A Robotic System for Steel Bridge Maintenance: Research Challenges and System Design

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Abstract

This paper presents the research on and development of a robotic system for stripping paint and rust from steel bridges, with the ultimate objective of preventing human exposure to hazardous and dangerous debris (containing rust, paint particles, lead and/or asbestos), relieving human workers from labor intensive tasks and reducing costs associated with bridge maintenance. The robot system design, the key research challenges and enabling technologies and system development are discussed in detail. Research results obtained so far and discussions on some key issues are also presented.

1 Introduction

Bridges are essential in transport infrastructure worldwide. There are over 30,000 road and rail bridges across Australia. Bridge maintenance or replacement is one of the largest expenditure items in traffic infrastructure development and maintenance. For example, the Queensland government allocated $350 million towards replacing approximately 100 old and obsolete road bridges in regional Queensland over the next five years - from 2006 to 2010 [Queensland, 2005].

Corrosion is the primary cause of failure in steel bridges [Hare, 1987], and is minimized by painting the steel structure. Paints used until the 1980s in most steel bridges in Australia contain red lead, and in some occasions asbestos. Periodical inspection and maintenance of these bridges is an expensive undertaking due to the associated environmental and employee health and safety issues.

Steel bridge coating maintenance consists of two procedures: rust/paint stripping and repainting. An effective and efficient method of large scale paint stripping is grit-blasting, and herein lies the critical problem. Grit-blasting is extremely labour intensive and hazardous [Rail Services Australia, 2000], and is the most expensive operation needed during steel bridge maintenance. Workers have to not only spend long periods of time handling forces of 100N and above [De Joode, et al., 2004], but also need to take precautions to avoid exposure to the dust containing hazardous chemicals. Furthermore, grit-blasting methods also create environment problems. For example, the blasting turns the toxic coating into a fine, airborne dust which workers may inhale and which will pollute the surrounding environment. With the full extent of the toxicity and long-term health damage caused by lead/asbestos being well known [HSE, 1998], the bridge maintenance operations must be completely enclosed in order to avoid contaminating the environment and to avoid potential risks to the general public's health. Thus, supplementing manual labour in grit-blasting with robotic aids will have a significant health, safety and economic impact.

2 Recent International Practice

There has been increasing research interest in the use of robotics technology in the maintenance of steel structures such as ships, steel bridges, storage tanks, etc. Several prototype systems have been developed and tested. Examples include Auto Blaster system [Tharr, 2000], a Robotic Bridge Maintenance System [Lorenc, Handlon et al., 2000] for bridge maintenance, HydroCat for removing coatings from structures with applications in marine and non-marine industries, Hull Jet for large ships, barges, floating dry docks and vessels, Pittman Vacuum Blasting System for ships [Tharr, 2000], crawling robots for tall buildings or tanks [Ross, Mares, et al., 2003], and a large robotic paint stripping system for aircraft maintenance [Schmitz, 2003].

The Robotic Bridge Maintenance System [Lorenc, Handlon, et al., 2000] for removing corroded paint and rust from the surfaces of steel beams in steel bridges is composed of a very large crane boom, an actuated platform, a 4-Degree Of Freedom (4-DOF) robot arm, a gantry table, a vision system (camera) and proximity sensors. This system is capable of remote inspection, spray washing, paint removing and painting. It can be tele-operated using the two cameras mounted on the robot and the bridge, respectively. For automatic operation, it relies on the availability of a CAD drawing of the bridge structure to minimize the challenges in sensing and surface mapping. Furthermore, some challenges in autonomous operations are overcome by requiring a remote operator to control the crane as well as perform surface classification. Tele-operation results in low productivity. Furthermore, the size of such a crane-based system prevents it being used in large bridge structures or in fully enclosed areas as required during the removal of lead based paints.

CAD drawings of most of the steel bridges are usually not available as those bridges were built over 50 years ago, or the drawings may be out of date due to the changes made in the bridges, for example, wood foot path, plastic pipe lines, electrical power lines, etc. The key challenge in the use of robotic systems in bridge maintenance is the need for a robot to operate in a cluttered, unknown or partially known complex 3D environment with heavy tools. A robotic system or techniques to be developed for this purpose should address issues of *complexity* and *uncertainty*, and meet the requirements of *productivity*, *safety* and *cost-effectiveness.*

3 System Design

The proposed robotic system consists of a 6-DOF industrial robot, a moving platform, a sensor package equipped with a laser range finder, cameras and a capacitive sensor network, and a high performance computer (Figure 1a). A relatively large robot is needed in order to handle the blasting nozzle reaction force. The whole system is placed on the floor of a scaffold which is fully enclosed. The system must be able to work in three modes: manual, semi-autonomous, and autonomous:

(1) *Manual mode*: the manual mode is designed for system testing and cleaning the most difficult sections that cannot be handled automatically.

