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REGULAR PAPER

Reconfigurable swarm robots for structural health monitoring: a brief review

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Abstract Autonomous monitoring of infrastructure systems offers a promising alternative to manual inspection techniques which are mostly tedious, expensive and prone to error. Robot-based autonomous monitoring systems not only provide higher precision, but they also allow frequent inspection of infrastructure systems at a much lower cost. Recent advancements in robotic systems have led to the development of reconfigurable swarm robots (RSR) that can change their shape and functionality dynamically, without any external intervention. RSR have the advantages of being modular, on-site reconfigurable, multifunctional, incrementally assemble-able, reusable, fault-tolerant, and even repairable on the orbit. Newly-developed reconfigurable robots are expected to bring a radical change in the prevailing structural health monitoring techniques, thus augmenting the efficiency, accuracy and affordability of inspection operations. This paper presents a holistic review of the previous studies and state-of-the-art technologies in the field of RSR, and argues that RSR offer great potential advantages from the perspective of monitoring and assessment of civil and mechanical systems. A roadmap for future research has also been outlined based on the limitations of the current methods and anticipated needs of future inspection systems.

Keywords Reconfigurable swarm robots · Structural health monitoring · Autonomous inspection

1 Introduction

Infrastructure systems are the skeleton of economic progress all over the world. The failure of infrastructure systems, such as buildings and bridges, invariably leads to loss of lives and financial setbacks. This calls for periodic inspection of aging infrastructure systems to prevent any catastrophe that may arise from material degradation or accidental high loads. The prevailing inspection techniques which are popular around the world are mostly manual. Manual inspection has the disadvantages of being subjective, labor intensive, expensive and hazardous. To address these limitations, several efforts have led to the development of autonomous monitoring systems that afford higher precision and safety at low operational cost. Autonomous monitoring techniques aided by robotic systems facilitate periodic inspection and targeted maintenance of infrastructure systems which prolongs the service life of structures. For several decades, a variety of sensing techniques has been developed for SHM or inspection systems. Myung et al. (2014) surveyed the robotics and automation technologies for civil infrastructure systems. The robotic development for SHM has focused on the inspection of structures more than the continuous monitoring of structures. These include most common types of locomotion robots.

Wheeled robots moving on horizontal surfaces were used for inspecting and measuring cracks in concrete structures (Yu et al. 2007). La et al. (2013b) proposed an autonomous robotic system for high-efficiency bridge deck

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inspection. Wall climbing/crawling robots were deployed for aircraft inspection (Siegel 1997; Bar-cohen and Backes 2000; Sheng et al. 2008), duct inspection (Luk et al. 2001), for sewage inspection (Kirchner et al. 1997; Adria et al. 2004), pipe cleaning and inspection (Li et al. 2009), and tube inspection (Kostin et al. 1999). Potential application is power transmission line inspection (Nayyerloo et al. 2009; Corley 2009). Bouchard (2010) developed the LineScout robot that can climb on high-voltage power lines for inspection. This robot system is equipped with cameras, a thermo-infrared imager, and a smart navigation system to determine the defective locations. Besides, snake-like robots were designed for inspecting confined spaces and rough terrains that are hard to navigate, such as air ducts, pipes, and tubes too small for humans to enter (Mori and Hirose 2006; Erico 2010). Xu et al. (2011) proposed a novel robotic system for inspection of cable-stayed bridges. Kim et al. (2012) introduced a wheel-based cable climbing robot for inspection and monitoring of suspension bridges. Qiao et al. (2013) proposed a self-locking mechanism for in-pipe robots to carry out maintenance works inside pipelines. Cho et al. (2013) proposed a cable climbing robot for visual inspection of hanger cables in suspension bridges.

Aerial vehicles such as quadrotors, miniature helicopter, unmanned aerial vehicles (UAVs) (Zhou et al. 2016) have been extensively deployed in structure inspection and monitoring. The Robotic Institute of Carnegie Mellon University in collaboration with the Department of Civil and Environmental Engineering at Northeastern University has recently developed an aerial robotic infrastructure analysis system called the Aerial Robotics Infrastructure Analyst Project (ARIA 2017) to rapidly model and analyze civil infrastructures using small, low-flying robots. The main limitation with this type of robots is the limited payload capacity, and thus cannot carry many sensors (Pratt et al. 2008). Fumagalli et al. (2012) studied the modeling and control of a flying robot for remote inspection of industrial plants for contact inspection.

Several underwater prototype vehicles have been designed for inspecting oil storage tanks and pipelines (Conte et al. 1996; Bodenmann et al. 2009; Abdulla et al. 2010). La et al. (2013a) developed an autonomous mobile robotic system for nondestructive inspection and evaluation of bridge decks. Robotic inspection of steel bridges was investigated by Mazumdar and Asada (2010), Zhu et al. (2010), Romero (2010), Pagano and Liu (2017), and Chotiprayanakul et al. (2012).

Recent developments in the use of robotics in inspection and SHM include the deployment of small robots as wireless sensor carriers. The mobile units autonomously navigate on a large structure. The swarm of robots forms a mobile sensor network. Each robot sensing node can explore its surroundings and exchange information with its peers through wireless communication. The provided information can be used for updating the finite element model of a large-scale structure, but measurement locations need to be as dense as possible. In addition, the use of mobile sensors offers the possibility of collecting adaptive and high spatial resolutions data with relatively small number of mobile sensing nodes. Thus, the problem of limited power supply for wireless sensor networks can be solved by using the mobile units as charging stations (Churchill et al. 2003; Roundy 2000; Sodano et al. 2004). The mobile robots can be paired, to be used to locally excite small section of the structure and collect corresponding response. Vibration signals caused by local excitation can provide more abundant information for damage detection and localization.

Modular robots are used in inspection and SHM. Modular robots are built using multiple small modules that makes it possible to build a robot capable of going through rough terrain and uneven surfaces. Yim et al. (2007), Salemi et al. (2006), and Murata and Kurokawa (2007) developed self-reconfigurable robots with multiple modules automatically morphing to arbitrary shapes using reconfigurable connections. Several other researchers (Lee and Lee 2009; Zhu et al. 2011) developed mobile sensor nodes by connecting two magnet-wheeled modules by a flexible beam. The developed nodes had the capability of being equipped with accelerometer, that can be attached and de-attached from structural surfaces. Fischer and Siegwart (2007) presented a pair of wall-climbing robots with magnetic wheels. Wheel-based (Xu et al. 2008) or reconfigurable robots (Yuan et al. 2010) have also been developed for bridge cable inspection.

