Survey and Introduction to Focused Section on Mechatronics for Sustainable and Resilient Civil Infrastructure

***Abstract*—The application of mechatronics in civil engineering has increased the sustainability and resilience of large-scale civil infrastructure, whose safe operation is among the utmost important issues concerning human society and our daily lives. Meanwhile, challenges faced in large-scale infrastructure applications bring about interesting and new topics for research in mechatronics. This paper firstly reports a brief survey of the recent research progresses on the construction automation in civil engineering, intelligent sensing, structural monitoring and health management, and feedback control of structural vibration. Next, a brief highlight to eight papers in this "Focused Section on Mechatronics for Sustainable and Resilient Civil Infrastructure" is provided. Finally, some latest topics, challenges, and the future trends of mechatronics application in civil infrastructure are discussed.**

***Index Terms*—sensing, control, actuator, field robot, vibration, construction equipment, civil infrastructure.**

I. Introduction

SUSTAINABILITY and resilience of large-scale civil infrastructure are of utmost importance concerning human society and our daily lives [1]. Meanwhile, the demands for large-scale civil infrastructure have also created a large numbers of applications for mechatronics. For example, in the past few decades, intelligent machinery(with field bus controller network, GPS positioning and measuring, load-sensing energy type of electro-hydraulic control, sensors, field robotics, and smart structures in field and service) has played an important role in construction automation [2]-[5],vibration control [6]-[8], and active maintenance [9],[10] of large-scale civil structures, such as bridge, airport, high-speed railway, etc. As another example, the safety inspection of large civil structures has also adopted a variety of advanced inspection techniques such as bio-inspired robot inspection, image based structural inspection, sensor network, and multi-sensor data fusion. Furthermore, the application of mechatronics in civil engineering has propelled the development of mechatronics and control technologies, and has formed a cross-disciplinary field of smart structural technology. Sensing and feedback control is applied to civil structures for reducing excessive vibrations during strong dynamic excitation such as earthquakes, typhoons and other natural disasters.

Mechatronics applications for sustainable and resilient civil infrastructure can be divided into two aspects: (1) construction machinery and construction automation of civil structures; (2) intelligent civil structures with mechatronics components or systems, such as embedded sensors, smart materials, actuators, dampers, inspecting robots, etc. The coalition of mechatronics and civil engineering can make the civil structures adaptive to the requirements of sustainable and resilient development. The cross discipline to be formed by coalescing mechatronics and civil engineering is named civil mechatronics herein.

Although the machinery and equipment used in construction of civil structures were invented in the early 19^{th}century, a successful construction application was not realized until the end of the 19^{th}century when diesel and electric motor started replacing human, animal, and steam engine to provide driving power [1]. Around 1940's to 1950's, hydraulic transmission began to replace mechanical transmission, which greatly increased the manoeuvrability, operability, reliability, safety, and lightweight performance of the construction machinery. The modern construction machinery by employing mechatronics integrated technology was developed in 1970's, which further improved operating performance. The requirements of civil structure construction in hydroelectric power station, high speed railway, and urban metro have greatly enhanced the technological progress of the construction machinery. Now, construction machinery has expanded into a significant industrial sector.

The service life of large-scale civil structure, such as bridge, airport, high-rise building, nuclear power station, large hydroelectric dam, and oil-transmitting pipeline, is usually longer than 50-100 years. The condition monitoring and safety management for these civil structures are crucial for their safe operation. As early as 1980's, researchers began structural monitoring tasks with hundreds of sensors installed on a bridge [11]. Intelligent civil structures involve sensing, control, diagnosis, smart materials, actuator, self-repairing, and other key techniques.

The rest of this survey paper is arranged as follows. Recent progresses in civil mechatronics are overviewed in Section II. In section III, the highlights of papers in this Focused Section are introduced. Finally, the future trends and challenges are proposed in Section IV.

II. Recent Progresses on Civil Mechatronics

A. Sensors and Sensor Networks for Civil Infrastructure

The past few decades have witnessed substantial growth in the application of sensors and sensor networks for civil infrastructure. Latest sensing technologies are regularly used to measure the states of structures, such as strain, displacement, acceleration, and temperature. The measurements provide crucial information for structural condition monitoring and health management.

