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Revolutionary tools for smart cities, manufacturing, and mechanics

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Research Article
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ABSTRACT
New advances in advanced manufacturing, nano-information-technology, and smart civil infrastructure technologies follow an introduction to the convergent technologies that are driving the 4th Industrial Revolution. The article delves into the topic of the convergence of disruptive technologies. Energy harvesting, sensors, smart structures/materials, advanced manufacturing, nano mechanics/materials, structural control, multi-scale challenges, and simulation approaches are the main areas of focus.

KEYWORDS: Nano-materials; smart structures; energy harvesting; advanced manufacturing; simulation and multi-scale problems

Introduction

When it comes to developing novel molecular-level materials, sensors, devices, and systems, nanotechnology is by far the most efficient method [1–5]. However, there have been recent developments in smart materials across a wide range of applications, including sensing, miniaturisation, control, energy harvesting, structural health monitoring, improved manufacturing, and catastrophe mitigation [6–14]. All of these multidisciplinary fields have mechanics as a unifying factor [15,16]. About a century separated the first three industrial revolutions, each of which had a profound impact on global society. In terms of production, connection, education, and every facet of life, the fourth industrial revolution has already had enormous repercussions, and it occurred only a few decades after the third. Recent developments include, but are not limited to, cloud computing, big data, the Internet of Things (IoT), and so on. Internet of Things (IoT) enabled sensors will bring in $10 billion worldwide in 2020, says ECN magazine's January 2017 edition. Characteristics of the various industrial revolutions are detailed here [5,17,18]:

1st 1784: mobilized the mechanization of production using steam power.
2nd 1870: mass production with the help of electric power.
3rd 1969: Arpanet, internet, digital revolution and the use of electronics and IT to further automate production.
4th present: a convergence of new technologies: AI, nanotechnology, cloud com-puting, robotics, 3-D/4-D printing, biotechnology, big data…

According to the National Science Foundation (NSF; www.nsf.gov), some of the recent initiatives on smart systems involved:

Robotics: Electronic, mechanical, computing, sensing devices and systems, controls, and intelligent systems that enable ubiquitous, advanced robotics
Cyber-Physical Systems: Integration of intelligent decision-making algorithms and hardware into physical systems

Simulation

Engineering and science have been greatly impacted by the extensive use of digital computers and simulation [19-29]. An

precise physical model of the issue and a good understanding of the assumptions used are often the first steps towards a practical and effective solution in engineering. We can now model and analyse complicated physical systems and issues with the use of big data, cloud computing, simulation-based engineering and sciences, computer hardware, and the right software. To avoid making mistakes or just accepting computer findings at face value, it takes a lot of training and expertise to make good use of numerical data from programmes. Chong, a senior author, helped establish in 2005 the National Science Foundation Blue Ribbon Panel on Simulation-based Engineering Science, which was led by Prof. J. Tinsley Oden. The panel's ambitious proposals included topics such as computational mechanics, simulation, and related fields. Government organisations are still putting a lot of money into research and development, which has a significant effect on the fields of engineering and science. The present Fourth Industrial Revolution relies heavily on Engineering Science based on simulations [25]. To illustrate this point, consider the US President's Material Genome Initiative (MGI), which he unveiled in 2011. This programme aims to build novel material systems utilising powerful computer modelling and simulation techniques and extensive datasets. Its website may be found at https:// www.whitehouse.gov/mgi. According to MGI, the NSF Blue Ribbon Panel report was cited. Over the last two years, after the inauguration of MGI in 2011, the federal government has allocated more than USD 250 million for new research and development. Sector investments amount to a lot more. Problems essential to engineering science that relies on simulations [25] include:

Tyranny of Scales
Verification, Validation, and Uncertainty Quantification
Dynamic Data Driven Simulation Systems
Sensors, Measurements, and Heterogeneous Systems
New Vistas in Simulation Software
Big Data and Visualization
Next Generation Algorithms

According to the Moore's Law, the computer speed double every 18 months over the last 30 plus years. However the software usually lags behind the hardware. The following figure (Figure 1) is a rare example where the software is leading [26].