Recent advancements in robotic systems have led to the development of RSR that can change their physical or logical size and shape and functionality dynamically and autonomously. This paper argues that such newly developed robots may bring some radical changes in the prevailing structural health monitoring (SHM) techniques, thus augmenting the efficiency, accuracy and affordability of inspection operations. In the remain of the paper, we will present a list of current challenges for SHM, a holistic review of the previous studies and state-of-the-art technologies in the field of RSR, and argues that RSR may offer some great potential advantages from the perspective of monitoring and assessment of civil and mechanical systems. A roadmap for future research has also been outlined based on the limitations of the current methods and anticipated needs of future inspection systems. In general, this paper offers an initial review and study for applying RSR to SHM.

This paper is organized in the following order. Section 2 lists out the advantages and challenges of RSR for SHM. Section 3 details the design and other related aspects of reconfigurable robots. It also includes a case study on SuperBot. Section 4 introduces swarm robots laying out in details different domains of its application. A roadmap for future research is outlined in Sect. 5. Finally, conclusions are summarized in Sect. 6.

2 Potential advantages and challenges of reconfigurable swarm robots for SHM

With the recent advances in sensors, robotics, communication, and information technologies, it is now feasible to move towards the vision of ubiquitous connected communities, where virtually everything throughout the community is linked to an information system to provide continuous and systematic monitoring and condition assessment of dispersed infrastructure systems and components, thereby enabling maintenance personnel to efficiently manage such systems.

As societies throughout the world move from a "schedule-based" maintenance approach to a "condition-based" procedure in which infrastructure assets that exhibit recurring anomalous behavior would be given more frequent inspections and remedial measures, a crucial requirement to enable such an approach is the availability of abundant data that can be used to track the evolution of damage and deterioration in target assets of concern. The needed measurements will involve large amounts (in speed as well as volume) of data from heterogeneous sensors (both passive as well as active ones) that need to be acquired, fused, and interpreted so as to culminate in actionable decisions.

While the ever decreasing price of sensors is making the cost of individual sensors more affordable, the deployment of sensor networks and the associated instrumentation network components to operate and energize the sensors, collect the measurements, and transmit to a central location is still a daunting problem, particularly when a very high degree of spatial resolution is needed to achieve reliable detection, localization and quantification of small defects before they evolve into serious problems.

With the above in mind, given the current state-of-the-art and the rapid development of the robotics field, we argue that autonomous mobile robots, especially those that can self-reconfigure physically and logically (i.e., reconfigure their networking and communication connectivity), would play increasingly vital roles in future structural monitoring systems. In particular, future RSR systems could offer the following valuable solutions:

1. For identification of optimal locations: Since autonomous robots are sensor-driven, they can use sensed information in situation to guide their action to search for a place where the sensed inputs are most salient (thus optimal). For example, a vision-guided robot may follow a hint of crack to the place where the crack is most obviously visible. This is quite different from non-robotic sensor networks where the location of installed sensors is fixed and non-changeable. This capability can also reduce the number of sensors and deliver the least number of sensors to the most critical locations, and that would greatly reduce the cost of the monitoring system.
2. For in situ active sensing: Autonomous mobile robots are mostly self-contained where they can carry the required devices and perform the active sensing using their on-board power, sensors, and actuators. In addition, the tools for active sensing will be the end-effectors used by the robots, they can be dynamically changed and adapted based on demand.
3. For data fusion from distributed and multiple modalities: The types of sensors used by the robots can be heterogeneous and different from robots to robots. This will offer a variety of different sensor modalities (i.e., vision, acoustics, chemical, electromagnetic, etc.) for a swarm of robots to act collaboratively. Data fusion can be performed on-board or relayed back via communication to a data center for further analysis. The algorithms developed for data fusion can in turn guide the robots to perform more effective data gathering in order to obtain better results of fusion. For example, one may discover after the initial fusion that a visual input from a particular angle is critically missing, and send a robot to gather that data.
4. For delivering sensors to difficult locations: Robots with different mobility and morphing configurations are especially useful for this purpose. For example, to go through a narrow passage, a robot may conclude that its current body is too big and become a snake to go through it. Similarly, a robot may first fly and purge onto a high structure, and then attach itself to the structure and crawl into a position. New methods of attachment are being developed rapidly (e.g., gecko feet or suction devices are for vertical wall climbing), and future robots will be able to crawl, climb, burrow, fly, and dive for different purposes.
5. For combing autonomous decision-making with remote controllability by human operators: All robots will have on-board decision making capability as well as wireless capability to remotely communicate with humans. This combination will serve at least two main purposes: (a) to report newly discovered information to human, and (b) to consult with human for difficult decisions. For instance, if a flying robot equipped with an image sensor detects a crack somewhere on an infrastructure system during inspection, it can inform

the human operator through wireless network about the presence of the crack. The human operator can then make a decision about the optimum angle and distance from object in which image of the crack should be captured for better quality and resolution. These robots should be able to change their shape, size, function, and formation to overcome difficulties. As an example, such a robot can become a snake to go through a pipe, grow multiple and extra legs to cross gaps in structures, change end-effectors from gecko-like feet to tentacle-like manipulators, disassemble a large robot into a swarm of small robots and self-form a sensor network in situ, and repair/replace sensors and reconfigure existing networks.

6. Revisiting and data comparison: Since intelligent robots will have the capability to locate themselves with accurate location information, it is feasible for them to revisit the same location with certain frequency and interval in order to collect the data at different times for comparison. Such comparisons are critical to detect early signs of defective regions. For example, comparing images taken at the same location at different times can reveal changes that may indicate problems. Compared to the fixed sensor networks, such revisiting can be focused or targeted to only those locations that have problems.
7. On-demand shape optimization: Reconfigurable swarm robots are capable of on-demand shape optimization that is critical for a deployable SHM systems. For example, to perform *simultaneous* inspections or manipulations at different locations, such as aligning an extended structural element from both ends, a reconfigurable robot could morph into two or more smaller robots and move to the desired task locations, or vice versa. In addition, after or during the inspection task, a reconfigurable robot can switch into other functions that are critical at the time. For example, it can perform attitude control by becoming multiple robots and move into the appropriate locations (such as corners) and function as individual but collaborative activities. These capabilities are clearly beyond a robot that has a fixed configuration. No matter how many optimizations were built-in initially, a fixed-shape robot cannot adapt to unplanned events such as changing its arm length or relocating its cameras to elsewhere on the body.
8. Resilient to single-point failures: Reconfigurable swarm robots are resilient to single-point failures that are often catastrophes for robots with fixed configurations. For example, a failure in a critical component, such as power bus or communication units, can paralyze the entire robotic inspection system if its configuration is fixed. On the contrary, a reconfigurable robot distributes its functions among modules, and if a module fails, other modules could reconfigure to set aside the damaged module and continue with a new configuration.
9. Flexible and low-cost deployment options: Reconfigurable swarm robots provide flexible and low-cost deployment options that are not possible otherwise. Unlike a fixed-shape robot that must be launched in a single payload with expensive protections (due to the large mass or fragile structure), a reconfigurable robot can be deployed as individual and lightweight modules in one or more batches with simple locking mechanisms so that they can unpack and assemble into larger robots once in position. This will allow future robots to be deployed incrementally, with extendibility, upgradeability, reparability, and without restrictions on its final shape, size, and function. This provides a tremendous cost saving.

