Automation in Construction 139 (2022) 104273

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Review

Intelligent robotic systems for structural health monitoring: Applications and future trends

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ARTICLE INFO

Keywords:
Robotics
Drones
Climbing robots
Soft robots
Structural health monitoring
Defect inspection
Vibration measurement

ABSTRACT

The application of the cutting-edge technologies of robotics and computer science to structural health monitoring (SHM) of bridges have gained much attention. This review describes existing robotic systems in three areas: (1) rigid robotic systems, such as mobile robots, wall-climbing robots, cable-climbing robots, and flying drones, for the inspection of surface/subsurface defects; (2) mobile robots, climbing robots and flying drones for dynamic response (e.g., accelerations, displacements) measurement, modal identification, and cable tension force estimation; (3) multimodal rigid robots and soft wall-climbing robots with SHM potential. The development of multimodal robotic systems, such as flying and perching drones, hybrid terrestrial–aquatic robots, hybrid aerial–aquatic robots, and hybrid flying and walking robots, have great potential for performing multiple inspection tasks when various Nondestructive Evaluation (NDE) tools are integrated with those robotic systems. Another trend is to design soft robotics with smart materials for inspection tasks in some special/space-confined environment because of the advantages of lightweight, high adaptability, and less requirement for electric motors compared with rigid robotics. This comprehensive literature review is intended to provide guidelines for choosing the appropriate robotic platform for defect inspection or vibration measurement of bridges and other types of civil infrastructure. It also can give some insights into the development of versatile robots for SHM applications.

1. Introduction

Over the past decades, many bridges, especially long-span suspension bridges and cable-stayed bridges, have been constructed around the world, but bridge safety issues happened frequently in recent years, such as the collapse of the Minnesota I-35 W bridge [1,2], the vortex-induced vibration (VIV) of twin-deck Yi Sun-Shin suspension bridge [3] and Humen suspension bridge [4]. Therefore, structural health monitoring (SHM) with intelligent robotics and advanced sensing technologies is promising to ensure the safety of bridges and to reduce maintenance and rehabilitation costs [5–7]. Intelligent robotics can be used for performing defect inspection tasks (e. g. cracks, corrosion, concrete spalling) and the advanced sensing technologies help monitor structural response (e. g., accelerations, displacements, strains). After obtaining structural condition data, the performance status of bridges can be evaluated, and then maintenance or rehabilitation programs can be further made to ensure the safe operation of bridges.

Conventional defect inspection methods highly depend on specialized devices such as inspection vehicles or temporary scaffolding. The inspection vehicle is expensive to use and the temporary scaffolding is usually impossible when bridges are constructed in mountainous areas and across valleys and rivers. Traditionally, a specialized inspector visually detects cracks and manually marks their locations, but the detection accuracy is affected by the experience of inspectors. To address those issues, hand-held cameras were widely used to capture crack images, and then the width and length of cracks were computed using computer vision technologies and deep-learning algorithms [8–11]. In recent years, much attention has been given to the application of cameras installed on various robotic platforms (e.g., climbing robots, unmanned aerial vehicle) to automate the defect inspection process in civil engineering, such as fatigue crack detection of steel structures [9], measurement of unpaved road surface distresses [12], cracks of highway

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https://doi.org/10.1016/j.autcon.2022.104273
Received 30 September 2021; Received in revised form 7 March 2022; Accepted 16 April 2022
Available online 28 April 2022
0926-5805/

bridges [13,14]. The inspected cracks belong to local defect, which cannot be directly used for decision-making on the overall performance of bridges.

Investigation of vibration magnitude and dynamic properties is essential to the determination of the global performance of bridges. Dynamic tests including the ambient vibration test [15,16] and impact vibration test [17,18] have been employed for extracting dynamic properties, such as natural frequencies, damping ratios, mode shapes and modal flexibility, which are important parameters for the global condition assessment [19], damage detection [20,21] and vibration serviceability evaluation of bridges [22]. But conventional dynamic testing methods mainly use contact-type sensors for measuring structural responses, such as accelerometers, strain gauges, and long-gauge fiber optic strain sensors, which are time-consuming and costly to use because of the requirement of long electrical wires for connecting sensors and data acquisition system.

Here we review the recent developments in robotics for SHM of bridges, providing an alternative for bridge condition assessment and safety evaluation (Fig. 1). Section 2 will describe various robots for defect detection, including surface defects (e.g., cracks and concrete spalling) and internal defects (e.g., delamination and rebar corrosion). Section 3 reviews the existing rigid robotics systems for vibration measurement (e.g., acceleration, displacement) and dynamic properties extraction of bridges. Section 4 describes recent developments in the field of robotics that show great potential for multipurpose SHM of bridges.

2. Robots for defect inspection

Bridge collapse accidents frequently occur due to the coupling effect of material degradation and traffic overload and have caused severe economic loss and casualties. Because conventional visual inspection methods always feature a certain degree of subjectivity and highly depend on expensive inspection vehicles, and more robust and cost-effective defect inspection techniques are urgently needed to ensure the safety of bridges. This section reviews the use of various robotics (i.e., mobile robots, climbing robots, aerial robots, and emerging multipurpose drones) to automate the process of defect inspection of bridges. A summary of existing robotic platforms is shown in Table 1.

2.1. Ground mobile robots

Due to the rapid development of robotics and artificial intelligence, various mobile robotic platforms have been developed for defects inspection of bridges [23–25]. One important inspection task is the detection of cracks in the bridge deck. However, traditional methods feature a certain degree of subjectivity and the inspection process is labor-intensive. To address this issue, Klinkhachorn et al. developed an autonomous ground vehicle for detecting air- and water-filled defects by incorporating both infrared thermography (IRT) and ground-penetrating radar (GPR) on the mobile platform [26]; Lim et al. developed a robotic crack inspection and mapping system [27], with which crack images of bridge deck can be collected efficiently in the area of interest by path planning algorithm. But this robotic platform can only detect surface cracks of bridge decks and the inner defects cannot be inspected. To address this issue, a novel autonomous robotic system, named RABIT, was developed for various defects inspection of bridge deck by incorporating several NDE tools on the robotic platform, such as impact echo (IE), electrical resistivity (ER), ground-penetrating radar (GPR), and ultrasonic surface waves testing, from which three most common defects (e.g., rebar corrosion, delamination, and concrete degradation) of concrete bridges were detected and characterized [28,29]. This robotic platform is more advantageous than the conventional robotic system integrated with cameras only, one limitation of this robotic system is that the underside of typical concrete bridge cannot be inspected. To increase the functionality of mobile robots, Charron et al. developed a mobile ground robotic platform consisting of a rugged mobile platform, thermal camera, and RGB camera to produce high-quality three-dimensional (3D) point cloud maps and performing defect localization and quantification tasks for the underside of bridge decks [30]. In addition, a semi-autonomous mobile robotic system consisting of a mobile vehicle platform and a robotic arm (Fig. 2 (a)) was developed for the inspecting the underneath and underside of bridges [31]. The mobile vehicle platform holds the robotic arm and moves along the top of the bridge on the parapet, and the robotic arm captures images of cracks.