Many recent developments in mechatronics found applications in structural health monitoring (SHM) systems. An SHM system measures structural performance and operating conditions via various types of sensing devices, as well as evaluates safety conditions using damage diagnosis or prognosis methods. Among latest sensing technologies, "smart" sensors with embedded computing and wireless communication have attracted wide interest. The ability to integrate sensors with wireless communication and embedded computing has motivated a flurry of research in developing wireless sensors for SHM [12],[13]. Not only laboratory demonstrations, but also large-scale field applications of wireless SHM research have grown at an impressive rate [14]-[16],[28]. In many studies, wireless sensing nodes are associated with high-precision accelerometers for vibration measurements. Although recent development in wireless sensing devices has helped to reduce hardware expenses, the cost of a wireless node with a high-precision accelerometer is still at least several hundred dollars, which makes dense instrumentation of static sensors still prohibitively expensive for large structures.

Compared with static sensors, mechatronics-based mobile sensors offer flexible architectures with adaptive and high spatial resolutions that can provide abundant detailed information about a large civil structure. It is anticipated that by incorporating mobility with sensors, mobile sensors will play an essential role in next revolution of sensor networks [17]. Some early researchers developed suction-based climbing robots for inspection in hazardous environments [18]-[20]; these robots weight tens of kilograms and have a relatively large size. In another example, a smaller beam-crawler was developed for wirelessly powering and interrogating battery-less peak-strain sensors; the crawler can move along the flange of an I-beam by wheels [21]. Exploiting magnetic on-off robotic attachment devices, a magnetic walker was later developed for maneuvering on a ferromagnetic structural surface [22]. Other researchers developed a remotely-controlled model helicopter acting as a mobile gateway, which charges and communicates with static wireless sensors fixed on a structure [23]. A combination of different sensors carried by robots can provide more complete information about the structure. In this regard, a modular paired structured light system, which consists of lasers and a camera, was proposed to measure the 6-DOF motion of a structure [24],[25].

Most recently, mobile sensor networks with dynamic reconfiguration have been explored for SHM. For example, a magnet-wheeled mobile sensing node originally conceptualized in [10],[26], with a total mass of 1kg and length of 22cm, was developed by incorporating a flexible compliant beam between the front and rear wheel-pairs. A previously developed wireless sensing unit [13] is incorporated with additional functionality of commanding small servo motors that actuates the magnet wheels. Embedded software for the wireless sensing unit and the server software are both enhanced to provide remotely controlled mobility. As demonstrated in [27], the accelerometer can be attached onto or detached from the structural surface by bending or straightening the compliant beam of the flexure-based MSN, which also offers flexibility for transiting over concave or convex corners of a steel portal frame. Advanced mechanical analysis was conducted to the compliant mechanism that exploits beam buckling; the results match very well with experimental measurements [15].

B. Structural Control

Some main progresses in civil structural control include vibration-isolation and vibration control to protect the structure against natural hazards via damper or actuator. Because the actuators in active control need continuous power supply during operation, their reliability in hazardous events has been a concern for practical applications. As a result, damper-based semi-active control requiring smaller power supply has attracted more interesting practical applications.

Spencer and Nagarajaiah [29] reviewed state of the art in structure control, and summarized the pros and cons of existing control methods, control systems and actuation mechanisms used in the structure control. Using permanent magnet array, Yao and Wen developed magnet springs to reduce structural response during earthquakes [6]. Song and Washington studied mechatronic design and control of singly and doubly curved composite actuator systems [7]. Vibration control is often applied to flexible structures using damper or elastic components; the integration of VLSI circuits and mechatronics in flexible structure was studied in [30]. Guo *et al*. [31] and Oha *et al*. [32] developed the inspection system for pipe line and bridge, respectively. Addressing Stuttgart smart shell with hydraulic actuator, Weickgenannt *et al*. studied the active vibration control of a double-curved shell [33] and kinematic modeling of 3-SPR-parallel hydraulic manipulator [34].

C. Hydraulic Transmission and Control in Construction Machinery

Large construction worksites are complex production systems that consist of numerous human workers, mobile construction machines, and trucks collaborating to carry out tasks. Hydraulic transmission and control plays an important role in manipulation of construction machinery and equipment.