Additionally, designing and deploying robots to climb complex structures such as pipes, bridges, and high-rise buildings, has many difficulties. Different from the conventional wheeled robots, these robots must have limbs (“hands/legs”), must maintain and maneuver their center of mass (COM) dynamically, and must have means to attach themselves on the structure or surface of interest, and must overcome (physical) gaps along their paths. Since conditions during climbing cannot always be fully anticipated before launch, these robots often find they are in situations where they wish to have a longer limb to overreach a gap, or to have a few extra hands/legs to maintain their positions, or to be able to leave a part of their body in order to install a desired sensor in place. These requirements are just beyond the capabilities of any type of conventional fixed-shape robots. However, reconfigurable swarm robots can overcome these shortcomings for applications that are widely encountered in various scenarios of SHM, which is the scope of future work.

Using multi-robotic or swarm robots to self-form effective sensor networks is another challenging task. Previous work in this area has been aimed at establishing and maintaining communication between entities in an unknown and dynamic environment. The challenge is due to the unknown locations and distances between entities, obstacles that may block or deflect signals, unexpected changes in the environment, and movement of, or damage to, the entities. One possible solution is to deploy a group of intelligent robots to explore the environment and position themselves to provide communication and data collection capabilities. Such robots must self-configure into an effective network, self-optimize the performance of the network, self-heal changes and detected damage, and adapt to movements of the critical entities.

3 Reconfigurable robots

To test and prove these advantages and values, one needs to prototype and demonstrate a set of reconfigurable swarm robotic systems that can morph into multiple configurations, recover from module failures, and alter its existing configurations at command (e.g., collaborating with human operators). In this section, we first review the state-of-the-art of reconfigurable robots for this purpose.

Reconfigurable robots, also known as modular and self-reconfigurable robots, has typically have hardware designs of reconfigurable modules and connectors, as well as software and algorithms for distributed and resilient control. In essence, a reconfigurable robotic system is an assembly of interconnected modules which can change its shape and functionality dynamically and autonomously to adapt to different working environments (Yim et al. 2007; Brandt et al. 2007). Research in modular self-reconfigurable, robotic systems has been going on for the past two decades (Fukuda and Nakagawa 1988; Fukuta 1994; Yim 1994; Yim et al. 2002). Researchers have demonstrated that homogeneous and heterogeneous building block systems that attach/detach to/from each other (Yim 2003; Rus 2001; Christensen 2006) and form arbitrary shapes or structures (Galloway et al. 2010; Tolley et al. 2010). A book has been written that describes dozens of self-reconfiguring robot research systems (Stoy et al. 2010). Will et al. (1999) and Castano et al. (2000) introduced a homogeneous CONRO building block for deployable and reconfigurable robots. The CONRO module proposed by one of the authors is said to be one of the first modules for reconfigurable robots that are self-contained and autonomous. Murata et al. (2002) proposed a distributed self-reconfigurable robotic system called modular transformer (M-TRAN) composed of homogeneous robotic modules facilitating versatile robotic motion.

Salemi et al. (2006) described the architecture and design philosophies of a modular deployable self-reconfiguring robot popularly known as SuperBot. The multifunctional capacity and ability of the robotic system to endure in rough environment were experimentally demonstrated using rolling track configuration (Chiu et al. 2007). Hou et al. (2007) presented a new remote controlled gait called tricycleBot, which is implemented on a SuperBot. It can carry payloads with satisfactory speed with backward, forward and sidewise movement. Brandt et al. (2007) presented a self-reconfigurable modular robot called ATRON which had the versatility of being deployed for a wide range of applications. Shiu et al. (2008) proposed a two-dimensional self-reconfigurable robot called Octabot, built of modules comprising eight e-type electromagnets. Zhong et al. (2008) proposed a mobile self-reconfigurable robot known as Tanbot with an embedded navigation system where several modules can dock together one by one to form a complete robot. Another modular robot called UBot was presented by Tang et al. (2009). The UBot had compact, strong, flexible modules enabling it to execute efficient locomotion, self-reconfiguration and manipulation tasks. Meng et al. (2011) developed a new self-reconfigurable modular robot called Cross-Ball, which harnesses bio-inspired morphogenesis mechanisms to adapt to dynamic environments automatically. Wu et al. (2013) proposed an underwater self-reconfigurable robot with tree-like configuration. Most recently, Jing (2016) demonstrated an end-to-end tasking and controlling system using the SMORES-EP robotic hardware modules.

In the field of reconfigurable robots, the current research challenges involve several major aspects such as: modular design, connector design, dynamic power sharing, recharging, dynamic configuration discovery, fault-tolerate control, topology-adaptive control, and effective and efficient human interface. There are software libraries for intelligent behaviors, as well as physics-based high-performance simulators for experimenting large-scale inspection in real and synchronized time. Most recently, theoretical frameworks for self-planning reconfiguration and inspection, and an optimal control policy for modules to share power and other valuable resources are also emerging.

4 Module design

In the area of module design, there are two basic types of modular and reconfigurable robots: lattice- and chain-based. Table 1 describes the two types of design and summarizes their advantages and disadvantages. From this table, it is clear that chain-based robots are advantageous in terms of shape flexibility, and locomotion and manipulation simplicity. There are some modular robotic systems that have been designed to integrate advantages from both lattice- and chain-based systems. For example, M-TRAN (Murata et al. 2002), SuperBot (Salemi et al. 2006), and SMORES (Davey et al. 2012).