Ground mobile robots have the capability of inspecting various defects of bridge deck and the underside of bridges, however, they cannot be directly adopted to inspect other difficult-to-reach structural elements, such as bridge tower, bridge piers and bridge bearings. Therefore, more sophisticated robotic platforms with multiple locomotion capabilities need to be further developed. The advantage of ground mobile robots is that the load-carrying capability is larger than climbing and flying robots, and various NDE sensors can be integrated to this robotic platform for detecting multiple kinds of structural defects (e.g., crack, concrete spalling, steel corrosion and delamination).

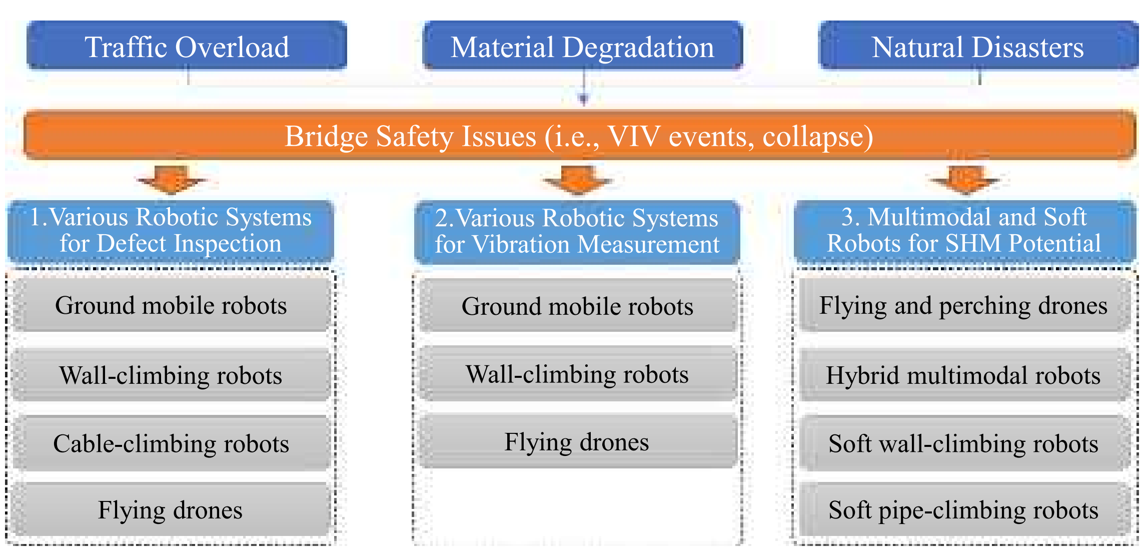

Fig. 1. Summary of various robotic systems for SHM applications.

Table 1
Summary of robotic platforms for defects inspection of bridges.

Type of Robots	Author	Locomotion	Sensors	SHM Tasks
Mobile robots	Lim et al., [27]	Ground-based movement	Camera	Crack inspection and mapping
	Kee et al., [28]		Camera, ER probe, GPR, IE	Delamination, concrete elastic modulus, corrosion maps
	Sutter et al., [31]		Cameras	Concrete crack inspection
Climbing robots	Liu et al., [34] Liu and Liu, [35]	Vertical wall climbing	Camera	Concrete cracks inspection of bridge piers and towers
	Peel et al., [36]	Vertical wall climbing	Camera	Bearing inspection of concrete bridges
	Nguyen and La, [41]	Inclined wall climbing	Camera, hall-effect sensors IR, IMU, Eddy current	Visual and in-depth fatigue crack inspection of steel structures
	Xu et al., [43]	Inclined cable climbing	Cameras	Surface damage of cables
	Yun et al., [44]	Inclined cable climbing	Cameras, MFL sensors	Inspection of cable surface and inner defects
	Cho et al., [42]	Vertical cable climbing	Three cameras	Surface defects inspection of vertical hangers of suspension bridges
Aerial robots	Chen et al., [50]	Aerial flying	Camera	Inspection of surface cracks/ joint openings on bridge decks
	Kang and Cha, [51]	Aerial flying	Camera	Surface cracks detection of concrete structures
	Seo et al., [53]	Aerial flying	Camera	Concrete spalling and steel corrosion inspection
	Ellenberg et al., [56]	Aerial flying	Infrared cameras	Subsurface delamination inspection
Multipurpose drones	Sanchez-Cuevas et al. [58]	Aerial flying and physical contact	Camera, supersonic sensors	Crack depth measurement
	Ikeda et al. [59]	Aerial flying and physical contact	Camera, robotic arm	Defect image collection in narrow and confined spaces, impact hammer testing
	Jiang et al. [60]	Aerial flying and wall climbing	Cameras	Real-time crack length and width measurement

Note: ER: Electrical resistivity; GPR: Ground-penetrating radar; IE: Impact echo; IMU: Inertial Measurement Unit; MFL: magnetic flux leakage;

2.2. Wall-climbing robots

To automate the inspection process of hard-to-access components of bridges that require regular visual inspection to ensure safe operation, such as bearings, piers, and towers, various wall-climbing robots have been developed, with some typical robotic platforms. According to the climbing mechanism, the existing rigid wall-climbing robots can be classified as pneumatic wall-climbing robots or magnetic wall-climbing robots. The pneumatic wall-climbing robots use suction cups or a negative-pressure mechanism for climbing non-ferromagnetic surfaces such as glass, concrete, and wooden materials [32,33]. Because most civil infrastructure is made of concrete materials, pneumatic wall-climbing robots have been widely applied for inspection tasks in civil engineering. Liu et al. developed a negative-pressure adhesion mechanism-based wall-climbing robot for automated crack detection of bridge towers and piers, and a line structured light method was added to the robotic platform for discriminating real bridge cracks from fake bridge crack caused by light variation [34,35]. It is found that the required minimum adhesion force for the robot moving on bridge surface was 25 N and the simulated adhesion force by adjusting Proportion Integration Differentiation (PID) parameters was around 50 N, which was larger than the minimum adhesion force and could keep the climbing safety of the robot. In addition, a climbing robotic system had been developed for bridge bearing inspection, and the Adaptive Monte-Carlo Localization algorithm was adopted to localize the robot in a known map created from point cloud data, from which the geometry changes of bridge bearing and foreign objects around the bearing can be observed [36]. Results showed that the localization accuracy of the developed system was less than the defined threshold of 10 cm in both lab environment and real bridge environment, and the initial position given to the robot had effect to the trajectory accuracy.