Effective fleet management requires intelligent construction machinery which can provide interoperability and seamless connectivity over wireless peer-to-peer networking [35]. Intelligent machine is an example of cyber-physical systems, and it is designed to have a close integration of networked computational units that collaborate to control physical elements, requiring new computing and networking abstractions that enable real-time orchestration [4].

Guaranteeing human worker safety is one of the main challenges in increasing automation level in construction worksites. This requires reliable mechatronic design solutions for human detection and avoidance technology from both semi and fully autonomous machines. Planning and vision systems working together with intelligent machines can be used for the manipulation of crane, transporter, and excavator. Using virtual reality and simulation to develop a simulator or monitor can assist operator with manipulating the machine, decreasing fuel consumption and preventing accidents. Eaton and Book [36] successfully developed an excavator simulator.

In order to be applied to large-scale and complicated engineering construction, construction worksites require very large forces and effective workspace from construction machinery. Hydraulic construction machines composed of wheeled or tracked mobile base platform equipped with hydraulic working devices and implements provides an optimal solution for this problem. The required mobility and high force attachment devices are provided by hydraulic actuators with high power-to-weight ratio, rapid response, compactness and reliable performance.

The mobile working machine manufacturers utilize hydraulic actuators widely due to reasons mentioned above. However, the major drawbacks in utilizing fluid power transmission systems are large energy losses and complexity in their control. The mechatronic controller design for hydraulic manipulators is very challenging due to non-linear characteristics of hydraulic control. In addition, hydraulic control systems suffer from inherent low damping which calls for advanced motion control to increase the work smooth performance. With respect to complexity of control, recently theoretically sound stability guaranteed multi-DOF hydraulic manipulator controllers operating in free space has been reported in [37]-[40]. In research conducted by [39],[41]-[43] encouraging power consumption reductions has been reported in high performance energy-efficient free space motion control of multiple degrees of hydraulic manipulators. Control of the physical interaction between a robotic manipulator and the environment is crucial for the execution of a number of practical tasks where the robot end-effector has to manipulate an object or perform some operation on a surface. In the robotic interaction control design for hydraulic excavator were presented in [44]-[46]. However, state of art still lacks research results on advanced high performance mobile hydraulic manipulator interaction control with rigorous stability guarantees.

One of the bottlenecks in introduction of more advanced closed-loop controlled robotic functionalities to construction machinery operating in harsh environmental conditions is a lack of easy-to-install, low cost and reliable motion sensors [47]-[49]. High accuracy and resolution joint position measurement is relatively straightforward with commercial contact-type angular sensors, such as magnetic or optical rotatory encoders that can easily provide accuracy of more than 1 arcsec. However, in addition to a high price, the drawback of this technology is two-folded [49]. Firstly, these sensors require a mechanical coupler to the manipulator rotating axles that is subject to assembly accuracy and failures in harsh outdoor environments. Secondly, obtaining low-noise low-delay estimates of the joint angular velocities and angular accelerations is a less trivial task [50],[51]. However, by using cost-efficient “strap-down” inertial sensors such as rate gyros and linear accelerometers based on micro-electromechanical systems technology, reconstructing the “true” rotatory joint positions, angular velocities and angular accelerations directly without unwanted phase delay or distortion is possible by geometrically modeling the linear and angular motion effects involved, see e.g. [52]-[55].

Today, more and more operator assisting functionalities which utilize mechatronics designs are introduced. As mentioned, excavator is a highly versatile platform to attach various hydraulic working attachments. Many manufactures are providing operator assisting functionalities for helping production rate and precision of typical excavator works. The most advanced technology uses instrumented excavator boom, stick and bucket together with GPS positioning systems to assist operator to level the ground to match the desired 3D construction site surface map. Other examples of operator assisting functionalities for hydraulic manipulators include acceleration feedback control [54], resolved motion rate controls of a mobile concrete pump [55], and suspended load anti-sway control systems [56]. Field bus based controller network and distributed electro-hydraulic proportional system were successfully applied in elevating transporter with multi-axle drive and multi-suspension [57], and software steering trapezium and coordinated control strategy were proposed by Li *et al* [57].