4.1 Connection mechanism

The connecting mechanism among modules is the critical element for the success of a reconfigurable robot (Nilsson 2001). A successful design requires solving many challenging problems, including docking strength, power consumption, docking reliability, docking compliance/tolerance, communication, power sharing, sensing for alignments, and sensors for docking status. The existing connection mechanisms can be classified into four classes: mechanical, magnetic, electrostatic and vacuum as shown in Table 2. A recent advance in this subfield is to design connection mechanisms that support

Table 1 Comparison between chain-based and lattice-based reconfigurable robots

Reconfigurable robot	Chain-based	Lattice-based
Description	Set of modules that can attach to any modules on the chain	Set of modules that can only attach to their neighboring modules in discrete locations on a lattice
Advantages	Can form multiple geometric shapes including chains, trees, and loops Modules can perform locomotion and manipulation without changing their connections	Reconfiguration process is pre-aligned and relatively easy and can be done without any feedback
Disadvantages	Difficult reconfiguration process	Each module cannot change its own geometric shape The configurable structures are limited to lattices Whole robot's manipulation and locomotion are not efficient to achieve and must utilize multiple modules to move locations Multiple modules must work together to provide even very simple capabilities such as moving or bending
Example robots	CONRO, PolyBots, CKbots, GZ, REPLICATOR	ATRON, Festo Molecube, Cubelets
Sample references	Murata et al. (1998), Yim et al. (2000), Bojinov et al. (2000), Rus and Vona (2001), Castano et al. (2002), Murata et al. (1994)	Fukuda et al. (1994), Castano et al. (2000a, b), Yim et al. (2000), Murata et al. (2002), Østergaard et al. (2006), Jørgensen et al. (2004), Brandt et al. (2007)

Table 2 Comparison among connector mechanisms used by robotic systems

Connection	Mechanical	Magnetic	Electro-static	Vacuum
Description	Connection and disconnection are controlled by mechanical force (e.g., gendered connector, hook, gripper)	Connection and disconnection are controlled by magnetic force	Connection and disconnection are controlled by current magnitude and direction	Connection and disconnection are controlled by airflow
Advantages	High connection strength	Easy to implement	Easy to implement	High connection strength
Disadvantages	Mechanism can be complex Connections may be stuck permanently if one side is to malfunction	Ferromagnetic parts reduce its usability in certain tasks Lose connection if one end is out of service	Low connection strength Requires special circuit on connection surfaces Lose connection if one end is out of service	Requires external pneumatic system Continuous airflow is required to maintain connection Lose connection if one end is out of service
References	Østergaard et al. (2006), Jørgensen et al. (2004), Yim et al. (2002), Lyder et al. (2008), Shen et al. (2009), Li et al. (2010), Mondada et al. (2004), Yun et al. (2008), Sproewitz et al. (2008), Wei et al. (2011), Shimizu et al. (2005), Tolley et al. (2008), Gillies and Fearing (2010), Shen and Will (2001), Castano et al. (2002), Yim et al. (2003), Murata et al. (2001), Ünsal et al. (2001), Nilsson (2002), Zykov and Lipson (2006)	Murata et al. (2002), Kirby et al. (2007), Diller et al. (2011), Suh et al. (2002), Goldstein et al. (2005), Zykov et al. (2005)	Weller et al. (2009), Karagozler et al. (2009)	Garcia et al. (2011)

single-side-operation so that system can continue reconfiguration even if single modules may malfunction. For example, Shen et al. (2009) proposed the SINGO connection mechanism where a key strength of it is the use of a genderless mechanical connector mechanism that supports single-side-operations.

4.2 Control system

In the area of software, the control of modular robots is of two types: centralized and distributed control. The advantages and disadvantages of these two approaches are summarized in Table 3.

A control system for a modular robot needs to be adaptive to dynamic changes in the robot topology, scalable, and fault tolerant. Meister et al. (2013) presented a framework for automatic generation of dynamic equations and adaptive control strategies for modular self-reconfigurable robots. Collins and Shen (2016) proposed an integrated and scalable framework based on particle swarm optimization for path planning and inverse kinematics of hyper-redundant manipulators. Adaptive locomotion and manipulation for self-reconfigurable robots was studied by Collins and Shen (2017). The distributed nature of modular robots makes distributed control more advantageous for SHM related applications as shown in Table 3. A major advantage of distributed controller is fault tolerance and scalability, as well as dynamic detection of topological changes in configuration (Shen et al. 2002; Salemi and Shen 2004). Table 4 summarizes the ongoing research in this field and illustrates the capabilities and advantages of existing systems.

4.3 Operational requirements

The unique nature of the reconfigurable robots offers many possible operational scenarios for inspection. This versatility requires novel modes of operations. An example concept of operations is as follows:

1. A set of robots is unstowed and assembled on site.
2. The modules autonomously configure themselves into appropriate robots.
3. The configured robot is then teleoperated to desired worksite.
4. Once at the worksite, the robot autonomously reconfigures into a two-branch system with camera and light at the tips.
5. The robot performs the desired task (e.g., provide camera views at different angles).
6. The robot retracts to a safe location.

This operation scenario will require a combination of teleoperated and autonomous actions to be put into practice. These two types of control will form the basis of modes of operation. Based on existing reconfigurable robots such as SuperBot, MTRAN, ATRON, Molecube, Cubelets, GZ, CKbots, REPLICATORs, and others, the desired capabilities for individual modules include:

- Mechanically, an individual module should be able to behave as complete and independent robotic “cellular” system. For instance, a gimbal-like mechanism that can move and manipulate in any direction and orientation with continuous rotations and has at least two (e.g., six) universal connectors to connect with other modules or components.
- Electronically, the modules should be able to communicate neighbor-to-neighbor or wirelessly, and should also support dynamic (not just static) power sharing, passing, recharging, and management among modules.
- For intelligent control, the modules should penetrate and maneuver inside confined spaces or thread around obstacles similar to a snake going through a complex pipe system.
- For human interface, the operators should be required only to give high-level control commands such as forward, backward, left, right, twist, rotate, and so on, and the low-level control should be achieved by the modules themselves. The high-precision manipulation at the tip of the arm should be achieved by using inverse kinematics and close-range sensors near the end.
- For fault-tolerance, the reconfigurable robots should support automatic topology discovery during or after dynamic reconfiguration, and they should detect and tolerate multiple single point failures or even consecutive failures via wireless communication. Once the faults are discovered, the software should adapt its control strategy to ensure proper operations of the arm.

