Infrastructure Robotics: Research Challenges and Opportunities

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Abstract -

Infrastructure robotics is about research on and development of methodologies that enable robotic systems to be used in civil infrastructure inspection, maintenance and rehabilitation. This paper briefly discusses the current research challenges and opportunities in infrastructure robotics, and presents a review of the research activities and projects in this field at the Centre for Autonomous Systems, University of Technology Sydney.

Keywords -

Infrastructure robotics; autonomous robots; inspection; maintenance; civil infrastructure;

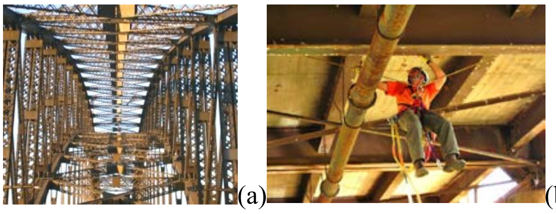
1 Introduction

Civil infrastructure in sectors such as transport (e.g. bridges, roads and tunnels), energy (e.g. power transmission line, transmission tower, power plant, gas/oil pipeline and offshore structure) and water (e.g. pipeline and dam) is progressively deteriorating, due to ageing, environmental factors, increased loading, damages caused by human/natural factors, and inadequate/poor maintenance. Appropriate operations of periodic inspection, maintenance and rehabilitation are needed to ensure that the designed life of service of civil infrastructure can be achieved or extended. However, because of the associated employee health and safety issues, these operations are very expensive undertakings.

A steel bridge is one of the many examples of civil infrastructure. There are approximately 42,000 steel bridges in Europe, and 210,000 and 270,000 steel bridges, respectively in the USA and in Japan [1]. Steel bridges such as the Sydney Harbour Bridge are very complex structures. Some sections (e.g. truss joints and box girders) in steel bridges cannot be inspected without special equipment because of the difficulty of access. Human inspection requires equipment (e.g. special lifts, scaffolds) and a team to support each inspector, which implies high cost and low productivity. Grit-blasting to remove rust and old protective coatings followed by re-painting is the common approach in steel bridge maintenance, but grit-blasting is extremely labour intensive and hazardous.

Therefore, supplementing manual labour in civil infrastructure inspection, maintenance and rehabilitation with robotic aids has potential for significant safety, cost and health impacts.

There is a significant amount of research on infrastructure robotics and development of robotic systems for practical applications. Examples include climbing robots for maintenance and inspection of vertical structures [2]; Shady3D robot for climbing trusses [3], climbing robot that can move in complex 3-D metallic-based structures [1][4]; the SM2 robot designed to walk along the I-beam structure of a space station [5][6]; robot-aided tunnel inspection and maintenance system [7]; and autonomous grit-blasting robot for surface preparation in steel bridge maintenance [9][10]. Robotic systems have also been deployed in various operations in construction [8] and material handling.


(a) (b)
Figure 1. Two example infrastructure environments ((b) from [11])

Although there are many robots that have been developed for civil infrastructure construction and maintenance, most of these robots are either laboratory prototypes that have not yet made it into the commercial world, or are limited to specific applications. These robots may not have enough intelligence and dexterity for performing various tasks autonomously in complex environments. Developing autonomous robots that can operate automatically for civil infrastructure inspection, maintenance and rehabilitation is challenging because the structural environment is normally complex, compact, unknown (to the robots), hazardous, and in field conditions (Figure 1). There are many research and engineering challenges that need to be addressed. A usual reaction is that, 'at least it's a structured environment', but old steel structures have usually not been digitally modelled, and any blueprints that are available are out of date. The bottom line is that the robot has to be able to build its own solid model of the environment, be aware of the conditions of the structures, plan its collision-free motion and perform various tasks automatically.