D. Field Robot and Construction Machinery in civil construction

Robotics in civil construction becomes more and more important due to the lack of labor and the need to reduce the construction cost. The field robots in civil construction can be classified as teleoperated systems, intelligent systems, inspection robots, etc. [58].

1) *Teleoperated systems in construction*

Teleoperated systems such as teleoperated excavators and remote controlled robots have received much attention in recent years due to its efficiency and safety in civil construction and industrial field [59],[60]. The teleoperated machines are operated by human using wired or wireless connection. The teleoperated systems have been used for hazardous and dangerous tasks such as outdoor construction, agricultural tasks, ship maintenance, etc.

The teleoperated excavators have been studied widely but the task efficiency might be decreased because of lack of sensors or monitoring data for control. To solve this problem, many methods have been proposed. IMUs(Inertial Measurement Units) attached to the human arm can help teleoperate excavators more conveniently [59]. The excavator is able to find and avoid obstacles to prevent accident during digging by sensing the obstacles through force/torque sensors. For the construction work in landslide, a remote controlled robot for drilling is developed [60].

2) *Intelligent systems in construction*

Intelligent construction robots can be categorized into two types: fully autonomous construction robots and semi-autonomous construction robots. A fully autonomous construction robot should complete given tasks without a human supervisor. By contrast, a semi-autonomous construction robot needs intervention of a human operator for the task operation. For both cases, a robot is expected to sense the environment and make an optimal task plan [61] or request intervention. Unlike teleoperated construction machines, intelligent construction robots can be easily operated by unskilled workers.

Assembling steel beams or installing curtain walls is a very dangerous work for human, but by using a robotic system, fewer workers are required and also can guarantee more safety [61],[62].

For earthworks, studies on intelligent excavators and autonomous wheel loaders are in progress [63]. Autonomous steel beam construction systems [64], [65] have been developed for constructing high-rise buildings. An aerial building construction robot with quadrotor [66] is also being developed.

3) *Inspection robot systems in construction*

Because most of civil structures are exposed to rain, wind, air, sun, and temperature changes, there is a possibility of cracks and unexpected displacement. An inspection robot system can be used to monitor the crack or displacement of structures. As the robot system has become compact, providing higher performance with a less power, the robot is able to explore narrow or steep terrain. A typical example is a quadrotor robot system. This system, composed of a quadrotor and a custom-made manipulator, has been designed for remote inspection of structures [67],[68]. Another example is a wall climbing robot. The wall climbing robotic platforms use magnetic wheels [69],[27] or adhesive materials[70], [71] or claws [72] or suctions [73] to inspect structures. Last example is a robot moving along a pipe or a cable. The wheel-based robot system uses camera or electromagnetic field for inspecting pipes or cables [74]-[76].

4) *Other robots for construction*

The exoskeleton robot system is a human-robot cooperation system that enhances the power of a wearer in various environments. Recently, the exoskeleton robot systems have been developed in various fields such as industry, military, rescue, and medical. In the construction field, the robot has been developed to assist workers to carry heavy loads [77]. The exoskeleton robot is controlled by analyzing EMG signals so that the user can lift various loads with the same power [78]. The exoskeleton robot can reduce the fatigue of workers, so that increasing the work efficiency and reducing the dangerous situation in the workplace.

In the underwater construction sites, many kinds of robots are researched since the construction areas are hard to reach and hard to work for a long time. An underwater excavator is one of the most representative robots [79]. In the underwater, the localization and sensing of environment are most challenging issues since the infrastructures and available sensors are strictly limited.

5) *Robot navigation (positioning, reconstruction/mapping)*

In the construction field, there have been many studies to apply robot navigation technologies such as positioning and 3-D reconstruction. Due to the complexity of construction projects and dynamic environment of outdoor construction site, monitoring the construction site and its reconstruction have always been important issues. Therefore many researchers have tried to develop the system to monitor the construction sites and reconstruct them in order to acquire the information for safety management, construction process management, and even for training and education of workers.