Table 3 Comparison between centralized and distributed control approaches

Control system	Centralized	Distributed
Description	Use all modules information for system control	Use local and neighbor modules information for system control
Advantages	Use standard control strategy	Distribute processing Fault tolerant Scalable
Disadvantages	Difficult reconfiguration process	Require specific control strategy
References	Yim (1994), Kiehn and Butt (2003)	Salemi and Shen (2004), Stoy et al. (2002)

Table 4 Comparison among ongoing researches in the area of reconfigurable robots

Robots	Manually reconfigurable	Self-reconfigurable	Remote control	Multi-functional	Distributed control	Dynamic topology discovery	Dynamic power sharing	Gimbaled joints	Connector (fault-tolerant)
Snake (Johnson et al. 2011)			✔						
Molecubes (Zykov et al. 2007)	✔					✔			
Cubelets (Schweikardt 2011)	✔								
GZ-I (Zhang et al. 2008)	✔		✔						
CKBots (Jing et al. 2016)	✔	✔		✔					
ATRON (Brandt et al. 2007)	✔	✔		✔	✔				
M-TRAN III (Kurokawa et al. 2008)	✔	✔		✔					
Replicator (Kernbach et al. 2008)	✔	✔	✔	✔	✔		✔		
SMORES (Davey et al. 2012)	✔	✔	✔	✔	✔	✔			
SuperBot (Salemi et al. 2006)	✔	✔	✔	✔	✔	✔	✔	✔	✔

- The reconfigurable connector mechanism should be genderless to allow any two connectors to connect and disconnect. Further, it should be fault-tolerant and single-side-operative and should connect and disconnect properly even if one side of the connection is not in action. This is to prevent the robot to be stuck at a failed point forever. Additionally, it should be continuously scalable for connecting heterogeneous components with different sizes. For example, with the same design, a large connector should connect to a smaller connector and vice versa.

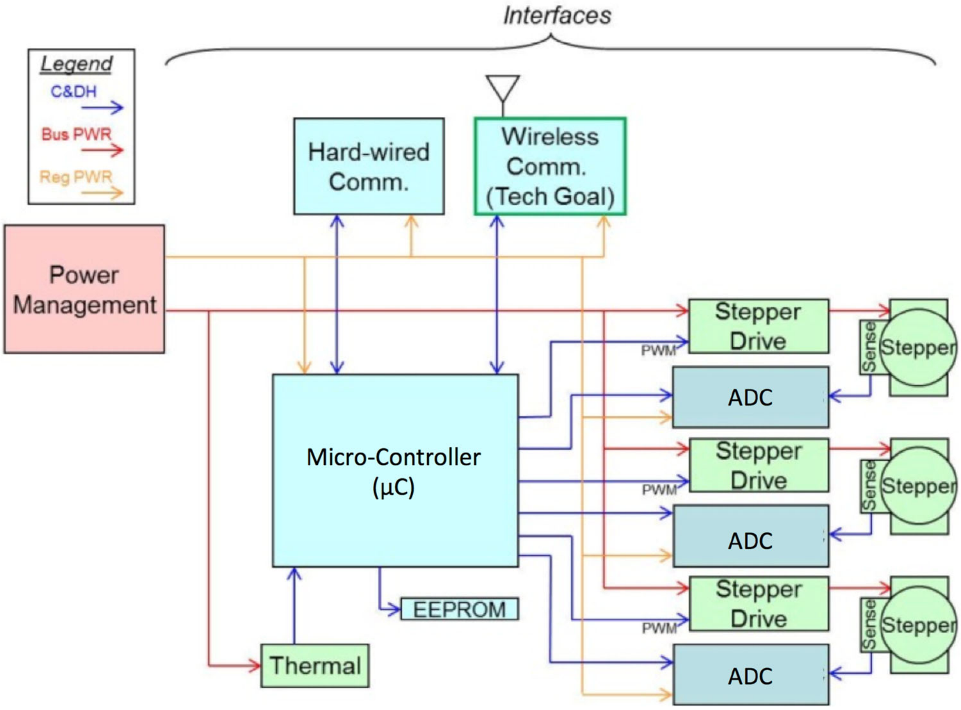
Ideally, an inspection robotic system should be able to climb and anchor on any structure. Its docking mechanisms are mechanical interfaces for communication and battery power. Such a robot should position itself at these worksites via self-locomotion or be positioned nearby sites by human operators. Once at a worksite, the robot can reconfigure as needed to perform the task at hand.

A typical block diagram for internal design of a one core module is illustrated in Fig. 1. In such robotic systems, each module generally consists of three articulating degrees of freedom (brushless DC or stepper motors), two motorized docking connectors, four unmotorized docking connectors, a microcontroller plus a field-programmable gate array (FPGA) (for interfacing to peripherals and glue logic), communication interfaces, power management, thermal, and the laser diodes/photodetectors (for docking, module identification, and collision avoidance).

The control of modular self-reconfigurable robots is another challenging task, as modules must be able to dynamically reconfigure into different configurations/functionalities and support plug and play with other types of devices. The controller requirements for such a modular system can be enumerated as follows:

- Distributed: to support decentralized control and avoid single point failures (i.e., a single module failure would not paralyze the entire system). A module must select its actions based not on its absolute address or unique identifier, but based on its topological location in the current configuration.
- Collaborative: to allow modules to negotiate the best actions for a global task.

Fig. 1 Constituent parts for reconfigurable modular robot



- Dynamic: to be able to adapt to the topological changes in the module network and support all possible configurations.
- Asynchronous: to synchronize modules' actions without a global clock.
- Scalable: to work for any configuration regardless of the shape and size.

4.4 SuperBot: a case study

SuperBot is a deployable self-reconfigurable robot (Salemi et al. 2006) designed and developed at the Polymorphic Robotics Lab at the University of Southern California since 2005. The 3DOF form factor of SuperBot makes each individual module have complete mobility in any direction in 3D space. This provides an efficient means for locomotion, manipulation and self-reconfiguration. The original objectives of the design include multifunction, modularity, and reconfigurability for NASA's vision of affordable and sustainable space exploration. This is a multi-million-dollar project that includes a team of nine universities/organizations (i.e., NASA Ames, Jet Propulsion Laboratory, University of Pennsylvania, University of Hawaii, Lockheed Martin, Raytheon, MDA Alliance Space systems, Metrica, and Life Science and Technology Research Inc.). The goal of the SuperBot project was to design and prototype a multifunctional robotic system that can support and sustain the large variety of tasks in space exploration. In particular, the SuperBots vision is to build a prototype system that consists of 100 reconfigurable and multifunctional modules and demonstrate in a desert environment with four distinct configurations and functionalities, including the reconfiguration process from one to another. The four configurations are: (1) a contracted configuration for transportation and landing, (2) a rolling configuration for traveling, (3) a climbing configuration for climbing and descending sandy slopes, and (4) a platform configuration for performing applications such as drilling, building, sample collection, or sustained living.