Moreover, magnetic wall-climbing robots have been developed for defect inspection of steel bridges. The adhesion mechanism can be classified as permanent magnet adhesion or electromagnet adhesion [37,38]. According to different climbing surface, the locomotion of this type of robot can be classified as legged, wheel-driven, or tracked. A climbing robot with four motorized wheels was developed for crack inspection and monitoring of steel structures, using the advantage of permanent magnets for adhesion force creation [39,40]. Nguyen and La developed a climbing robot (Fig. 2(b)) using reciprocating mechanism and magnetic roller-chains for visual and in-depth fatigue crack inspection of steel bridges, and it is capable of climbing different steel structural shapes, passing through joints, and transitioning from flat to curved surfaces [41]. The robustness of the above wall-climbing robotic systems has been validated by field testing of more than twenty different steel structures, demonstrating the great potential of applying to industry.

Although the climbing robot has the advantage of reducing both the safety risk for workers and the maintenance costs for government comparing with the traditional visual inspection method, the load-carrying capability of the climbing robotic platform is relatively low and only few NDE sensors can be integrated to the platform for defect inspection. And different climbing mechanisms (e.g., magnetic adhesion mechanism, negative pressure adhesion mechanism) are needed for climbing bridge components with different materials (e.g., steel structure, concrete structures). Compared with ground mobile robots, the control strategy for climbing robot is more complicated because of the multiple locomotion capabilities (e.g., climbing, traversing, attachment, detachment).

2.3. Cable-climbing robots

In addition to defect inspection of the bridge deck and hard-to-access components (i.e., piers, towers, bearings), the operational condition of stay cables/vertical hangers is critical to the safety of long-span cable-supported bridges, because most of the load on the bridge is supported by the cables. Various cable-climbing robotics have been developed in the past decades for automating the procedure of cable defects inspection. There are three main climbing mechanisms for cable inspection robots: magnetic, pneumatic, and electric. The electric method was widely used to develop cable inspection robots because of the advantages of easy control and constant climbing force. A multipurpose robotic crawler with installed cameras and NDT tools has been developed for defect inspection of the vertical hangers of long-span suspension bridges [42]. A robotic system for cable inspection usually consists of the climbing robot subsystem, the nondestructive testing (NDT) subsystem,

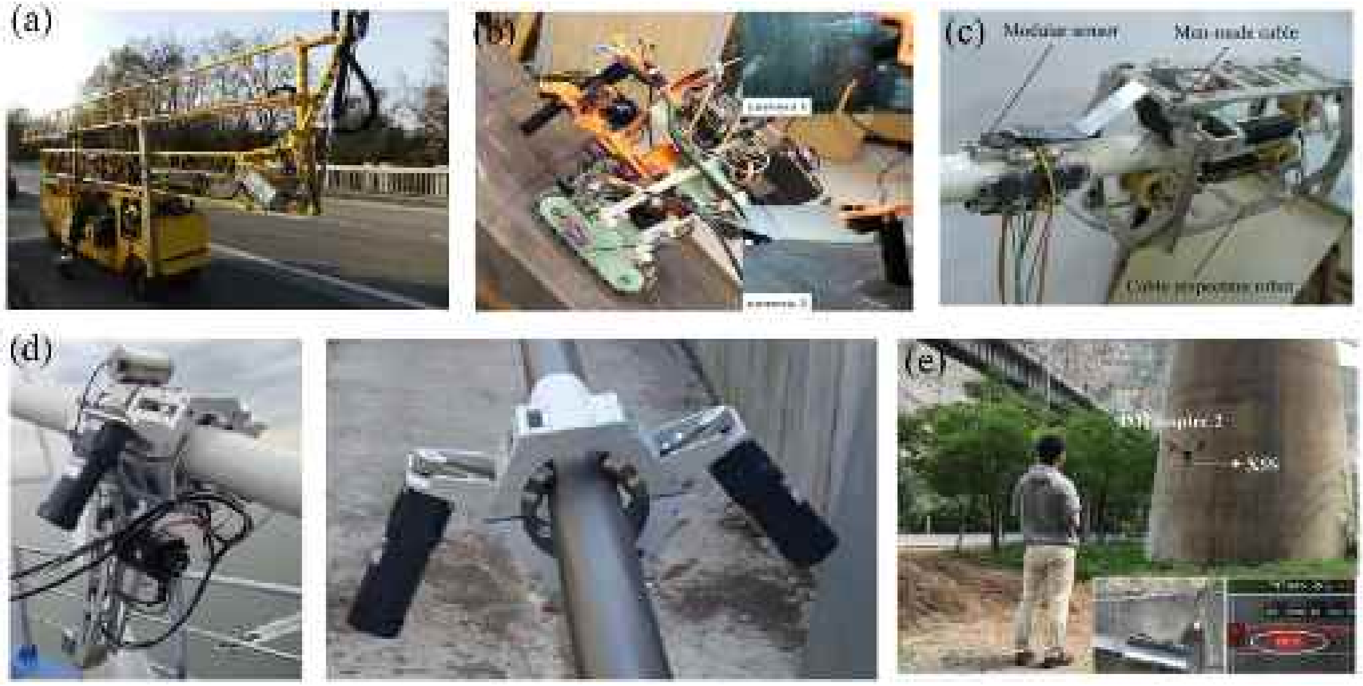

Fig. 2. Existing robotic systems for defect inspection of bridges (a) semi-autonomous mobile robotic system *(Reprinted with permission from* [31]*)*; (b) climbing robot for steel structures *(Reprinted with permission from* [41]*)*; (c) cable-climbing robot *(Reprinted with permission from* [43]*)*; (d) cable-climbing robot for stay cable inspection *(Reprinted with permission from* [44]*)*; (e) flying drone for bridge pier inspection *(Reprinted with permission from* [55]*)*.

and the control and analysis module [43,44]. A climbing robot subsystem consisting of an actuation module and an excitation module (Fig. 2 (d)) has been developed for climbing stay cables of bridges [43], and an NDT method based on magnetic flux leakage (Fig. 2 (c)) was developed to automatically detect cable flaws [44]. Zheng and Ding developed a cable-climbing robot for defects inspection of a cable-stayed bridge [45]; they subsequently developed a split-type wire-driven cable-climbing robot [46], which can climb along with bridge cables with diameters ranging from 90 mm to 110 mm and has an inchworm-like gait with a speed of 12 m/min. Hou et al. proposed a novel method for detecting surface defects of stay cables by combining a cable inspection robot and transfer learning on a cascade mask region conventional neural network to precisely identify and quantify the cable defects, which can be further adopted into maintenance strategies [47].