For large outdoor construction jobsites, GPS or wireless communication network can be used for tracking and positioning equipment operations, activities of workers, and any other construction resources [80], [81]. The collected data can be analyzed and evaluated for the construction work and finally construction manager can use the data for planning and management of construction site operation. Meanwhile, RF-based technologies and laser range finder are used for indoor positioning of workers and materials to be tracked [82], [83]. Based on real-time kinematic GPS, wireless data radio, and extend Kalman filtering algorithm, a positioning and collaborative control system for twin-crane to convey heavy girder was developed [3].

3-D reconstruction technologies are also widely studied in construction field, and several methods based on the image data were applied to generate 3D spatial model [84].

E. Health Monitoring of Civil Structure

Structural health monitoring or SHM is a broad term defined as is the process of comparing the current state of a structure's condition relative to a baseline or expected state to detect the existence, location, and degree of likely damage after a damaging input, such as an earthquake. A health monitoring system includes the placement of the sensor and sensor network, data fusion and fault symptom feature extracting, and health/fault assessment method.

Most efforts to date in this field have focused on structures in seismic zones and assessing damage after a major event, and in particular on computational methods to assess damage (e.g. [85]-[91]). Many current vibration-based SHM methods, particularly for large civil structures, are based on modal parameter damage detection in both the time series and frequency domain [85]-[91]. Current modal methods are more applicable to steel-frame and bridge structures where vibration response is more linear [87]-[91] and several assume one has data from the undamaged state [90], which is increasingly possible with advanced sensor technologies.

In addition, SHM technologies need to be able to identify localized damage, be robust in the presence of noise, and evaluate structural health rapidly or in real time [85],[86]. All of these characteristics are ones that can increasingly be met by emerging, improved sensor technologies that are more distributed, low cost, and easily used in volume, and/or can integrate computation directly with measurement.

Most existing methods that could potentially provide real-time SHM are modal or frequency based methods. These methods typically only use accelerometers as sensors and rely on the change in natural frequencies to detect damage [86],[90],[92]. However, a change in a frequency doesn't necessarily represent damage, particularly with highly non-linear responses [93]. Significant changes in story stiffness are often required as well, which would normally cause clearly visible damage [93]. Equally, references [92]-[94] identified changes in structural stiffness in real-time using a Least Mean Squared (LMS)-based adaptive filtering approach in real-time. However, this method requires measurement of velocity and displacement, which has often been considered impractical in many realistic cases due to excessive sensor requirements.

Recently there have been significant advances in GPS displacement monitoring technology for large structures [93]-[97]. Displacements can be measured with 1-3 mm accuracy for rates of up to 3-4 Hz, which include the modal frequencies of the rigid structure [94], and for 1 Hz, measurement errors have been stated as less than 12% [89]. The use of GPS opens up new opportunities in real-time structural health monitoring [93]. Equally, there are increasing advances in a wide range of displacement sensing technologies (e.g. [98]-[101]) that will enable further improvements in our ability to accurately identify and locate damage.

However, monitoring structural damage is just at the beginning. Buildings increasingly have the ability to monitor all their functions, such as climate and energy usage. Integrated together these present other forms of monitoring to improve lifecycle and services in these buildings, as well as making them more economic and cost effective. Even that is not the end of the age of the (fixed) sensors. Networking lets us integrate buildings and regions into wider area of monitoring and leads eventually, with other systems, towards what some are now calling "smart cities" where data from buildings, power grids, traffic and much more are integrated into an entire interconnected, some might dare say optimized, organism.

Thus, the next, "next age" is always around the corner. Increasingly the use of sensors to monitor, improve performance, and aid decision making, whether human or automated, is seen as an avenue to achieve significant social and economic benefits. More succinctly, our ability to sense our environment has always let us assess and monitor what is around us, with silicon and other advanced sensors and computation this ability is being dramatically enhanced via mechatronics-based methods and technologies.

III. Highlights in This Focused Section

After a rigorous review process, we have accepted eight papers for publication while unfortunately, given the page limit, we had to make the difficult decision to turn down many other high-quality submissions. The focused section is organized to group the eight papers in three topic areas, i.e. sensor and inspection system, structure control, and construction machinery.