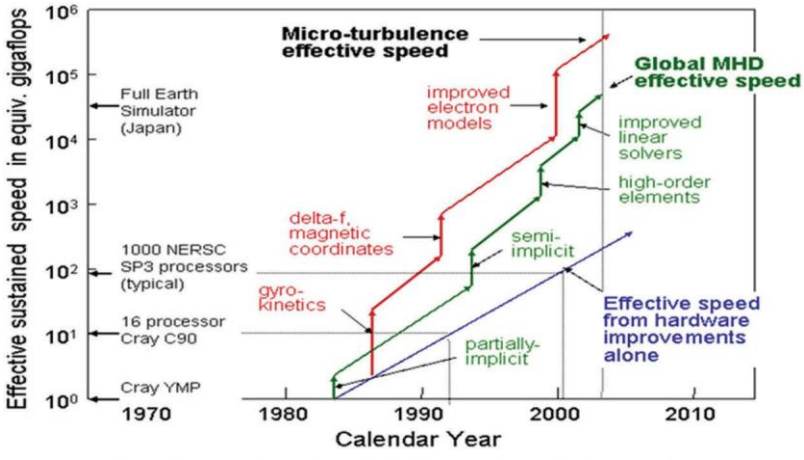


Fig: Moore's Law for MHD [magneto hydrodynamics] simulations. "Effective speed" increases from faster hardware and improved algorithms. [Keyes, et al ,2004]

Figure 1. Software speed leading hardware.

Multi-scale problems

By harnessing the power of atomic and molecular interactions, nanotechnology has the potential to revolutionise the way we create new materials, devices, and systems at the molecular level. This field has the ability to greatly enhance mechanical, optical, chemical, electrical, and other macroscopic material properties [1,3,25,27]. 'Nanoscale technology will have an effect similar to the Industrial Revolution,' said Rita Colwell, the former director of the National Science Foundation in 2002. Studying the multi-scale challenges is necessary since nanotechnology has to scale up in order to create practical systems and devices [20,28-32]. Table 1 below lists the many scales and the subjects they cover, as mentioned in an older version of Boresi and Chong's Elasticity work from 2000 [15].

Sequential and concurrent approaches are the two mainstays of multi-scale modelling. Here are some advantages and disadvantages of both approaches [33],

Sequential Multiscale Modelling

(pro) the idea is straightforward; the theories/principles at each level are mature (e.g. continuum mechanics, molecular dynamics, quantum mechanics, etc.), and therefore we just adopt different theories/principles at different scales and passed information in a bottom-up way or top-down way.

Table 1. Scales in materials/structures.

Materials	Structures	Infrastructures		
Nanolevel~	microlevel~	mesolevel~	macro-level~	systems integration
Molecular Scale	*Microns*	*Meters*	*Up to km Scale*	
nanomechanics self-assembly nanofabrication	micromechanics microstructures smart materials	mesomechanics interfacial composites	beams columns structures plates	bridge systems lifelines airplanes

(con) the connection between different length scales is weak, since not all information at one scale can be totally passed to its higher or lower scale.

Concurrent Multiscale Modeling

(pro) can solve the problem efficiently while still maintain high resolution at critical region
(con) some problems cannot be solved well. The typical un-solved challenge is how crack/dislocation/heat can propagate from the critical area to non-critical area.

Advanced manufacturing

According to the National Science Foundation, advanced manufacturing enables inno-vation capacity for manufacturing by emphasizing research on:

cyber-enabled, adaptive, agile, and distributed manufacturing for the 'Factory of the Future'. Cyber manufacturing uses advances in sensors, networks, software, modeling, simulation, and computation transforming the 'Factory of the Future' and create new manufacturing eco-systems, which are distributed, flexible, adap-table, accessible, efficient, economic, personalized.
nanosystems design and scalable nanomanufacturing
advanced biomanufacturing

Advanced manufacturing is a family of activities that depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or
make use of cutting-edge materials and emerging capabilities enabled by the physical and biological sciences, for example nanotechnology, chemistry, and biology.