(2) *Semi-autonomous mode*: the semi-autonomous mode allows the system to automatically blast a defined region, for example a given face of a girder, chosen by a remote operator based on the map which is obtained through autonomous exploration and map building.

(3) *Autonomous mode*: in the autonomous mode, the system will be capable of automatically grit-blasting an unknown steel structure from sensing and mapping the environment, identifying the areas to be blasted, and generating paths for the grit-blasting nozzle that satisfy the operational constraints (Figure 1b).

The safety of the system will be ensured by strategies and technologies for real-time collision detection and avoidance. Achieving autonomous operation requires addressing significant research challenges in sensor development, exploration and 3D mapping of a complex bridge structural environment, identification of material types in a bridge stracutre, robot path and motion planning and collision detection. Research outcomes will be evaluated through a comprehensive testing program both in the laboratory and on-site environments.

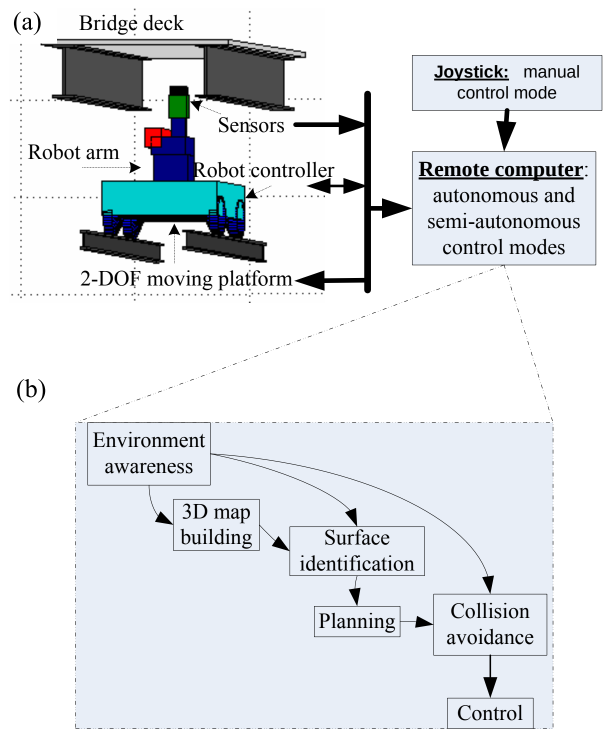


Figure 1 (a) System architecture of an autonomous robotic system for grit blasting in bridge maintenance; (b) Key components and the flowchart

3.1 Environmental Awareness

As most of the steel bridges do not have complete up-to-date CAD drawings due to the age of the bridges and possible changes made to the bridges, the bridge structure environment is initially unknown or partially known by the robotic system. Hence sensing and environmental interaction are important aspects of the system. Sensors and a small sensor network must be used to build the 3D geometrical map of a complex structural environment, while identifying material types of structural members and avoiding potential collisions with the unknown environment.

3.2 Exploration and 3D Map Building

A bridge maintenance environment is normally compact, complex and static, at least for the duration of the map building and grit-blasting. Sensor data acquired from different robot positions and robot arm poses must be transformed to a single global coordinate frame prior to incorporation into a three-dimensional map of the environment. This process (registration) demands accurate knowledge of the sensor position and orientation. While techniques exist for accurately zippering range data, the part of the environment able to be mapped from a stationary platform can be simply registered using knowledge of the robot arm position. As the robot arm carries the sensor package, an accurately known geometric model of the robot arm, in conjunction with joint positions describing the arm configuration at the time of data acquisition, is used to transform range data into 3D points in the coordinate frame of the robot base. As the location of the robot base is only approximately known, partial maps acquired from different robot base positions will require application of advanced simultaneous localization and mapping (SLAM) techniques before the data can be combined.

3.3 Material Type Classification

Bridge structures consist of steel work such as I-beams, wood pedestrian paths, concrete, plastic pipes, etc. Identifying the material types and target areas is critical for preventing non-metal structure members from being damaged. The limited number of material types in a bridge and the ultimate goal of identifying only metal simplify this task, but the complexity of the bridge structure, the geometric shapes of structural members and various composites of members with different material types make the identification difficult.