A. Sensor and inspection system

Under this topic, Laflamme *et al*. propose a soft elastomeric capacitor sensor for strain measurement over large surfaces. Converting strain into capacitance change, this sensor is characterized by low cost and large strain measurement range. It is demonstrated that deflection shapes of a simply supported beam can be reliably reconstructed using the sensor measurements.

La *et al*. have developed a mobile bridge deck inspection platform equipped with localization and navigation, sensor network, wireless on-board control system, as well as the associated extended algorithm for Kalman filter estimation and multi-sensor data fusion. The wheeled robot contains GPS localization and navigation system with real-time kinematic correction, as well as provides remove access to surface images and various nondestructive evaluation data. The kinematic modeling of the inspection system and motion planning are discussed.

Hanger cable is among the major structural components in suspension bridges. Cho *et al.* have studied the mechanism of a novel cable-climbing robot designed for cable inspection. Image data are wirelessly transmitted for inspecting broken wires in the cable. Motion control of the cable-climbing robot is described.

In another paper, Park *et al*. propose a multi-metric data fusion method to estimate displacement based on strain and acceleration data. This data fusion method doesn't need prior calibration, and has been successfully used for estimating the mid-span displacement of a cable-stayed bridge.

B. Structural control

Under this topic, Lin *et al*. have studied the parameter identification of nonlinear characteristics that describes electric current controlled squeeze-mode MR damper and semi-active structural control with this MR damper. A bi-viscosity model is proposed to establish the nonlinear model of this MR damper. It is shown that the parameter identification result of the bi-viscosity model is more robust to frequency variation than Bouc-Wen model. Based on this MR damper, a semi-active fuzzy controller is designed.

Ha *et al*. propose a current-driven cylindrical MR damper with accumulator, whose damping and stiffness characteristics can be adjusted. The authors have studied the modeling of nonlinear damping characteristics of this MR damper, as well as a second sliding mode control law that is free of chattering.

Finally, Zhang *et al.* propose a novel feedback control method to improve the accuracy of substructure system identification. The identification error is formulated through cross power spectral densities (CPSD). To reduce substructure identification error, feedback control is proposed to increase the CPSD of the inter-story acceleration, and decrease CPSD ratio between two adjacent inter-story accelerations in a narrow frequency range centered at the story substructure frequency. Experimental validation has been carried out with a shear-frame model structure.

C. Construction machinery

Under this topic, Wang *et al.* study modeling and control method for electro-hydraulic proportion control of the erection system in Shield Tunneling Machine. An experimental system is developed for performance demonstration. The paper addresses issues such as position feedback control design, integral-separation PI control law with anti-windup, position system, speed system, and the selection method of controller parameters.

IV. Future Trend of Civil Mechatronics

Civil mechatronics is a rapidly developing research field. Advances in mechatronics technologies can assist in the implementation of innovative structural control and health monitoring systems, as well as facilitate the construction machinery and equipment to be reliable, safe, and highly efficient in construction automation. Although many advances in this cross discipline have been achieved, there are still many challenging theoretical and technological issues to be resolved. Some possible future trends are listed as follows:

1) To further incorporate sensors with wireless communication and embedded computing and form smart sensor and smart sensor network with more powerful function;
2) To develop multi-sensing-function sensor chip with low power consumption, wireless communication, and advanced data processing algorithm;
3) To investigate advanced data fusion, feature extraction, and condition assessment algorithms;
4) To study the approximation realization method by semi-active control components such as damper and variable energy accumulator to realize active control;
5) By incorporating bio-engineering and information technique, to develop of novel mobile inspection robot for space structures and large bridges, high speed railways, high buildings, etc.;
6) To study image processing algorithm and realization approach to meet challenges in tough construction environment;
7) To develop field robot-group control, multi-wheel driving construction machinery, and field controller for complicated task such as aqueduct, track-bridge, and metro construction and harsh construction environment;
8) *To investigate virtual-reality simulation and control of teleoperated construction machinery;*
9) To study the integration method of construction management and health monitoring system, mobile communication network, and intelligent construction machinery and equipment;
10) To study advanced control theory, information techniques, advanced kinetics and mechanism theory, and advanced electro-hydraulic control system design theory for developing high performance construction machinery and group construction machinery.

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