It involves both new ways to manufacture existing products, and the manufacture of new products emerging from new advanced technologies [34,35]. Cloud manufacturing is also an enabling tool [36].
According to Jay Lee [18], future factories involve attributes based on 'self' sensing, controlling, networking – see Table 2.
Scalable nano-manufacturing (NSF 15–107; www.nsf.gov) is a NSF research initia-tive to *overcome the key scientific and technological barriers* that prevent the produc-tion of useful nanomaterials, nanostructures, devices and systems at an *industrially relevant scale*, reliably, and at low cost and within *environmental, health and safety guidelines.*
One of the shortcomings of 3-D printing [37] is the weak interfacial strength between layers of materials printed. The properties along the layers are different than those across the layers, behaving like a transversely isotropic material [15]. To overcome this weakness, vertical reinforcements can be pre-positioned like reinforce-ment in a concrete column shown below (Figure 2).

Table 2. Comparison of manufacturing technologies.

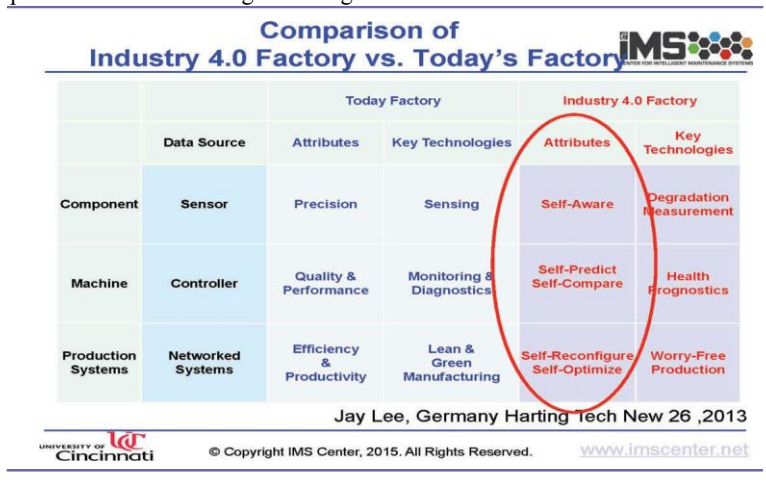




Figure 2. Vertical reinforcement in a column.

As for the 4-D printing [38], instead of building static 3-D items from layers of plastics, metals or other materials, 4-D printing employs dynamic materials, such as piezoelectric materials, that continue to evolve in response to their environment after fabrication.

Smart infrastructure

Smart structures refer to next-generation structures with self-diagnosis and prognosis, self-healing and repair, self-powered, and self-adaption abilities by integrating the technological advances in smart materials, smart sensors, structural health monitoring, structural control, and artificial intelligence. Smart structure technology may consider-ably enhance the functionality, reliability, safety and longevity of civil and mechanical structures. This section reviews the recent advances in the fields of structural health monitoring, structural control and energy harvesting.

Structural health monitoring

A sensory system is an important factor in structural health monitoring (SHM). For example, the Tsing Ma Bridge monitoring system established in Hong Kong in 1997 has around 280 sensors, including anemometers, temperature sensors, strain gauges, accelerometers, global positioning systems (GPS), displacement transducers, and level sensors [39]. An improved SHM system installed in the Stonecutters Bridge monitoring system (Hong Kong) later contains a total of over 1500 sensors [40], as shown in Figure 3. Various types of sensors produce a wide range of information for the imple-mentation of an effective SHM and facilitate bridge safety/reliability assessment.