3.4 Robot Path and Motion Planning

Planning of the blasting nozzle's path and robot motion is conducted after the map of the environmental is built and the areas to be blasted have been identified. Path and motion planning must attempt to maximize the grit-blasting coverage completeness, minimize the movement of the robot arm and the support platform and maximize efficiency/productivity. Challenges of planning also include partitioning a large surface (possibly with non-regular border shapes) and planning for blasting edges of structure members to prevent the adjacent non-metal members being damaged.

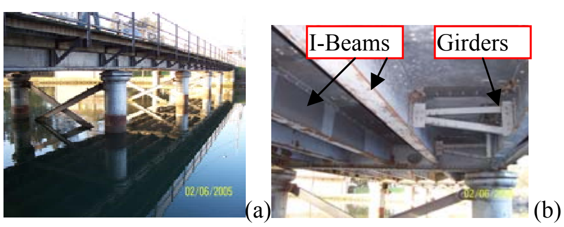


Figure 2 (a) An example bridge; (b) Part of the bridge structure

3.5 Collision Avoidance

Due to the complexity of the grit-blasting environment and the large robot size relative to the environment, collision avoidance is a very important issue. Collision avoidance is included in various stages of the autonomous operation:

(1) *Exploration and map building*. As this is the first stage that the robot senses and interacts with the environment, the robot does not have any information on the environment. Avoiding potential collision with the environment requires reliable sensors, a sensor network covering the whole robot arm and exploration algorithms.

(2) *Planning stage*. At this stage, the robot has built the 3D map of the environment. Intelligent planning algorithms are required to find collision free paths for the whole robot arm and at the same time maximize efficiency.

(3) *Grit-blasting stage*. Theoretically, the robot should not collide with the environment during grit-blasting if it follows the planned collision-free path and motion. In real operation, a collision control strategy (including sensors and algorithms) is still required to avoid potential collisions due to robot malfunction or any sudden changes of the environment.

4 Research Challenges and Preliminary Research Results

4.1 Algorithms for Exploration and 3D Map Building

The grit-blasting robotic system is in the first instance focused on steel bridges with relative simple structures such as the bridge shown in Figure 2a. Such bridges predominantly consist of a number of I-beams and girders (Figure 2b). A Hokuyo laser range finder [Kawata, Ohya, et al., 2005] is particularly suited to sense the environment in these bridges. Appropriate exploration strategy can then provide a dense 3D point cloud from which the geometry of the steel structure can be extracted. Laboratory experiments have demonstrated that the information from the laser scanner is sufficiently accurate for building the map of the blasting environment.

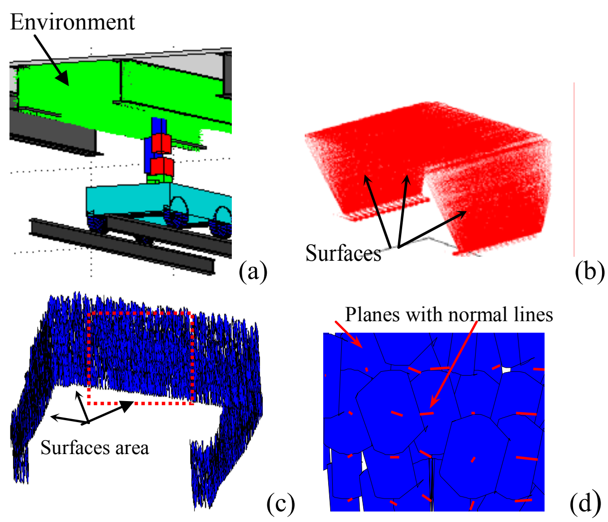


Figure 3 (a) Blasting environment; (b) Surfaces; (c) Surfaces and small blasting area; (d) Small planes with normal lines

While there has been significant progress in constructing 3D models from range images, such as a surface extraction technique [Lerensen and Cline, 1987], Volumetric Range Image Processing (VRIP) [Curless, and Levoy, 1996], next best view [Wong, et al., 1998], volumetric diffusion [Davis, Marschner, et al., 2002] and an updating procedure [Woo and Dey, 2006], these algorithms are mainly focused on accuracy instead of efficiency, and surface generation rather than integration of surface generation with the later stages such as material type identification, path and motion planning and collision avoidance.