Cable-climbing robots have been widely applied in bridge engineering for various defect detection of bridge cables or vertical hangers of long-span bridges but the application scenario is limited because of the limited locomotion capability of cable climbing. Although the climbing platform has automated the process of regular inspection of bridge cables, current cable climbing robot can only inspect one cable each time and operators are needed to install the robot from one cable to another cable, restricting the inspection efficiency. To address this issue, the state-of-art technology of swarm robotics could be one possible solution for defect inspection of multiple cables each time. Besides, the cable diameter of bridge cables is different and more advanced climbing robotic platforms need to be developed for adapting to different cables.

2.4. Flying drones

In recent years, flying drones, also called unmanned aerial vehicles, have been extensively investigated for their use in defect inspection of bridges because of their advantages of non-contact measurement, high mobility, and capability of capturing images of hard-to-access components of bridges, such as the piers, and towers [48,49]. Flying drones have been already used for inspecting surface cracks/joint openings on the decks of highway bridges [50] and for detecting surface cracks of concrete structures [51]. Potenza et al. proposed a robotics and computer-aided procedure for defect evaluation of bridges, from which superficial defects such as paint absence, efflorescence, and vegetation on structural elements could be detected through the color detection technique [52]. Other than surface defects detection, Seo et al. used a commercial drone (DJI Innovations) for inspecting concrete spalling, steel corrosion, and exposed corroded rebar of a three-span timber girder bridge (Fig. 4(a)) with a composite concrete deck [53]; Ayele et al. developed an automatic crack segmentation method for bridge piers using drone-captured images and deep learning-based data analytics [54]; Liu et al. investigated the drone platform for crack assessment of bridge piers and a 3D reconstruction method was used to project cracks onto a meshed 3D surface triangular model of the bridge piers [55] (Fig. 2(e)). Other than surface defects inspection, Ellenberg et al. investigated the capability of drone-installed color and infrared cameras for detecting subsurface delamination of bridge decks [56], and Omar et al. examined the possibility of drone infrared thermography for inspecting concrete delamination of bridge decks [57].

In addition to using commercial drones for defect inspection of bridges, various multipurpose flying drone platforms have been developed for bridge inspection. Sanchez-Cuevas et al. developed a novel drone platform for performing physical contact tasks in bridge inspection (Fig. 3(a)), which can measure both crack depth by supersonic sensors and bridge deformation [58]. Ikeda et al. developed a drone platform with three degrees of freedom robotic arm (Fig. 3 (b)) that can be adopted to capture defect images in narrow and confined spaces of bridges (i.e., bridge bearings) and can also be used for performing impact hammer testing [59]. Jiang et al. developed a multipurpose drone platform (Fig. 3 (c)) that is capable of both flying and wall climbing, and it has been adopted for real-time measurement of concrete cracks of long-span bridges and high-rise buildings with the aid of state-of-the-art deep learning technologies [60].

Compared with ground mobile robots, wall-climbing and cable-climbing robots, the flying drones have the unique advantage of approaching to some difficult-to-reach regions of bridges. One bottleneck problem of applying drone technology into engineering practice is

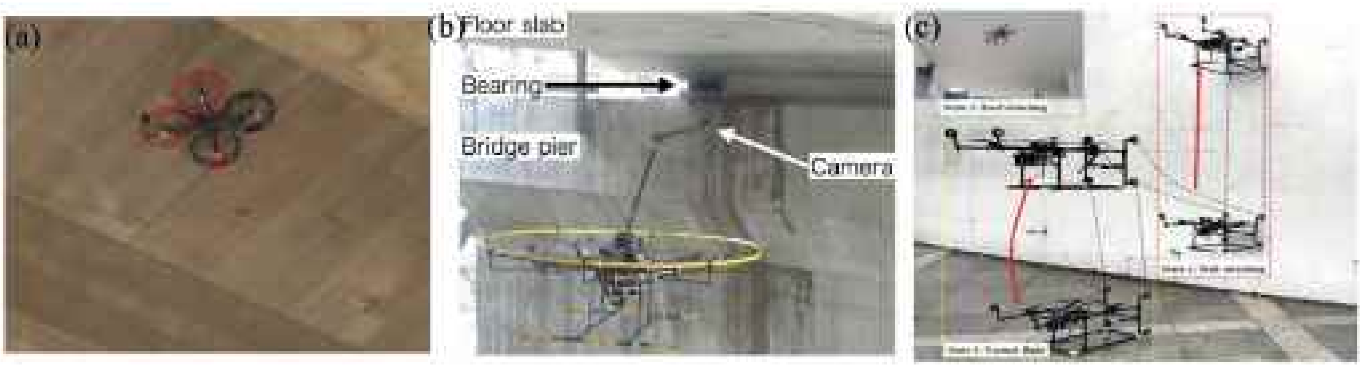

Fig. 3. Emerging multipurpose flying robotic platforms: (a) contact inspection with a drone platform *(Reprinted with permission from* [58]*)*; (b) drone platform installed with a robotic arm *(Reprinted with permission from* [59]*)*; (c) flying and wall-climbing drone platform *(Reprinted with permission from* [60]*)*.

the short duration time due to the limited power provided by lithium-ion battery, usually for 30 min. Another problem is how to localize the drone in GPS-denied environment, such as the underside of bridge deck. In addition, current drone platform uses the visual camera for surface defects inspection, few researchers started to develop more functional drone platforms for performing contact inspection tasks in regular inspection process. But the load-carrying capability of commercialized drone platform is relatively low, how to develop a versatile drone platform with high-payload carrying capability needs to be solved in the future. More importantly, a wind-resistant drone platform is also needed to be developed for capturing high-quality images in windy days and windy regions in bridge construction sites.

3. Robots for vibration measurement

Besides the development of various robotic systems for defect inspection, robotic platforms have been explored for monitoring vibration responses and investigating the dynamic properties of bridges. The application of existing robots for vibration measurement will be comprehensively reviewed in this section and a summary of existing robotic platforms being used for vibration measurement (i.e., acceleration and displacement) and modal identification of bridges are shown in Table 2.