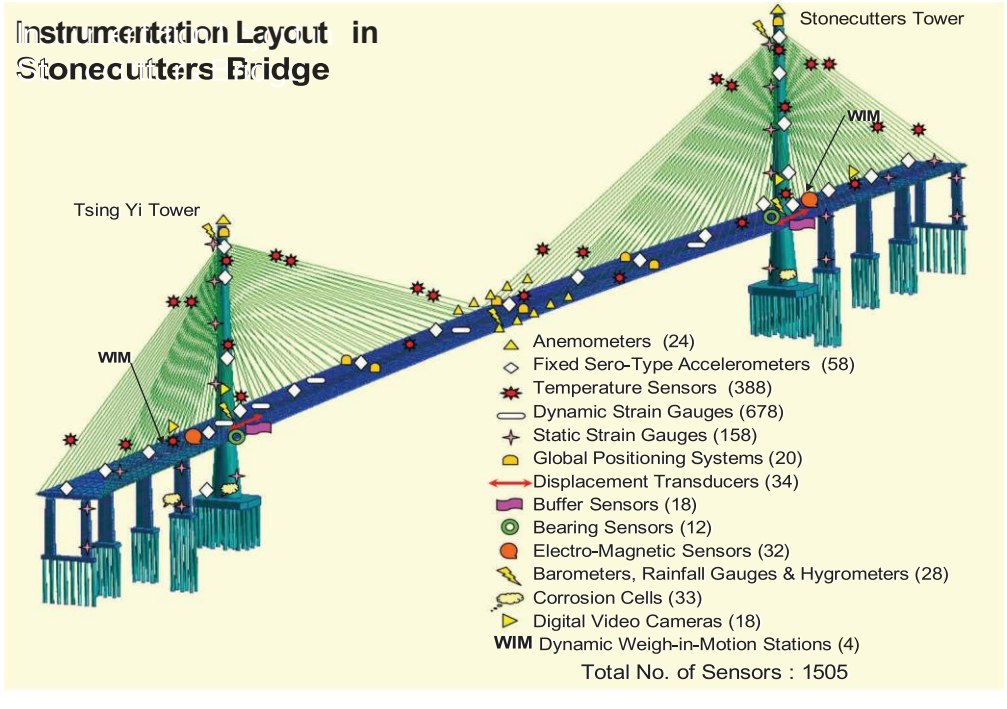


Figure 3. Layout of the sensory systems in Stonecutters Bridge [40].

The potential for the use of enhanced SHM methods is growing in tandem with the advancement of sensor technologies [41,42]. The three main types of parameters that sensors in a civil structure monitoring system can detect are: loading sources (e.g., wind, seismic, and traffic loading), environmental effects (e.g., temperature, humidity, rain, and corrosion), and structural responses (e.g., strain, displacement, inclination, and acceleration).

Due to their numerous advantageous properties, such as their tiny size, low weight, non-conductivity, rapid response, corrosion resistance, ability to withstand higher temperatures, immunity to electromagnetic noise and radio frequency interference, multiplexing, and wavelength-encoded measurements and data, fibre Bragg grating (FBG) sensors have become increasingly popular in structural health monitoring since the groundbreaking work of [43]. To communicate with the extensive network of FBG sensors from a central location, an interrogation unit is necessary. In [44,45], we found a study of many FBG sensor interrogation methods that presented four common methods: time-division multiplexing (TDM), spatial-division multiplexing (SDM), frequency-division multiplexing (FDM), and wavelength-division multiplexing (WDM). You may use these methods of questioning by themselves or mix them together with others. The inherent fragility of FBG sensors necessitates their sustained encapsulation prior to their integration into routine monitoring systems. The fact that FBG sensors may operate as both a sensor and a channel for transmitting signals is another appealing aspect of these devices. Numerous civil structure applications have been carried out with excellent success (e.g. [44,46],).

Level sensing stations, laser transducers, and linear variable differential transformers are examples of traditional displacement transducers; however, these instruments are limited to measuring relative displacement. Although they are useful for measuring absolute displacement, total stations are not ideal for continuous tracking. Global positioning systems are one new option. Despite its origins in navigation, GPS has proven to be an invaluable instrument for assessing structures' static and dynamic displacement reactions due to its continuous operation in all metrological situations and its worldwide coverage. At now, GPS can record displacements at 20 Hz with a horizontal precision of 1 cm and a vertical accuracy of 2 cm. As technology develops further, its measuring precision will be enhanced. On the other hand, it has several drawbacks, such being somewhat limited by multipath, having cycle lapses, being expensive, and needing adequate satellite coverage [47].