An incremental surface growing algorithm that uses information from the laser range finder has been investigated to generate platelets and associated surface normals for an approximation of the 3D structure of the environment [Paul, Liu, et al., 2007a]. The point cloud (Figure 3b) of the bridge structure environment (Figure 3a) from the laser sensor is further processed to generate surface area (Figure 3c) and small planes with normal lines (Figure 3d). The ability to robustly detect surface normals is important to planning of blasting nozzle's path and orientation.

Due to the complexity of the bridge environment, exploration algorithms are required to explore the environment for building a complete 3D map. A safe and efficient exploration algorithm, which uses the 6DOF robotic arm instrumented with the laser range sensor, is proposed for this application [Paul, Liu, et al., 2007b]. It starts with the robot arm in its most unobtrusive pose; assumes completely unknown surrounds; and performs an initial scan with the fifth joint so as not to enter unexplored areas. Then, through the range, tilt and pan considerations of the laser range scanner, the amount of information gained from a number of possible scans is calculated. The robot arm will then move, with assistance from a local path planner, to a physical location that will give the system the largest amount of desired information while avoiding obstacles or unexplored space.

Data fusion from multiple overlapping scans, to incrementally generate estimates of the uncertainty of the locations of and normals to the platelets is necessary to explore and map a large bridge structure.

4.2 Sensing Technologies and Classification Methods for Surface and Material Type Identification

The steel surface in a bridge that is in need of maintenance is in various states of decay. For efficient operation, the parameters used for sandblasting such as the angle of the sandblasting stream and the speed of nozzle movement, should be changed as a function of the deterioration of the surface. Parts of the bridge that consist of material other than structural steel, such as timber (normally used for path ways) and plastic pipes (for power lines, cables), etc. need to be identified and avoided.

Preliminary experiments showed that the visual appearance of the bridge structural environment is ambiguous with similar colour/texture areas occurring in different parts of steel, wooden or concrete structures indicating vision only discrimination may not be possible. Some strategies, for example surface analysis with a spectrometer [Palleschi and Schechter, 2006] and microwave based rust thickness and depth analysis of surfaces [Qaddoumi, et al., 2004] have been reported in the literature.

TABLE 1 EXPERIMENTAL RESULTS [KIRCHNER, LIU, 2007]

Object Material	Correct (%)	Incorrect (%)	Unknown (%)	Most Common Error (%)
Metal	84.04	15.96	0	Human (15.96)
Human	77.25	0	22.75	-
Concrete	73.34	1.11	25.55	Human (1.11)
Wood	94.60	0	5.40	-
Overall	82.31	4.27	13.42	Human (4.27)

A capacitive-based sensing approach, the Adaptive Capacitive Sensor for Obstacle Ranging (ACSOR), has been investigated for obstacle ranging [Kirchner, Liu, et, al. 2006]. Capacitive sensors have large areas of coverage with a relatively small sensor size because of the broad distribution of electric field, and are insensitive to lighting, noise, color, shape, surface and texture of the obstacles. Modifications have been made to enable the ACSOR ranging sensor to provide material type data for an object in the sensing field [Kirchner, Liu, et, al. 2007]. The ACSOR, previously capable of obstacle ranging (up to 300mm) in various densities of particle laden air, has been fitted with a noise and stimuli-response analyzing algorithm allowing the sensor to determine the material type of a sensed object. Experimental results shown in Table 1 have demonstrated the modified sensor's ability to successfully classify (4.45% incorrect classifications with an unintelligent 'hard logic' classifier) the material type, from a set of known material types, of several different sensed objects in typical indoors conditions.

A Hokuyo laser range finder based surface type classification system [Kawata, Ohya, et al., 2005] has also been investigated [Kirchner, Taha, et al., 2007]. The Hokuyo's firmware has been modified so that the sensor returns intensity data. A signal analysis algorithm allows determination of the surface type of the targeted object. Empirical results [Kirchner, Taha, et al., 2007] have demonstrated the system's ability to classify surface type (under curvature and orientation constraints) from a set of known materials common in grit-blasting environments.

Further experiments in laboratory settings and on-site blasting environments will be conducted to further verify the two approaches. Combination of the two approaches is expected to provide promising results. Geometric cues extracted during map building will be useful in classifying for example, bridge structure from pipes. Output from the classification of material types of structural members in the bridge maintenance envrionment will be integrated with the generated 3D geometric maps of the environment, thereby providing sufficient information for robot arm path and motion planning.