Figure 2 shows a single SuperBot module, the genderless, scalable, fault-tolerant universal SINGO connector among modules (Shen et al. 2009), and configurations made by the modules. Figure 3 contains numbered panes showing different functions of the modules. These behaviors are command and controlled by a fully distributed and self-organizing software system called Digital Hormones (Shen et al. 2002) that is inspired by biological systems.

SuperBot is ideal for SHM not only due to its capability to reconfigure itself to adapt to the relevant environment but, more importantly, different sensors can be incorporated into independent SuperBot modules (e.g., accelerometers, cameras, etc.) to form a dynamic sensor network. Furthermore, these modules can form robots that can actively measure characteristics of the structural systems (e.g., a module can induce an excitation while another one collects the response). This calls for the important topic of swarm robotics that is discussed in the following section.

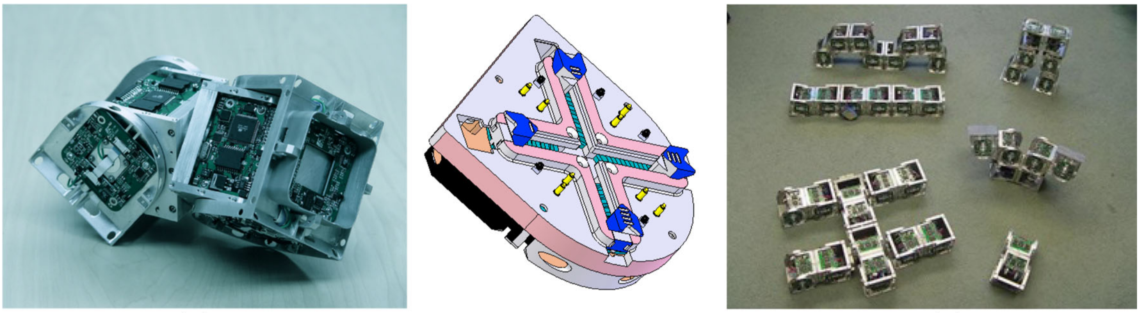

(a) (b) (c)

Fig. 2 **a** A single SuperBot module, **b** genderless, scalable, fault-tolerant universal SINGO connector among modules, **c** and configurations made by the modules

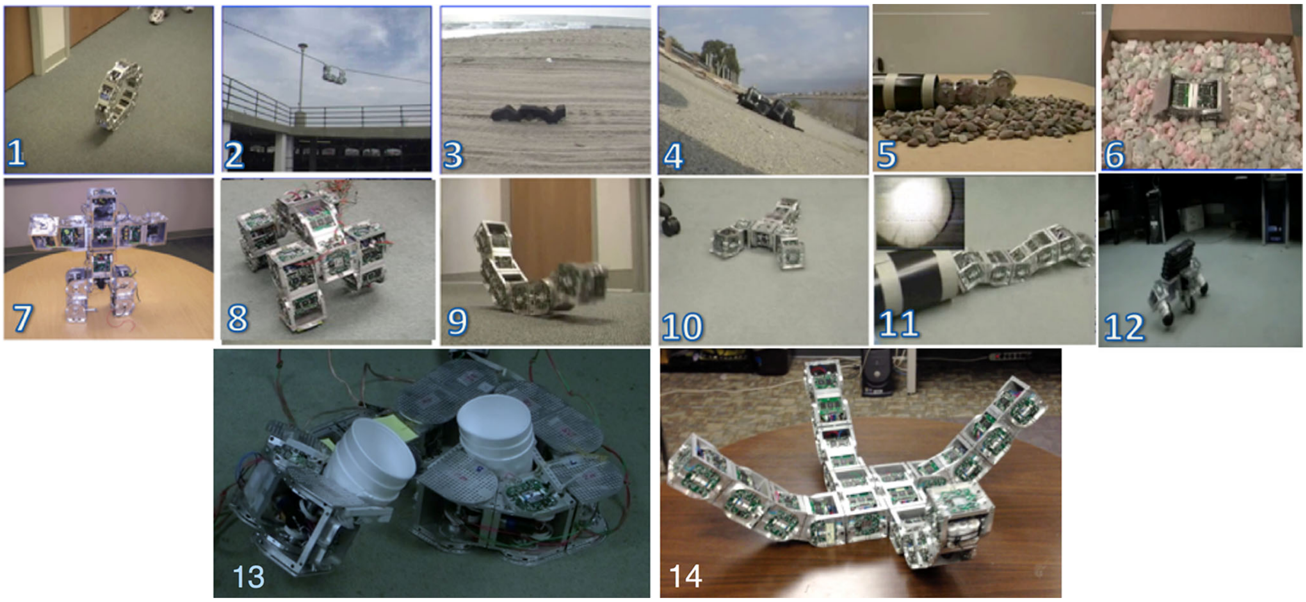


Fig. 3 Examples of SuperBot configurations, gaits, and multi-functionality. Starting from the *top-left picture* pane: **1** a "rolling track" formed by six modules that can roll for a long distance (>1 km) on even terrain or climb sand dunes; **2** a "rope climber" configured by three modules that can use two short arms and move on a horizontal rope across two high buildings, or climb a vertical rope to the top of a six-floor building; **3** a "caterpillar" robot formed by four modules that can form a chain and move like a caterpillar on rough terrain; **4** a "bug" robot formed by four modules that can climb over steep obstacles such as river banks; **5** a "crack explorer" robot formed by four modules that can go through pipes; **6** a "burrower" robot with one module that can dig into gravel and bury itself; **7** a "mini-humanoid" made by six modules that can walk on legs and hold objects; **8** A four-leg walking robot made of six modules; **9** A "snake robot" of four modules that can move as a snake, a sidewinder, and perform "sit-ups"; **10** a "scorpion" robot of three modules that can move and wedge itself into cracks; **11** an "explorer" robot with a camera that can be remotely operated; **12** a "transporter" robot configured by four modules that carries a payload up to 530% of its own weight; **13** a manipulator of eight modules with two grippers that can pour a cup from another; and **14** a cross-configuration of 10 modules that can curve up to form a dish-shape posture