Structural control

Technology that safeguards structures against excessive vibrations caused by dynamic loads (such as construction, traffic, wind, and earthquakes) is known as structural control. This technology helps to protect both structural and non-structural components from harm. Several structural control methods that function in active, semi-active, hybrid, or passive modes have received a lot of attention in the last several decades [48,49]. Many different types of damping devices are used in passive structural control to dissipate energy. These include buckling-restrained braces, viscous fluid, visco-elastic, tuned-mass, shape memory alloy, eddy current, and friction dampers. Using base isolation techniques to lessen the seismic input energy is another approach. Seismic security or base isolation

One way isolation works is by changing the fundamental period from short, occurring in the dynamic excitation frequency range, to long, occurring elsewhere. Low- to medium-rise structures, as well as nuclear power facilities, sometimes use base isolation as an earthquake resistant design element. To mitigate vibrations caused by wind, however, base isolation methods do not

work [50]. No additional power source is needed by the passive structural control systems. Control performance is significantly improved by active control as compared to passive systems, which are very simple [48]. The three main components of an active control system are sensors, actuators for control, and a computer or other centralised control system. Active structural control may make use of either feed-forward or feedback control; however, because to the difficulties in measuring excitation, feedback control is often used. The use of hydraulic or electromechanical actuators, which are driven from outside the system, to apply control forces to the host structures in a specific way is a common method of active control. It follows that active control systems for large-scale constructions need a substantial power supply. Active control systems may have restricted control performance due to the power supply and peak control force requirements, which are both within realistic limits. In 1989, Kajima Corporation used active management for the first time in a full-scale building at the Kyobashi Centre in Tokyo, Japan [51]. On the eleventh level, there were two hydraulic active mass drivers installed: one for torsional motion suppression (4.2 tonnes) and one for lateral motion suppression (1.2 tonnes), which together accounted for around one percent of the structural mass. Active control systems have been used in various contexts, especially in Japan, but their dependability and cost-effectiveness prevent them from being widely used in civil engineering projects [52].

To overcome some of the drawbacks of active control systems, semi-active control systems (Figure 4) are suggested. These systems provide great dependability with little external power requirements. Two types of semi-active control systems exist: those with adjustable damping and those with adjustable rigidity. A semi-active device's characteristics are fine-tuned in real time in response to the reactions of structures and/or stimulation. Modern structural vibration reduction techniques often make use of variable-orifice fluid dampers, controlled friction devices, controllable fluid dampers, smart transient mechanical devices (TMDs), and semi-active magneto-rheological (MR) fluid or elastomer dampers.

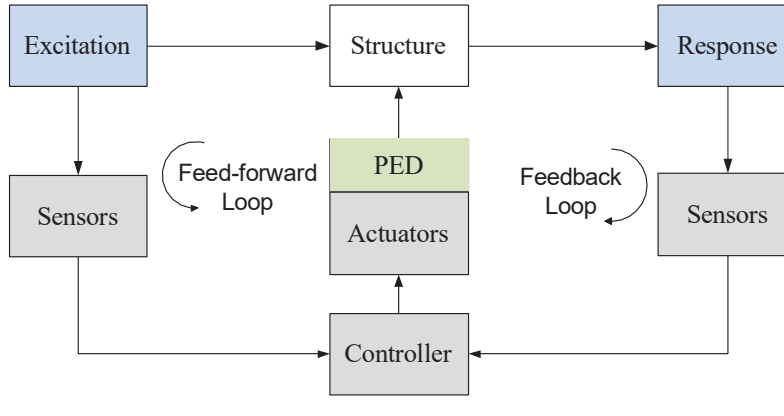


Figure 4. Schematic of the operation of a semi-active control system [49].

Variable stiffness devices or semi-active stiffness control devices work by tuning the stiffness of structural elements, thereby avoiding the resonant-type motion under dynamic excita-tions and reducing the input energy. Semi-active control systems do not add any mechan-ical energy to the structure, and the bounded-input and bounded-output stability of the system can be guaranteed [48]. Thus, they have received increasing interest because of their potential for a robust, reliable, and low-power structural control.