4.3 Intelligent and Adaptive Algorithms for Robot Path and Motion Planning

An adaptive path and motion planning algorithm is required for efficient robot arm motion planning to maximize the efficiency and productivity of the grit-blasting process. This algorithm plans the paths of the blasting nozzle such that various process parameters such as the grit size, angle of incidence, as well as the geometric properties of the target steel structure and the constraints to the robot motion are taken into consideration. The need to deal with the characteristics of the grit-blasting process requires special solutions in contrast to traditional path planning strategies used for industrial robots operating in a well defined workspace.

The position, orientation and speed of motion of the blasting nozzle have significant effect on the quality and efficiency of the grit-blasting process. Selecting an appropriate path for the nozzle is a challenging task as the coverage needs to be complete while minimizing the starting and stopping of the blasting device. As the blasting stream can damage soft materials up to a range of two meters, path planning needs to ensure that the blast stream is only directed to areas of the steel structure and not towards, for example, the enclosure erected around the part of the bridge that is being cleaned. Thus simple area coverage algorithms used in robotic spray painting cannot be used for path planning for grit-blasting. Furthermore, collision avoidance of the robot arm moving inside a bridge structure is an important consideration.

An optimization strategy for nozzle path and motion planning is being investigated to maximize the blasting efficiency while minimizing the overlap (over blasted area), 'island' (i.e. non-blasted area) and robot movement (time). Heuristic approaches that exploit the available surface and environment information are also being studied for nozzle path planning for blasting the remaining areas such as corners and edges of the structure [Tian, Kwok, et al., 2008].

4.4 Efficient Methods for Collision Avoidance

Collision detection and avoidance during both mapping and grit-blasting is a crucial and difficult problem that has to be solved. When the robot enters the maintenance environment, there is, at best, only a limited knowledge of the geometry of this space available. Thus while exploring the environment with a sensor package, some ability to detect collisions between the robot body and the environment is required. A capacitive sensor for collision detection has been developed [Kirchner, Liu, et al., 2006] and a sensor network distributed around the robot arm for collision prediction is being developed. This sensor network provides complete coverage of the whole robot arm and an ellipsoid field for collision avoidance algorithms to prevent the robot arm from collisions with the bridge structural members in the environment.

Collision avoidance with industrial robots is a mature field which has seen significant advances in the recent years. The main challenge in the proposed application is the need for a strategy that is sufficiently computationally efficient. Simplifying the geometry of the robot and its environment by approximating it with a series of spheres was found to be very effective for collision detection in the planning stage. Figure 4 shows how spheres enclosing the robot and the environment are used to detect collision based on a distance query method [Xu, Liu, et al., 2007].

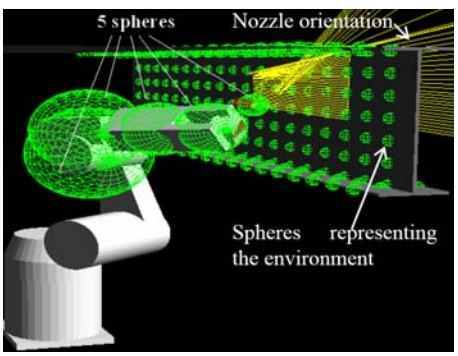
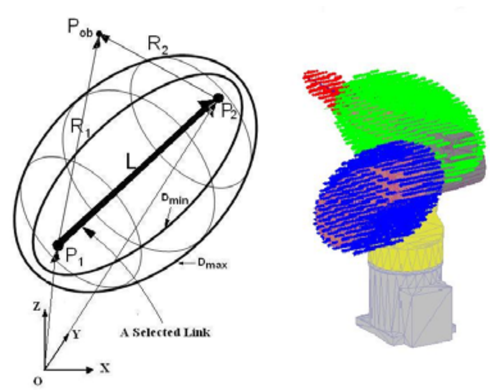


Figure 4. Spheres enclosing the robot arm and the environment can be used in collision avoidance. [Xu, Liu, et al., 2007]

For collision avoidance during grit-blasting, a three-dimensional force field (3D-F^2) method for efficient collision avoidance of the 6DOF manipulator in complex blasting environments while keeping the planned nozzle's path and speed unchanged has also been studied. The 3D-F^2 is defined as ellipsoid shapes (Figure 5) covering selected links of a manipulator by using the information from the capacitive sensor network [Chotiprayanakul, Liu, et al., 2007a]. When the manipulator moves and its ellipsoid force field approaches an obstacle in a defined range, a repulsive force will be generated and considered in the robot kinematic and dynamic analyses. In bridge maintenance, grit-blasting operations require that the blasting spot "moves" smoothly and continuously along the planned path on a surface at a constant speed. The grit-blasting operations also allow changes in length and orientation of the blasting stream. Thus, the blasting stream is considered as another link and the end of stream performs as a spherical joint fixed on the blasting surface. Various simulations have been conducted and the results show that the 3D-F^2 can retain the nozzle's paths and effectively avoid potential collisions in complex blasting environments. Figure 6 gives one example of the study [Chotiprayanakul, Liu, et al., 2007b].