3.1. Mobile and climbing robots

Dynamic properties are important for examining the dynamic performance of bridges and can also be employed to calibrate the finite element model, which is essential for the bearing capacity assessment of the bridge. However, only modal shapes with low spatial resolution are identified from conventional methods because of the limited number of available sensors. To address this issue, several mobile robotic platforms have been used for dense vibration measurement and modal identification. To identify dense modal shapes from vibration data, a mobile robotic platform was developed to increase the measurement positions (Fig. 4(a)), one stationary sensor and one mobile sensor were used to identify spatially dense modal shapes of a concrete bridge [61]. In addition, a magnetic wall-climbing robot (Fig. 4(b)) was developed for dense acceleration measurement of steel structures, from which dense modal shapes were identified [62,63]. The identified dense modal shapes of a footbridge using the measured dynamic accelerations are in good agreement with the calculated values of calibrated finite element model, verifying effectiveness of the developed robotic methodology [63].

Ground mobile robots have been adopted for measuring dynamic responses of bridge deck and the magnetic wall-climbing robot has been used to collect the acceleration time histories of steel structures, and the measured data has been processed for modal parameters identification of bridges. But the robotic platform for climbing concrete structures (e.g., bridge tower, bridge pier) and arch bridges is still lack. Besides, only natural frequency, damping ratios and mode shapes are identified from measured data, advanced data mining algorithms are needed to be further developed for identifying more meaningful structural parameters (e.g., modal flexibility, stiffness distribution) for condition assessment of bridges.

Table 2
Robotic Platforms for Vibration Measurement of Bridges.

Type of Robots	Author	Locomotion	Sensors	SHM Tasks
Mobile robots	Marulanda et al., [61]	Ground movement	Wireless accelerometer	Dense acceleration measurement, modal identification
Climbing robots	Zhu et al., [62] Zhu et al., [63]	Magnetic wall-climbing	Wireless accelerometer	Dense acceleration measurement, modal identification, and damage detection of steel structures
Aerial robots	Reagan et al., [67]	Aerial flying	Two cameras	Full-field displacements measurements
	Yoon et al., [64] Yoon et al., [65] Hoskere et al., [66] Bai et al., [68] Chen et al., [69]	Aerial flying	Camera	In-place vertical displacements measurement, modal identification
	Tian et al., [71]	Aerial flying	Camera	In-place horizontal displacements measurement, modal identification, cable force estimation
	Ribeiro et al., [70]	Aerial flying	Camera, inertial measuring unit	In-place horizontal displacements measurement
	Garg et al., [72]	Aerial flying	Laser Doppler vibrometer	Transverse dynamic displacement measurement
	Perry et al., [73]	Aerial flying	Optical and infrared cameras	Three-dimensional displacement measurement

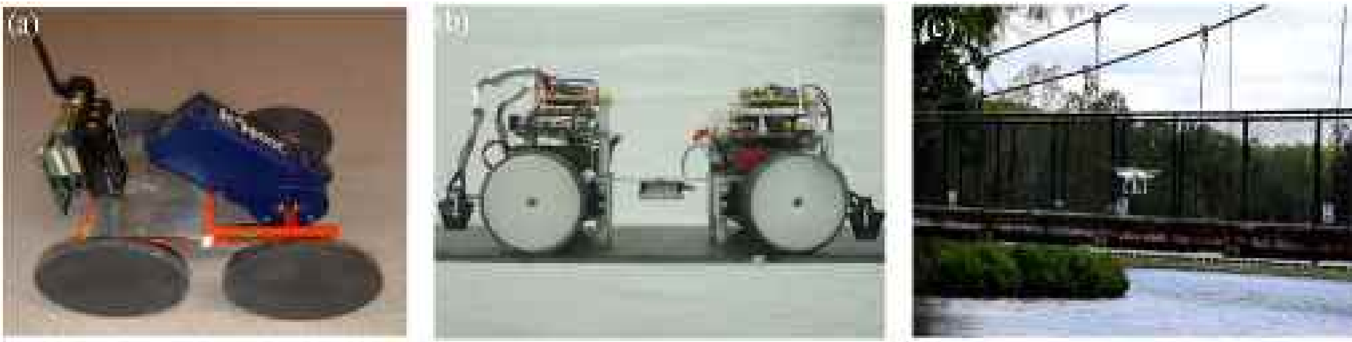

Fig. 4. Robotic systems for bridge vibration measurement: (a) mobile sensors *(Reprinted with permission from* [61]*)*; (b) flexure-based mobile sensing nodes *(Reprinted with permission from* [62]*)*; (e) flying drone platform *(Reprinted with permission from* [66]*)*;

3.2. Flying drones

The mobile/climbing robotic platforms are useful for obtaining dense modal shapes of the bridge deck and steel truss bridge, but they still need to contact the surface of bridges. To further improve testing efficiency, flying drones are widely investigated for use in rapid structural response measurement of bridges because of their unique advantage of non-contact measurement. Yoon et al. investigated the feasibility of using drone-captured videos for modal identification of a laboratory steel model with correlation functions [64], and they then applied the drone platform (Fig. 4(c)) for measuring dynamic displacement and extracting the dynamic properties of a footbridge [65,66]. The identified modal shapes using the measured displacement from the flying drone platform are in good agreement with results identified from dynamic accelerations of contact-type accelerometers. Reagan et al. proposed to use two cameras installed on a drone platform for dynamic displacement measurement using the digital image correlation (DIC) technique [67]. Recently, the translations and rotations of a flying drone were automatically filtered out for accurate displacement monitoring [68], and a homography-based method was proposed for vibration measurement of an experimental bridge model by combining a flying drone and DIC technology [69]. An innovative methodology based on video systems installed on flying drone platforms was proposed for estimating the in-place horizontal displacements of engineering structures [70]. In this method, the relative displacements of the flying drone were firstly assessed by a target tracking method, then the structural displacement was obtained by subtracting the movement of the drone estimated from the data measured by an embedded inertial measuring unit (IMU). Further, a drone platform was used for the in-plane horizontal displacement measurement of the cables of long-span bridges, and the cable tension forces were further determined by combining the identified dynamic properties and geometric parameters of the cable [71].

Apart from using drone platforms and vision sensors to measure the in-plane displacements of engineering structures, the transverse displacement of civil infrastructure such as railway bridges is also an important parameter for condition assessments to ensure safe operation. A laser doppler vibrometer (LDV) was mounted on a drone platform for contact-free transverse dynamic displacement measurement [72]. A portable 3D displacement measurement technique was proposed by combining a flying drone and computer vision. Optical and infrared cameras were installed on the flying drone platform for dynamic displacement measurement and a corresponding data processing algorithm was developed. The difference of this platform is that it can measure the 3D displacement of a structure whereas existing drone-based methods can only measure displacements in one or two directions [73].