The comparison among the three categories of vibration control technologies reveals that a better control performance is often associated with higher complexity and low reliability. It will be appealing in practical applications if the reliability of passive control and the performance of active control can be achieved simultaneously. In the past studies on active control, it has been noted that the linear quadratic regulator (LQR) algorithm, which is a commonly adopted optimal control theory for active dampers, may produce a damper force-deformation relationship with an apparent negative stiffness feature that benefits control performance [53]. Thus, passive negative stiffness damper (NSDs), whose force-deformation relationship is shown in Figure 5(a), may be able to achieve control performance comparable to those of active dampers. Very recently, a family of NSDs have been developed, including passive negative stiffness springs based on the snap-through behavior of a pre-buckled beam, a passive negative stiffness mechanism composed of pre-compressed springs, a friction pendulum sliding isolator with a convex friction interface, and a magnetic NSD (MNSD) with several coaxially arranged magnets [54], as shown in Figure 6. In addition to NSD, inerter dampers are also recognized as another efficient vibration isolation technology. The force produced by inerter is proportional to the relative acceleration between the device terminals [55]. Figure 5(b) shows the typical force-deformation relationship of an inerter damper, which is similar to negative stiffness characteristics but is frequency-dependent.

The inerter can be made mechanically through rack-and-pinion [55] or ball-screw, as shown by Figure 7 Some researchers also developed some tuned inerter dampers by emulating the prin-ciple of TMD, including tuned viscous mass dampers [57,58], tuned mass-damper-inerter systems (TMDI) [59] and tuned inerter dampers (TID) [60]. The main advantage of inerter is that the inerter can be designed to have an apparent mass significantly larger than its

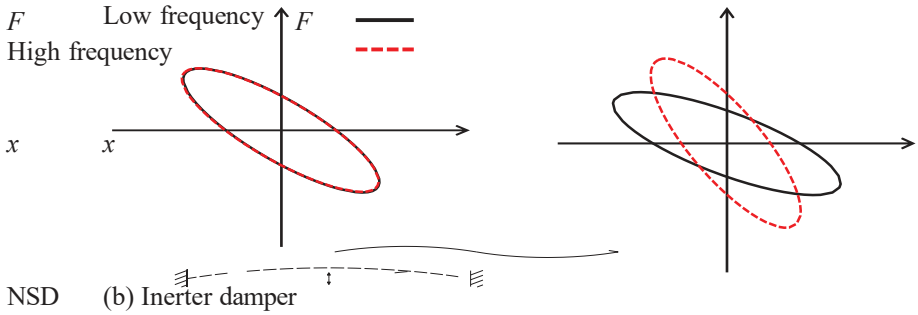


Figure 5. Force-displacement of NSD and inerter damper. (a) NSD, (b) Inerter damper.

Figure 6. Representative negative stiffness mechanisms. (a) a pre-buckled beam. (b) a pre-compressed spring with snap-through behavior. (c) a friction pendulum isolator sliding. (d) a magnetic negative stiffness on a convex friction interface mechanism.

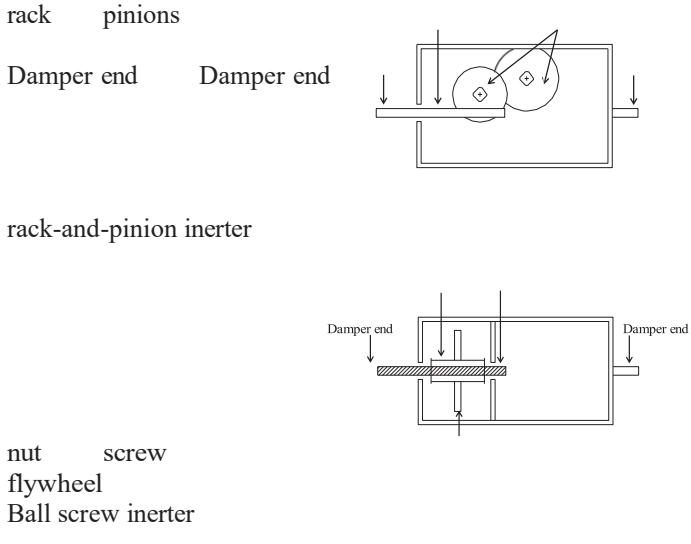


Figure 7. Representative inerter mechanisms [56]. (a) rack-and-pinion inerter. (b) Ball screw inerter.

actual mass. This advantage of inerter offers the potential for much higher mass ratios than those feasible for TMDs [60].