2 Infrastructure Robotics Research

Infrastructure robotics is about research on and development of methodologies that enable robotic systems to operate autonomously in civil infrastructure inspection, maintenance and rehabilitation. Deploying autonomous robotic systems in such applications has specific research challenges. These challenges include, but are not limited to:

1. Sensing technology and sensor network that can be used in field environments for sensing, inspection, and assessment of surface and structural condition of civil infrastructure;
2. Robot environmental awareness, localisation and mapping of true 3D complex environments such as trusses;
3. Robust and reliable mechanisms for adhesion and grasping that allow robots to stay and move along various structures (e.g. trusses) safely;
4. Efficient algorithms for real-time robot motion planning and collision avoidance in true 3D environments;
5. Methodology (e.g. co-design between end users and researchers) for robot and user interface design;
6. Development of robot teams and human-robot teams for applications in infrastructure construction, inspection and maintenance;
7. Interaction strategies for intuitive physical human-robot interaction;
8. Prototype autonomous robots that have the required payload for conducting various operations such as blasting, cleaning, painting, and object manipulation, and can be used in different structures;
9. Uncertainty handling;
10. Machine learning that allows robots to adapt to various structural and field environments and conduct various tasks.

Besides the research challenges, there are many engineering challenges in developing robots for civil infrastructure inspection, maintenance and rehabilitation. Examples include:

1. Design of lightweight robots that can move and climb in compact and complex structures;
2. High torque to weight ratio actuators that allow robots to have enough payload for performing tasks such as blasting, painting and object handling;
3. Failsafe robotic system design;
4. Protection of sensors and robots for dust and water proofing;

3 Infrastructure Robotics Research Activities in the Centre for Autonomous Systems

The Centre for Autonomous Systems (CAS) at the University of Technology, Sydney (UTS) has been conducting infrastructure robotics research since 2003. Besides conducting fundamental research in two research themes: (1) robots in unknown and complex environments: sensing, localisation, mapping and motion planning; and (2) human-robot interaction: human models and control, CAS has been doing enabling research and development of robotic systems for various applications in collaboration with industry. Infrastructure robotics has been the centre's flagship research, with $6.5 million worth of externally funded industry projects in infrastructure robotics since 2006. Currently seven academic staff members, five research fellows, three research engineers and a number of PhD students are involved in these projects.

UTS CAS's infrastructure robotics research focuses on applications in the following sectors:

- Transport: bridge inspection, condition assessment and maintenance;
- Water: underground pipe condition assessment;
- Energy: transmission tower inspection, condition assessment and maintenance;
- Ports: automation of container handling vehicles;
- Mining: underground mining vehicles;
- Underwater and offshore structure: semi-autonomous underwater robot for submerged structure inspection, condition assessment and maintenance.

3.1 Autonomous Robotics Systems for Steel Bridge Maintenance

This research focused on addressing research and engineering challenges in developing autonomous robots for steel bridge maintenance, i.e. autonomous grit-blasting (Figure 2). Theoretical research and enabling methodologies developed include: (1) Sensing technology for object ranging and surface classification [12][13]; (2) Algorithms that enable robotic manipulator-based exploration in complex 3D environments [14]; (3) Algorithms that can efficiently build 3D maps of complex steel structures [15][16][25]; (4) Algorithms for efficient robot motion and blasting planning [17][18]; (5) Collision detection and avoidance algorithms that make it possible for a large robotic manipulator to move safely in complex 3D environments, including the 3D force-field approach for collision avoidance [19] and an algorithm for collision detection and distance query [20]; (6) Effective methods for human-robot-environment interaction [21], including an extended hand-movement model [23], effect of view distance and movement scale on haptic-based operation [22], and workspace mapping; and (7) Ease of user-robot interaction, facilitated by an interface designed jointly by the project team and four bridge maintenance professionals [24].