5 Swarm robotics

Recent advancements in robotic technology introduced a new genre of robotic system called swarm robots. Swarm robots consist of a large number robotic modules coordinating among each other in a way analogous to the collective behavior of social insects such as ants and bees. In comparison of reconfigurable robots discussed above, individuals in a swarm robotic system may not physically connected to one another (e.g., UAVs) and their collective behaviors are generally guided by simple control mechanisms to collectively execute a complex task (Shen et al. 2004; Barca and Sekercioglu 2012) like local sensing and communication capabilities, parallelism in task execution, robustness, scalability, heterogeneousness, flexibility and decentralized control (Yogeswaran and Ponnambalam 2010). Swarms of robots have been deployed in many applications. According to a recent literature review, swarm robotics has been studied in the context of various tasks such as aggregation, pattern formation, self-assembly and deployment, object clustering, collective search and exploration, coordinated motion, and foraging among many others (Yogeswaran and Ponnambalam 2010; Brambilla et al. 2012, 2013; Liekna and Grundspenkis 2014; Ryu et al. 2015).

Aggregation is one of the fundamental behaviors of swarms in nature and is observed in organisms ranging from bacteria to social insects and mammals. Aggregation helps organisms in many ways such as avoiding predators and resisting hostile environmental conditions (Dorigo et al. 2004). In robotics, aggregation is deployed to get robots in a swarm sufficiently close together and communicate to each other with limited range. The self-organized aggregation behaviors for swarm robotic systems is essential to form a robot cluster and perform needed communication tasks (Soysal and Şahin 2005). Additionally, aggregation is used for swarm robotic behaviors such as self-assembly and pattern formation (Erol and Ec 2007).

One of the important applications of the robotic swarm is the self-organization and self-assembly in unknown environments such as sewers, ducts, tunnels, caves or narrow passageways (Maxim et al. 2009; Trianni et al. 2014; Shen et al. 2004). For self-assembly, the robotic modules physically connect to each other to form a particular shape/structure. Rubenstein et al. (2014) has developed a decentralized system of autonomous swarm robots which can form complex two dimensional shapes cooperating through local interactions. Rubenstein and Shen (2009) has presented a distributed control method for a collective robotics system to form and maintain a predefined shape robustly and consistently. Rubenstein and Shen (2010) has proposed a method that enables a collective to scalably form a shape without knowing the size of the collective. Self-assembly adds to the efficiency by increasing the pulling power of the robots. It also affords stability to the swarm system while moving on rough terrains. A connected structure of robotic swarm can easily cross over a hole which is otherwise not possible for a single robot. It also helps by guiding others in the assembly to traverse a desired path. Additionally, a self- assembly is generally more robust because of the combined capabilities of heterogeneous robotic modules (Kernbach et al. 2008; Dorigo et al. 2013; Trianni et al. 2014; Dorigo et al. 2004).

Another important application for swarm robotics is swarm-guided navigation where instead of each robot navigating and localizing itself separately, the swarm is guided by directions supplied by previously deployed robots forming a communication relay. Robots forming a chain from a pray to the nest and indicating directions to other robots in a foraging task (Nouyan et al. 2008), navigation via exchanging navigation messages (Ducatelle et al. 2011) and flying robots navigating wheeled robots (Hayes and Dormiani-Tabatabaei 2002) are some of the swarm-guided navigation examples. The use of swarm formation in navigation requires collective decision-making by robots (Wessnitzer 2003). This means, that all robots must agree on common decision to determine their path and target. Communication between robots is made directly by exchanging messages (e.g., voting) or indirect communication using local sensor information (e.g., follow nearest robot) (Montes De Oca et al. 2010; Garnier et al. 2009).

Besides navigation purposes, the swarm of robots are also deployed in environment mapping and localization (Paul et al. 2011). A direct application for self-localization of swarm of robots is to assist fire-fighters in search and rescue operations in an industrial warehouse in the event or danger of fire (Alboul et al. 2010). Mapping is an important step to assist swarm navigation (Dorigo and Roosevelt 2005). Some works addressed the use of vision-based self-localization by enabling small robots to localize themselves with global image features at a reasonable accuracy (Hofmeister et al. 2009).

Another related task is obstacle avoidance and path planning, which are used to navigate robots in the environment while avoiding obstacles (Desai et al. 1999; Van Den Berg et al. 2006; Hettiarachchi and Spears 2009; Garro et al. 2007; Rigatos 2008; To et al. 2009). Hole-avoidance task can be viewed also as obstacle avoidance. Robots may not only avoid the hole but also assemble into a larger structure and overcome the hole that a single robot would fall into (Dorigo and Trianni 2005; Trianni et al. 2004).

Besides self-localization and self-organization, self-deployment is another field of application for swarm robotics. Robots are dispersed in the environment to perform area coverage tasks and mapping (Sahin et al. 2007). Potential applications of self-deployment include surveillance and security (Howard et al. 2002; McLurkin and Smith 2007). Swarm of robots can be deployed for transporting an object, including pushing, grasping and caging (Yamada and Saito 2001; Wang et al. 2004; Groß et al. 2006). Potential applications for swarm robotics in entertainment business had been raised in multiple applications. Robot soccer games have been proposed as a benchmark problem for artificial intelligence, multi-agent and multi-robot algorithms. The soccer game is a special multi-agent system in that the robot players of one team have to cooperate while facing competition with the opponent. The cooperative and competitive strategies used play a major role in robot soccer system (Shen et al. 1998; Duan et al. 2007). In addition, a team of robots must possess various skills and capabilities for decision-making and communication (Liekna and Grundspenkis 2014). Application of swarm robots in the inspection of civil infrastructure systems has still not gained momentum as it is evident from the limited number of articles available in literature. Clark et al. (2017) proposed an autonomous control scheme for remote structural inspection aided by multiple UAVs. The proposed path planning scheme offers the advantages of scaling and distributive flexibilities, collision avoidance capability, and nominal computational requirements. Nejadfard et al. (2011) developed a multiple robot system for inspection and repair of dome shaped structures. In this system, the robots were connected to each other by strings to form a close ring. The robots were positioned on the dome in such a way that they could cooperatively keep each other stable by controlling the tension in the strings. Yinka-Banjo et al. (2014) presented a swarm intelligence based hybrid model to regulate cooperative behavior of multi-robot systems for tunnel safety inspections. Pierce et al. (2012) proposed a multi agent reconfigurable robotic platform for remote health monitoring and nondestructive evaluations.