Energy harvesting

Energy harvesting is recognized as an emerging and promising technology in the next few decades [61]. Solar, wind, radio-frequency(RF) waves, and structural vibrations can provide green, sustainable, reliable and localized energy sources to low-power devices or systems, such as wireless sensors networks, semi-active controllers, alarm systems, etc. For example, Spencer et al. [62] proposed solar and wind energy harvesting as the power supplies for 113 wireless sensors in the smart monitoring system for Jindo Bridge in South Korea. The energy-harvesting performance is monitored by the wireless sensors themselves, which enables sensing nodes to manage the sensing scheme automatically with respect to battery voltage status. Hassan et al. [63] proposed an energy-

harvesting wireless crack monitoring sensor powered by a solar energy harvester. A comprehensive taxonomy of different energy harvesting sources for wireless sensor power supply has been presented in [64].

Meanwhile, vibration-based energy harvesting is one of the most rapidly growing research area [65–67].A typical configuration is a standard linear or nonlinear oscillator, in which part of the damping energy is converted into electrical energy by appropriate transduction mechanisms, including, but not limited to, piezoelectric, electromagnetic and electrostatic transductions [68], as shown in Figure 8. Piezoelectric transducers transform mechanical strain into electrical charge, known as direct piezoelectric effect [69]. Electromagnetic transducers generate voltage due to a relative motion between magnets and coils[70]. Electrostatic transducers are to utilize the variation in capacitance that can cause voltage increment in a constrained charge system or charge increment in a con-strained voltage system [71]. The corresponding damping characteristics of these three transducers are different as well. More detail information about conversion mechanism are given in [72], and related derivation for output powers and efficiencies are given by [73]. Ambient vibrations, such as vibrations of mechanical and civil structures induced by various dynamic loads, provide energy sources for vibration-based energy harvesting. A special assessment of energy harvesting potential from a variety of vibration sources has been presented in [74]. Among them, civil structural vibration shows a relatively high feasibility because dynamic loadings, such as wind, earthquake, waves, and traffics, always result in relatively high structural vibration, especially for large-scale flexible structures. For example, a case study [75] shows that a power of more than 85kW could be harvested in buildings using an appropriate method. Recently, Tang and Zuo [76] utilized a regenerative TMD to harvest vibration energy from a three-storey building prototype, about 60mW energy was harvested when a proper harmo-nic force was applied to the prototype building. Zhu et al. [77] developed a dual-function EM device for simultaneous vibration control and energy harvesting. Later on, a self-powered vibration control and monitoring system (Figure 9) was developed based on energy-harvesting dampers and wireless sensors [78]. The effectiveness of energy-harvesting dampers was further illustrated in high-rise buildings during earth-quake and stay cable vibration mitigation under wind loads [79,80]. In addition, Peigney and Siegert [81] employed a cantilever piezoelectric harvester to harvest traffic-induced vibration energy in a bridge. A relatively low mean power of around 0.03mW could be harvested and a controlled voltage ranging from 1.8V-3.6V was observed. Garuso et al. [82] successfully harvested as high as about 600W power from wind-induced bridge vibration through an adaptive tuned-mass energy harvester
under a relatively high wind speed.

Conclusions

The article begins with a brief introduction to the convergent technologies that will mostly propel the Fourth Industrial Revolution, before moving on to discuss recent advances and current best practices in advanced manufacturing, smart structures, nano-, information-, and scientific fields. Advanced manufacturing, sensors, nano mechanics/materials, smart structures/materials, energy harvesting, multi-scale challenges, and simulation methodologies are all part of the discussed convergence of these revolutionary technologies. To the research communities, the writers extend their gratitude for the comments and suggestions they received.

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