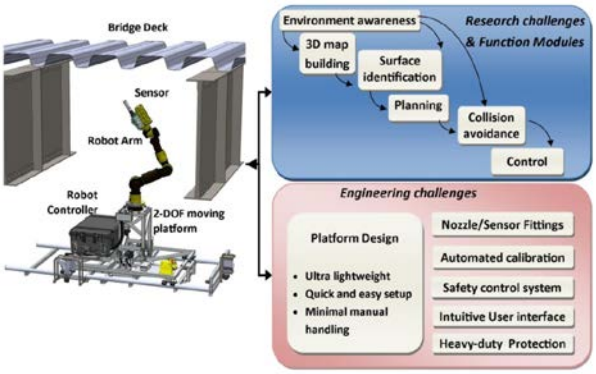
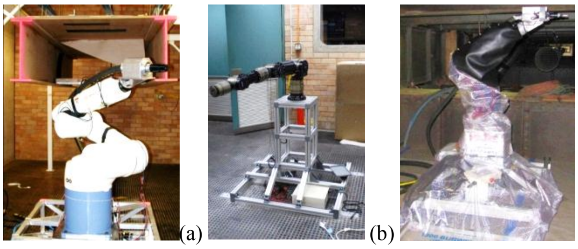


Figure 2. The steel bridge maintenance robotic system: research and engineering challenges



(a) (b) (c)

Figure 3. Prototype grit-blasting robotic systems: (a) prototype 1 with a Denso robot arm; (b) prototype 2 with Schunk joints; (c) The robot installed in a maintenance site

These research outcomes have been fully tested and implemented in the two generations of prototype autonomous grit-blasting robots developed by CAS (Figure 3). Two fully operational grit-blasting robots are installed onto the Sydney Harbour Bridge for maintenance of the iconic bridge, significantly reducing the time that the grit-blasting workers are exposed to the OH&S risks and increasing the productivity of the maintenance program. An Australian start-up company, SABRE Autonomous Solutions Pty Ltd, has been formed, with a significant amount of industry investment, to commercialise this robotic technology for broad applications such as bridge maintenance, steel fabrication, cleaning and surface preparation.

3.2 Bio-logically Inspired Climbing Robots for Autonomous Inspection of Steel Structures

This research focuses on developing a biologically inspired climbing robot for inspection and condition assessment of steel structures where human inspectors cannot reach, or are not allowed access due to the compactness of structures and the OH&S requirement, such as box girder structure. Research work includes analysis of an arthropodal system [31] and ant locomotion [32], exploration methods [26][27], map building, motion planning, collision avoidance, surface inspection, robot design [28], adhesion mechanism design [29][30] and robot control. Two prototype robots have been constructed (Figure 4) with the first field trial conducted in September 2013. Three more field trials are to be conducted in June, September and November 2014. It is expected to deliver one fully functional robot for extensive testing in February 2015.

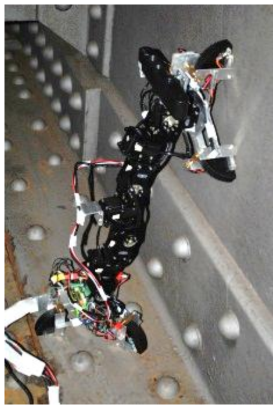


Figure 4. A prototype climbing robot for steel structure inspection

3.3 Concrete Bridge Box Girder Inspection

This research focuses on demonstrating the feasibility of automated solutions for the structural health inspection of concrete box girders [33]. Novel combinations of perceptual robotic sensing allows for highly-detailed surface condition pictures to be remotely evaluated by human operators while the robot navigates inside the enclosed structure. The proposed technique makes it feasible to safely monitor areas over a sequence of inspections, leading to more effective maintenance procedures. Functionality to automatically identify defects/regions of interest is also being investigated.

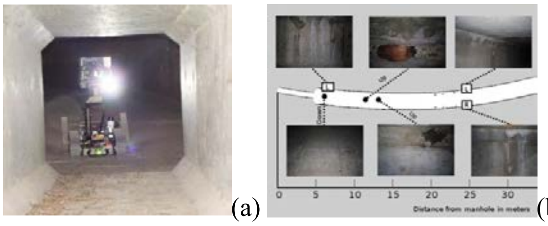


Figure 5. (a) Packbot robot with appropriate suite of sensors in a concrete bridge for remote inspection and condition assessment; (b) generated map annotated with high-res images taken by the robot

3.4 Coordination of Autonomous Vehicles for Automated Container Handling – Automation of Port Infrastructure

This research addressed several research issues associated with the use of a large fleet of autonomous robots/vehicles for automated container handling (Figure 6) in dynamic environments. Methodologies that are able to significantly improve the efficiency of multi-robot systems in dynamic container handling environments have been developed, including simultaneous task allocation and motion coordination methods [34], multi-objective optimisation-based scheduling [35], a crossover approach [36] and an genetic algorithm for job scheduling [37], a comprehensive mathematical model and a job grouping method [39], a parallel scheduling algorithm [38] and task allocation under uncertainty [40].