6 Roadmap for future research

Global structural health monitoring market is expected to see an exponential growth in near future owing to several reasons such as growing demand for cost-effective infrastructure maintenance, rapid urbanization and increasing concerns over uncertain natural calamities. It is estimated that the market will grow from 701.4 Million USD in 2015 to 3407.7 Million USD by 2022 at a compound annual growth rate of 25%. However, complexities involved in inspection of large scale infrastructures, excessive cost, measurement inaccuracies, lack of expertise are some of the factors which are restraining this growth. Technology advancement coupled with latest trends such as robotic-aided inspection using RSR will certainly lead to improved accuracy and reduced cost propelling the growth of SHM market. However, there are some challenges that need further attention when RSR are used for infrastructure monitoring:

1. Identification of optimal locations: Development of a methodology where multiple mobile agents can communicate and optimize the data collection process through the establishment of algorithms that can produce near-optimal plans for data collection in real time, where optimality is defined in terms of the amount of the collected data with certain spatial and temporal resolution, given existing resource constraints (e.g., the number and availability of sensing agents), for effective localization of defective regions. In short, there is lack of pre-installed sensors at critical locations where these locations may dynamically change due to the environmental and/or usage factors.
2. In-situ active sensing: Development of mobile sensing systems that have additional active sensing capabilities (e.g., a robotic system that can excite part of a structure using a small hammer and receive the propagated wave within a fraction of a meter from the excitation point). Such mobile systems can communicate with collaborating robotic systems with vision-based sensors and "crawl" near the defective regions to collect more detailed data about the detailed characteristics of the suspected defect. There is a great need for simultaneous and active inspection actions using probes and response measurements.
3. Data fusion from distributed and multiple modalities: Using the localization module discussed above, the data captured by vision-based systems, static passive and active sensors, and mobile active sensors can be processed and combined, and different characteristics of a defect can be retrieved through the fusion of the heterogeneous data captured by the sensors, leading to generation of a "health map". The challenge is how to distribute a network of collaborative sensors that is effective and efficient for a particular health monitoring task involving large scale of inspection areas.
4. Delivering sensors to difficult locations: How to maneuver on a complex structure to reach the desired points. There is a pressing need to develop novel methods that are capable of delivering the right sensors to the right places at the right time. Such robots are essential for structural health monitoring because many critical monitoring places are difficult to reach using conventional robots. In particular, there is a need to create mobile swarm robots for delivering sensors and active probes on structures. These robots should be self-reconfigurable and polymorphic robots that can be launched to climb trusses, go through pipes, attach to high-structures (such as tall buildings, extended bridges, dams, petrochemical facilities, etc.), spread on structures as a swarm, carry monitoring sensors, and install/repair sensors in places unreachable by conventional robots. These robots should also be capable of carrying actuators and/or active sensors (e.g., small hammers, piezo-electric "exciters", etc.) to excite certain points in a potential problem area.
5. Autonomous decision-making: The ideal inspection robots should be able to autonomously collect the needed monitoring data from the target system or be permanently installed into the structures to monitor its health. The robots should be capable to make autonomous decisions on where, when, how frequent to inspect target regions in order to create an evolving health-map or to deliver special sensors to problematic areas for special inspections. Future studies should aim at proposing advanced methods for autonomous decision making which can be implemented with minimum or no human interference. It is also expected that existing algorithms for robot navigation, path planning, self-organization, cooperative search, and mapping

will be improved over the time and new algorithms will be proposed that will be computationally more efficient, fault tolerant and robust.

6. Revisiting and data comparison: Since a fundamental challenge in structural health monitoring is the need to accurately and reliably detect, locate, and quantify small evolving changes (e.g., a “small” crack in a structural component), it is crucial to be able to revisit the same location(s) in a target structure and ensure that the rate of growth of a specific crack within a “crack map” detected in a previous inspection episode is within acceptable performance limits. Such a challenging requirement necessitates the ability to identify the inspecting robot location within a fraction of a millimeter, when one is dealing with situations that GPS signals are unavailable.
7. Inexpensive and portable sensors: One of the main purposes for replacing manual inspections with robot based inspection is that it reduces the cost. Researchers should focus on developing inexpensive but more powerful and portable sensors so that inspection operation becomes more economical. Shape and size of the robots should also be optimized to make them light weight and power efficient without compromising their functional purpose.
8. Big data challenges: Another potential research direction, which lags the progress made in other fields, is to ensure efficient storing, processing, analysis, and visualization of huge amount of heterogeneous data collected by a variety of sensors mounted on swarm robots. Exploration and maintenance of large collection of data are important so that useful information can be extracted from them during future review. Safety and security of the data are other important areas which merit attention.
9. More resilient robotic modules: The robots used for inspection and health monitoring operation are often subjected to adverse environmental conditions. Futuristic technologies should offer viable solution to this problem by developing robots that are more resilient and weather-proof.

7 Summary

This paper presents a holistic review of available literatures on application of robotic systems for inspection and monitoring of civil infrastructures. Various classes of robots including wheeled, crawling, snake, underwater and aerial robots suggested by previous studies for inspection of aircraft, duct, pipeline, sewage, power transmission line, oil storage tank, and steel bridge have been described. The challenges and advantages of modular self-reconfigurable robots have been discussed. Reconfigurable robots developed by previous researchers have been presented. State-of-the-art of various aspects of reconfigurable robots such as modular design, connector mechanism and control system has been outlined. The potential utilization of SuperBot for structural health monitoring operations has been reviewed. Additionally, the latest advancements in the field of swarm robotics have been highlighted. Studies focusing on different tasks executed by swarm robotics such as aggregation, pattern formation, self-assembly, object clustering, assembling and construction, collective search and exploration, coordinated motion, collective transportation, self-deployment, and foraging have been discussed. Research works dedicated to the application of swarm robotics in inspection and monitoring of infrastructure systems have also been reported. Finally, the limitations and challenges with state-of-the-art technologies have been figured out and a roadmap for future course of research is provided.

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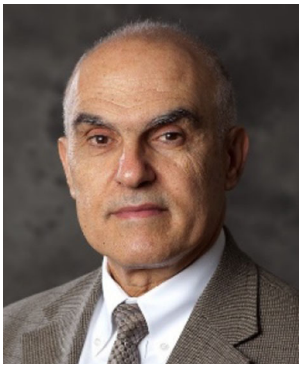

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