Abovementioned flying drones use the installed cameras and LDV for sensing the displacement of bridges, researchers have explored to investigate the feasibility of drone platform for carrying and deploying other sensors (e.g., wireless accelerometers, strain gauges) for structural health monitoring. Zhou et al. developed a drone platform integrated with a robotic gripper for deploying Martlet wireless sensor network on structures, from which the dynamic accelerations of the investigated beam were measured and further used for modal parameters identification [74]. Although many researchers have paid attention to drone platforms for vibration monitoring of bridges, the vibration of drone platform including the low-frequency motion and the high-frequency noise induced by the electric motor has effect on the displacement measurement results. Drone motion elimination methods for obtaining accurate displacement measurements need to be further explored. Another issue is that existing flying drone systems can only perform a single task each time (i.e., defect inspection or vibration monitoring), therefore multipurpose drone platforms are urgently needed to enrich the collected condition data of bridges.

4. Emerging multimodal robotics with SHM potential

Existing mobile robots, climbing robotic platforms and flying drones can only complete one SHM task each time (i.e., defects inspection or vibration measurement). To increase their versatility and reduce the costs of applying robotic platforms in engineering practice, the development of multimodal robotic platforms with multifunctional capabilities is attracting much attention. In this section, various multimodal robotic platforms, including flying and perching robots, hybrid terrestrial–aquatic robots, hybrid aerial–aquatic robots, hybrid terrestrial–aerial quadrotors, flying and walking robots, and recently developed soft robots will be reviewed. A summary of emerging multimodal robotics with SHM potentials is shown in Fig. 5.

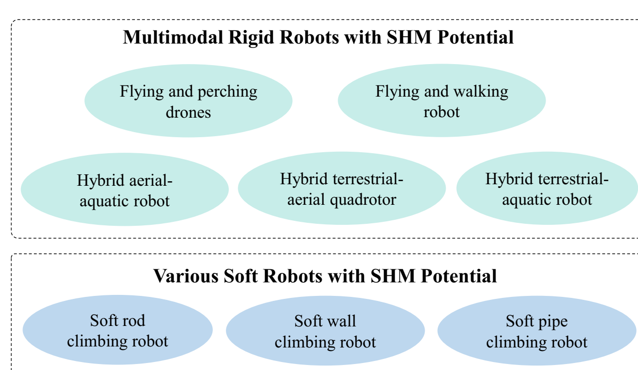

Fig. 5. State-of-the-art robotic systems with SHM potentials.

4.1. Multimodal rigid robotic platforms

4.1.1. Flying and perching drones

Commercial drone platforms are widely used in civil engineering for defects inspection and vibration measurement, but can only perform a single SHM task, which does not meet the requirement of multiple inspection tasks for bridges. To increase the versatility of drone platforms for multifunctional purposes, various flying and perching drones have been developed in recent years, which have great potential for SHM applications. Zhang et al. installed a compliant bistable gripper on a quadcopter platform for perching on cylindrical objects [75]; Thomas et al. developed an avian-inspired grasping drone for pick-and-place tasks, transportation, and the placing or retrieving sensors [76]. This robotic platform can fly and grasp a cylindrical object using feedback from a monocular camera and an IMU sensor. Kalantari et al. integrated a dry adhesive gripper on a quadrotor micro air vehicle platform for perching on smooth vertical walls [77]. Recently, Graule et al. used a switchable electro-adhesive to develop a flying robotic insect that can perch on a wide range of materials (i.e., natural leaf, wood, and glass) and requires three orders of magnitude less power [78]. Mishra et al. integrated a robotic soft grasper to a hexacopter platform for collecting various contaminants, and an image-based visual servo scheme was developed for autonomous object detection and grasping [79]. The soft robotic grasper has the advantage of being lightweight compared with traditional rigid graspers and it can simplify the control strategy of grasping mechanics. Inspired by the perching and resting actions of birds or bats in nature, a flying and perching drone was developed by using 3D-printed landing gear [80]. This drone platform is capable of perching and resting on streetlights, horizontal rods, edges, or corners of buildings and the perching capability helps the drone extend its flight time.

The recently developed flying and perching drones are promising for SHM applications because of their unique advantage of multiple locomotion capabilities (e.g., flying, perching, grasping). One possible problem of applying those drone platform is the switching of different grasper or landing gear for grasping or perching on different structural components with different shapes (e.g., the cable with circular shape, the bridge tower with rectangular shape). And it is difficult to control the flying and perching drone for grasping targeted structural components and performing SHM tasks because of the time delay in the process of long-range signal transmission, therefore more advanced remote-control technology is needed to be developed to precisely control the drone platform. Besides, the problem of signal interference could happen when the robotic system inspects the inner defects of box girder. The perching capability is useful for extending the duration time of drones and the grasping capability could be further explored for deploying sensors on structures and for the purpose of post-disaster rescue. For applying those versatile robotic platforms into civil engineering, the expert in the field of robotics and civil engineering could work together to develop a multifunctional robotic platform for performing SHM tasks.

4.1.2. Hybrid multimodal robots

For adaption to complex environments, various hybrid multimodal robots have been developed in recent years, which are promising for SHM applications because of their multifunctionality. This section will review recently developed multimodal robots including flying and walking robots, hybrid aerial–aquatic and hybrid terrestrial–aquatic robots, and hybrid terrestrial–aerial quadrotors. Daler et al. developed a flying–walking robot for application in cluttered environments, consisting of a flying wing with adaptive morphology, and powered by a single locomotor apparatus, which greatly reduced the overall complexity and weight of this multimodal robot [81]. Pratt et al. developed a dynamic underactuated flying–walking robot that consists of a quadcopter and passive–dynamic legs that are adapted for terrestrial locomotion without the requirement of additional actuators, simplifying the design and decreasing power consumption [82]. Kalantari et al. developed a hybrid terrestrial–aerial quadrotor robot, in which a quadrotor drone platform was hinged at the center of a cylindrical cage [83]. This robot has the advantage of obstacle avoidance compared with terrestrial-only robots because it simply flies over obstacles. And it provides longer operational distance and time compared with aerial-only drones by eliminating the need to hover [83]. But the balance of required time for task completion and energy-efficient path needs to be solved by developing path planning algorithm and the possibility of installing various NDE sensors for SHM also needs to be further explored. Thorel et al. proposed a hybrid design of terrestrial–aerial quadrotors that can move on the ground to save battery power [84]. In addition, various small-scale robotic platforms have been developed for confined environments. Chen et al. developed an insect-scale robot with a multimodal flapping strategy, which is capable of flying, swimming, and transitioning between air and water [85]. Chen et al. developed a hybrid terrestrial–aquatic microrobot that can walk on land, swim in the water, and transition between the two using a combination of surface tension, buoyancy, and electrowetting [86]. Reven et al. designed and fabricated an unmanned aerial and traversing robot for bridge inspection [87]. This robot has the capability of flying and traversing bridge elements by combining the advantage of unmanned aerial vehicle and climbing robot, which has longer operational time (∼ 1 h) and can provide high quality images from cameras. And the robotic system was specifically designed to attach to some special structural elements in civil infrastructure (e.g., flanges in I-beams or girders or any plate-like elements)., providing a great potential for inspecting the difficult-to-access places of elevated and complex bridge [87].

