-to-day life of patients, and also facilitate the rehabilitation of stroke or spinal cord injury patients helping them to regain the ability to walk. The paper "Advances in Automation Technologies for Lower-Extremity Neurorehabilitation: A Review and Future Challenges" by Deng *et al.* provides a comprehensive review on recent technological advances in wearable sensors, biofeedback devices, and assistive robots for lower-extremity neurorehabilitation, which is one of the most active application areas of assistive robotics. The authors envision that these advanced technologies will become commercially available for the daily care of patients in the very near future despite the required improvements in safety, security, efficiency, and usability.

E. Smart and Unobtrusive Sensing

In the past decade, considerable efforts have been made on developing advanced biomedical and healthcare sensing systems to enable physiological and psychological monitoring [82], [83], which can be applied in novel application scenarios, such as human–robot interface and interaction, pervasive and personalized healthcare applications, etc., [84], [85]. From technology point of view, trends for those sensing devices are to be featured as unobtrusive, miniaturized, comfortable, networked, and long lasting to meet the requirements for smart and unobtrusive sensing [30].

In most of the cases, the sensing devices or smart sensors are integrated in living or working space, or be embedded in a garment, or have direct contact with human body for relatively long time, therefore, more emphases have been put on sensor miniaturization and enhanced user experience. The resulting sensors should be unobtrusive and easy to be attached on human body or hidden into a wearable system [86], [87]. Examples can be found in wearable or implantable medical devices, including advanced biosignal acquisition and processing circuits and system integrations [88–97], neural recording and neural tissue stimulator [98–106].

In contrast, quite many issues have been identified as potential challenges, which hinder the wider use of these unobtrusive sensing systems [107–109]. These issues include: multi-parameter measurement, multisensorial data fusion, materials biocompatibility, large health data collection and proper analysis, power consumption and energy scavenging, security of private information, encryption and authentication of data communication, smart sensor miniaturization and system's wearability, etc. These challenges need to be further addressed in order to improve the security, efficiency, accuracy, and the interoperability of the smart and unobtrusive sensing systems. And these identified challenges may help researchers and developers in the field with possible directions for the further research. The paper "Noncontact Wearable Wireless ECG Systems For Long-Term Monitoring" by Majumder *et al.* systematically reviews latest advances in key technologies for ambulatory ECG systems, including flexible electronics, wireless communications, system architectures, integrated circuits, and commercial portable ECG systems, then a new design of noncontact wearable ECG system based capacitive electrode is proposed, which presents a good balance among signal quality, size, and power consumption.

IV. FUTURE DIRECTIONS AND CHALLENGES

Despite all the optimism around Industry 4.0 and Healthcare 4.0, we should keep in mind that we are at the early stages of the adoption of these visions for manufacturing and healthcare. While the steady adoption of these two visions is continuing during the last years, many inherent challenges remain and new ones are arising from the new progresses made in implementing them. Massive funds are currently allocated to research and development supporting the scope and quality of Industry 4.0 and Healthcare 4.0 expansion, which is a good sign that these two visions are taking roots and expanding.

The challenges are inherent to the nature of Industry 4.0 and Healthcare 4.0 systems. As explained in Section II-B, Healthcare 4.0 systems have the same characteristics as those of Industry 4.0. For example, these systems can be distributed to fall under diverse political authorities, cultures, managerial practices, legal systems, or governance policies. This context, in which the systems operate, requires concerted collaborations not only at the technical level, but also at other facets, such as the legal and the political ones. These systems involve assets that are critical and expensive. They exchange data that is strategic and vital to several stakeholders. Therefore, security of the data and the installations are of paramount importance. The privacy of the users and the compliance to regulations related to privacy or other regulated activities in many countries can determine the success or the failure of revolution whether in industry or in healthcare.

These challenges can be partially overcome by adopting new standards for communication between the components of Industry 4.0 ecosystems. Also, new system architecture design patterns to separate these challenging aspects (such as legal, security, and privacy) are needed. We saw with the expansion of service oriented architecture as a design solution to put together services that are distributed and require some "intelligence" to make good use of their capabilities was greatly supported by the enterprise service bus architectural pattern. Similar patterns need to be developed for systems of Healthcare 4.0 to decouple the challenging aspects (e.g., security, privacy, legal, and managerial aspects).

To best assist patients and clinical professionals, Healthcare 4.0 embraces the future developments across the broadest healthcare space: cognitive computing, smart homes, cyborg clinicians, and robotics, etc. Powered by AI and natural human–robot interfacing technology, healthcare robotics is boosting up and gaining the capability of interpreting human intentions and interacting with environments and other agents, either people or robots. This provides a powerful tool for patient's rehabilitation, assistive, and independent living. However, significant challenges can be foreseen for the future adoption of healthcare robotics: the acceptance of healthcare robotics applications in clinical practice; the availability of quality training data from which to build and maintain AI applications in robots; the human safety issue during human–robot interaction, in particular, in the uncertain and dynamic environments, and the corresponding legal issues. Solutions at different levels (e.g., technical, legal, and political level) are required before healthcare robotics can find its wider use in the future in the above-mentioned application scenarios.

Another challenge that is put by Healthcare 4.0 and Industry 4.0 is on the shoulders of education institutions. Universities and professional schools need to come up with programs that prepare the engineers, technologists, and other qualified staff to conceive, build, assess, operate, and maintain these systems. University programs, such as eHealth, biomedical engineering, and smart systems engineering, are timid steps in this direction to provide qualified personnel for these tasks. For a more adapted training that brings on the top of health and biomedical background (in the case of Healthcare 4.0), an understanding of privacy, security, and cognitive computing systems related issue would be needed to support the Healthcare 4.0 vision.

The growing awareness of the visions of Industry 4.0 and Healthcare 4.0 will certainly bring more discussions leading to concerted solutions to some of the above challenges.

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