Figure 6. Automated straddle carriers for container handling

3.5 Robotic Technology for Condition Assessment of Buried, Pressurised Water Mains

This research focuses on developing methods for advanced analysis of sensor data obtained from condition assessment tools of buried large water mains (Figure 7) through physical and probabilistic modelling. The project is focused on non-destructive inspection techniques (NDT) generally based on electromagnetic and acoustic sensing with the ultimate aim of improving the accuracy and level of confidence in the estimate of the geometry of pipe being inspected. This, in turn, allows the utilities to evaluate the remaining life of this critical assets with more certainty in their estimates [41][42]. This is a project carried out in collaboration with other universities, water utilities in Australia, UK and USA, and the participation of major international providers of NDT inspection technologies.

Figure 7. Section of a typical large water main exhumed from the ground and being inspected in a lab

3.6 Semi-autonomous Robot for Underwater Structure Cleaning and Inspection

This research focuses on developing a semi-autonomous robotic system that will enable safe and cost-effective cleaning and inspection of submerged structures. The system concept being considered is a semi-autonomous robotic system that can explore the environment around bridge pylons, build a surface condition map of the submerged bridge pylons, clean the pylons by using high pressure water blasters, and perform a detailed inspection after the cleaning process. Research work includes design of the robotic system that can be used for various submerged structures; surface condition monitoring; 3D map building; control of robot navigation under uncertainties; manipulation of underwater blasting tools; maintaining robot stability under water current and with the reaction force from the high pressure blasting nozzles; and blasting planning based on marine growth for maximum productivity and minimum damage to the pylon surface.

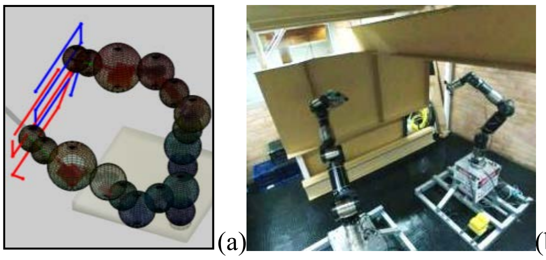


Figure 8. Two autonomous grit-blasting robots for cooperative blasting: (a) simulation and (b) testing in the lab setup

3.7 Grit-blasting Robot Team for Steel Structure Surface Cleaning

This research focuses on developing methods for automated monitoring of the robotic grit-blasting process; inspection of surface quality; control of the robotic system for blasting surface spots that are missed out in previous blasting operation or where the quality is not good enough; and coordination of multiple grit-blasting robots for cooperative blasting operation (Figure 8).

3.8 Human-interactive Robots for Strength Augmentation of Workers in Infrastructure Maintenance

This research aims to improve our understanding on how robots can be enabled to provide physical assistance to diverse human workers performing labour intensive tasks in infrastructure maintenance, and to develop methodologies that enable the development of assistive robotic systems (Figure 9). The research questions that are being answered include how much assistance is needed for a worker [43][44], how to provide the required assistance[45], what are the strategies for intuitive human-robot interaction and safety of human workers when they are in physical contact with robots.

Figure 9. An 8-DOF scaled-down proof-of-concept prototype robot

4 Conclusion and Remarks

Advances in sensing, mapping, actuation, locomotion and control have made it possible to build robotic systems that are able to operate in unstructured and cluttered outdoor environments. As a result, a number of complex tasks associated with the maintenance of civil infrastructure can now be carried out by robots. Main focus of the research effort to-date has been on addressing important occupational health and safety issues. Grit-blasting and inspection of complex steel structures are among the applications that have been described in this paper. All the indications are that robotics will play a significant role in maintaining civil infrastructure in the near future.

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