The flying and walking robots are promising for inspecting the surface defects of bridge deck by walking capability and collecting vibration responses of hard-to-access components of bridges using the flying capability. The hybrid aerial–aquatic robot could be further developed for detecting the defects of superstructures and underwater bridge piers, and the hybrid terrestrial–aquatic robots could be used for the inspection tasks of bridge deck and bridge substructures. Besides, the hybrid terrestrial–aerial quadrotors could be integrated with NDE sensors for SHM tasks of bridge deck and bridge superstructures. One possible problem of applying those excellent robotic platforms into practice is the tradeoff between multiple locomotion capability and load-carrying capability. And the control strategy of multimodal robots is complicated due to the change of different locomotion modes and the control of carried sensors or grippers for performing SHM tasks at the same time.

4.2. Soft climbing robots

This section will review recently developed soft wall-climbing robots and soft rod−/pipe-climbing robots for use in dangerous and complex environments such as high-voltage cables, nuclear power plants, and underwater sites.

4.2.1. Soft wall-climbing robots

Most conventional wall-climbing robots rely on rigid actuators, so they are relatively heavy and difficult to control. Recently, soft wall-climbing robots have been developed through the rapid progress in smart materials and additive manufacturing [88,89]. Gu et al. developed a tethered soft robot made of dielectric-elastomer artificial muscles and electro-adhesive feet for multimodal locomotion (i.e., climbing, crawling, and turning), which is capable of climbing walls made of various materials at a speed of up to 0.75 body length/s. Carrying a camera, this soft robot has been applied for inspection tasks in a vertical tunnel and it can change its height to navigate through confined spaces [90]. Hu et al. developed an inchworm-inspired soft climbing robot for inclined/vertical curved surfaces, flat surfaces and even moving in an underwater environment [91]. Another inchworm-inspired soft crawling–climbing robot, consisting of three pneumatic actuators connected in series, negative pressure sucker feet, and a semi-automatic controlling system was developed by Zhang et al. [92]. This soft robot has multimodal locomotion, including crawling, climbing, and transitioning between them, and can move from a horizontal plane to an inclined plane with a slope up to 75°, which has potential applications for inspection and surveillance of civil infrastructure.

4.2.2. Soft pipe-climbing robots

Soft climbing robots have attracted much attention from researchers because of their potential applications on walls or inside tubes. However, making a soft robot climb on the outer surface of a rod or tube with agile and efficient motion has long been a challenge. A pipe-climbing robot made of soft pneumatic actuators was developed for grasping and moving along cylinders with various diameters [93]. This robot is composed of extending and bending fiber-reinforced pneumatic actuators, the former actuator being used for grasping circular pipes and the latter actuator being adopted for generating forward/bending motion for direction control. Inspired by the winding climbing locomotion of arboreal snakes, Liao et al. developed a tethered pneumatic-actuated soft rod-climbing robot [94], which consists of two winding actuators and a telescopic actuator. They demonstrated that the developed robot can perform climbing locomotion like a snake, including turning around a corner along a rod, climbing a vertical rod with a maximum speed of 30.85 mm/s, and carrying a larger payload than existing soft climbing robots. It also could be applied in environments such as high-voltage cables, nuclear power plants, and underwater sites. Jiang et al. developed a soft pipe-climbing robot with bioinspired propulsion to increase its adaptability to different working scenarios. It consists of two origami clutches and two pairs of soft modular legs: the origami clutch is used to achieve multimodal locomotion and the soft modular legs are designed for multimodal climbing [95]. This soft climbing robot has three climbing modes, comprising out-pipe versatile mode, out-pipe high-force mode, and in-pipe mode, which can be achieved by choosing the leg-type for the different working scenarios. Most recently, a versatile quadruped soft rod-climbing robot was developed for climbing parallel rods, consisting of four bending actuators and a telescopic actuator [96]. This robot is capable of climbing parallel rods at an inclination angle of 90° at a speed of 2.33 mm/s and is suitable for inspection tasks in dangerous environments (i.e., nuclear pipelines and high-voltage cables). A soft multi-legged robot inspired by the octopus has been developed for climbing columnar objects, consisting of eight flexible legs and a truck comprising three flexible links [97]. This bioinspired robot can climb various columnar objects, such as vertical circular pipes (one or two parallel pipes), rectangular pipes, natural trees, and natural tree branches. For fast fabrication, a fully 3D-printed modular pipe-climbing robot was recently developed that can climb pipes with various diameters, inclinations, radii of curvature, and even outer/inner walls, because of its modular soft grippers and inchworm-inspired body [98]. A summary of the type and functionality of emerging multimodal robotics with SHM application potential is shown in Table 3.

The state-of-the-art soft climbing robots could be adopted for inspecting the defects of cable-stayed structures in civil engineering because of the advantage of easy control and low-cost. One possible problem of applying those robotic platforms into practice is the limited load-carrying capability because the robotic platform is fabricated with various soft materials with lightweight properties. The integration of micro-cameras and micro electronic devices with developed soft robots is a possible solution. And the soft robots and rigid robots could collaborate with each other for performing different SHM tasks at the same time, for example, the soft robots could be used for inspection tasks in space-confined environment, whereas the rigid robots are adopted for performing multiple SHM tasks in other environments.

5. Conclusions and future trends

Conventional methods of defect detection are highly dependent on specialized inspection vehicles and visual inspection and are dangerous and time-consuming to conduct. Advanced robotic technologies show great potential for automating defects inspection and vibration measurement of bridges. Detailed observations are given as follows.

Table 3
Emerging multimodal robotics with SHM potential.

Type	Author	Locomotion	Components	Functionalities
Flying and perching robot	Thomas et al., [76]	Aerial flying and perching	Flying drone, robotic arm	Fast pick-and-place operations, grasping circular objects
	Graule et al., [78]	Aerial flying and perching	Flying robotic insect, electro-adhesives	Perching and detachment on nearly any material
	Mishra et al., [79]	Aerial flying and perching	Hexacopter, soft robotic grasper	Autonomous object detection and grasping
	Kalantari et al., [77]	Aerial flying and perching	Micro air vehicle, dry adhesive gripper	Perching on smooth vertical walls
	Hang et al., [80]	Aerial flying and perching	Flying drone, modularized landing gear	Perching and resting on a set of common structures
Flying and walking robot	Daler et al. [81]	Multi-modal flying and walking	Flying wing with adaptive morphology	Flying and walking in cluttered environments
	Pratt et al., [82]	Aerial flying and terrestrial walking	Quadcopter, passive–dynamic legs	Flying, passive walking down inclined surfaces, active walking on flat surfaces or up inclined surfaces
Hybrid terrestrial-aquatic robot	Chen et al., [86]	Terrestrial walking and aquatic swimming	Quadrupedal microrobot	Walk on land, swim in the water, and transition between the two
Hybrid aerial-aquatic robot	Chen et al., [85]	Aerial flying and aquatic swimming	Insect-scale robot, electrolytic plates	Flying, swimming, transitioning between air and water
Hybrid terrestrial-aerial quadrotor	Kalantari et al., [83]	Aerial flying and terrestrial walking	Quadrotor, cylindrical cage	Particularly suitable for indoor exploration, obstacle avoidance
	Thorel et al. [84]	Aerial flying and terrestrial walking	Quadrotor, omnidirectional ball casters	Energy-saving purposes
Soft robots	Gu et al., [90]	Wall climbing, crawling, turning	Dielectric-elastomer artificial muscles, electro adhesive feet	Climb walls made of wood, paper, or glass
	Liao et al., [94]	Rod climbing	Two winding actuators, a telescopic actuator	Climbing locomotion likes snake, the potential for some special environments such as high-voltage cables, nuclear power plants
	Jiang et al., [95]	Pipe climbing	A soft linear actuator, two origami clutches, two pairs of soft modular legs	Climb on the exterior of pipes travel inside pipes. Potential for inspection of pipelines in hazardous environments

- Various rigid robotic platforms, such as mobile robots, wall-climbing robots, cable-climbing robots, and flying drones, have been reviewed for their capabilities for surface and subsurface defects detection of bridges, especially for some hard-to-access components (i.e., under/beside the bridge deck, bridge piers, towers, bearings). To increase the adaptability of existing drones for performing contact inspection tasks, several multipurpose robotics based on drone platforms have been developed in recent years. Specifically, a drone platform with a spherical protection frame was developed for obstacle avoidance through flying over obstacles compared with terrestrial-only mobile robot; For performing contact inspection tasks, a drone platform with a robotic arm was developed, and it can be adopted for impact hammer testing.
- Existing robotic platforms, such as mobile robots, climbing robots, and flying drones, have been investigated for vibration measurement and dynamic properties extraction of bridges. Conventional vibration measurement methods use contact-type sensors to collect the vibration responses of bridges, but installing those sensors for a large-scale bridge requires a lot of time and cost. To reduce measurement costs and increase testing efficiency, some mobile robots and climbing robots have been used for dense vibration measurement and nodal identification. In addition, flying drones have been widely investigated for their use in measuring in-plane displacement, out-plane transverse displacement, and 3D displacements using installed vision cameras and Laser Doppler vibrometers. The flying drone platform is more efficient than the mobile and climbing robots because of its unique advantages of noncontact capability and high mobility.
- Although various types of robots have been developed for defects inspection and vibration measurement of bridges, most can only perform one SHM task at a time and cannot adapt to some complex or confined environments. Therefore, several recently developed multimodal robots, such as flying and perching robots, flying–walking robots, hybrid terrestrial–aquatic and aerial–aquatic robots, hybrid terrestrial–aerial quadrotors, and soft climbing robots, have been comprehensively reviewed for their promising in automating SHM tasks of bridges.

Based on this review, the following three directions are considered as the future trends in the SHM field.

- Development of versatile multipurpose robotic platforms for SHM applications. Many inspection tasks need to be conducted for the safety evaluation of bridges, however, most existing robots can only perform one kind of various SHM tasks (e.g., defect inspection or vibration measurement), limiting the widespread use of those robotic platforms. Therefore, the development of a versatile flying drone platform integrated with robotic arms, various NDT devices and advanced sensors such as synthetic aperture radar (SAR), active microwave imaging system is promising for performing multiple SHM tasks each time. The challenging problem of this kind of drone platform is to develop a versatile platform with high payload capability. Besides, the surrounding environment of bridges is extremely complicated when bridges are constructed in dangerous and mountainous areas. It is essential to develop a flying drone platform with navigation capability in a GPS-denied environment that can adapt to confined environments (i.e., inside a box-girder, the underside of the bridge deck, and the bridge bearings).
- Development of soft wall-climbing and soft pipe−/rod-climbing robots for SHM applications. Different from existing rigid robotic platforms, soft robots are made of smart materials that have the advantages of lightweight, easy fabrication, and control. Several bioinspired soft climbing robots have been developed in recent years for climbing inclined/vertical walls and pipes with different shapes. But some of them are tethered, which is inconvenient for application in engineering practice; therefore, the development of tether-less soft climbing robots is promising for SHM applications. Another challenge is that the load carrying capacity of soft robots is relatively small compared with their rigid counterparts. Therefore, future work can be focused on the development of soft climbing robots with large payload carrying capabilities. The soft robots are promising for inspection tasks in dangerous and complex environments such as high-voltage cables, nuclear power plants, and underwater sites.
- Development of multipurpose robotic systems for maintenance and repair tasks for bridges and other types of civil infrastructure. Various robotic platforms for defect detection and vibration measurement tasks have been reviewed. After detecting the defects of engineering structures, the next step is repair, such as repairing cracks, cleaning rust steel structures, and removing dust. Traditionally, repair and maintenance tasks are conducted by expert engineers and few studies are focusing on the development of versatile robotic platforms for replacing these tasks because of the complicated design/control strategy and complicated repair procedures. Researchers and engineers in the fields of robotics, civil engineering, and relevant disciplines could collaborate together to achieve these goals.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors are grateful for the financial support from Fundamental Research Funds for the Central Universities (2682022CX077), National Key R&D Program of China (No.: 2019YFC1511105) and the Science and Technology Program of Guangxi Province (No.: 2021AA01007AA).

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