(a) (b)

Figure 5. (a) Definition of a 3D force field; (b) A robot arm covered by a 3D force field [Chotiprayanakul, Liu, et al., 2007a]

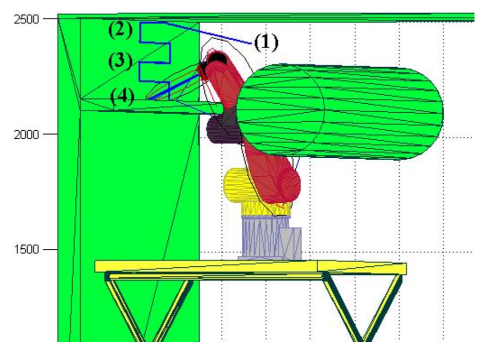


Figure 6. A case study in a complex blasting environment [Chotiprayanakul, Liu, et al., 2007b]

Figure 7. A prototype system and a mock-up section of a bridge structure

5 Challenging Development Issues

This project includes a many design and manufacturing tasks. Development of a prototype autonomous grit-blasting system is the most important and challenging one. This development involves the integration of all functional components (e.g. sensing, map building, planning, etc.) of the autonomous robotic system and the integration of the system with grit-blasting equipment. While this development is still underway, significant progress has been made. Figure 7 shows the platform and a mock-up section of a bridge structure. An industrial robot is placed on a platform sitting on a rail system which allows the robot to move along the bridge structure.

5.1 Blasting Nozzle Reaction Force Reduction

In grit-blasting operation, the high escape velocity of blast grit through the nozzle generates a reaction force of up to 88N in the opposite direction to the blast grit flow [Kirchner, Paul, et al., 2006] (Figure 8). When the nozzle is mounted on the robot end effector this reaction force may reduce the accuracy and/or life expectancy of the robotic manipulator if its payload is approached. Using a robotic manipulator with higher payload is a good option for many applications, but this option is limited for the bridge maintenance application because of the complexity and space constraint of the bridge maintenance environment. A mechanism which is able to reduce the reaction force on the robot end effector is required.

A force transfer mechanism is being developed for reduction of the blasting reaction force. This mechanism uses the internal pressure of the compressed air from two small delivery hoses to generate a force "pushing" the nozzle in the opposite direction to the blasting reaction force. It uses the rigidity of delivery hoses to 'deflect' the majority of the force through the hoses to a fixed anchor point. Experimental results have demonstrated the effectiveness of this mechanism although some improvements are needed for practical application.

Figure 8. A force transfer mechanism [Robertson, 2008]

5.2 Hose Management System

During the grit-blasting operation, the blast hose needs to move and be flexible to allow for all movements of the robot manipulator. A roller arm assembly (Figure 9a) has been designed and attached to the platform to provide supports for the blast hose (Figure 9b). More experiments will be conducted to test the performance of the hose management assembly in various conditions.

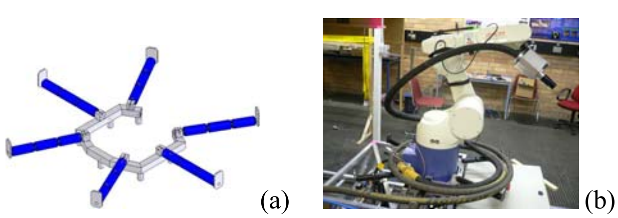


Figure 9. A roller arm assembly for blast hose management [Robertson, 2008]

Other important development issues include (1) system integration; (2) operational safety of the system and of people around the blasting environment; (3) a real time control system to manage the active components including air compressors, grit supply equipment, the robot arm and the associated platform; (4) user interface development; (5) protection of the robot system, including the moving platform, from fine dust and lead particle poisoning. Vibration of the robot arm when coupled with the grit-blasting device and its effect on grit-blasting quality will also be investigated.

6 Conclusion

The paper presented research and development on a robotic grit-blasting system designed to remove old paint, rust and debris from steel bridges. The system design, key research issues and important development issues are discussed and some research results are presented. By working closely with the industrial partner, considerable and significant progress has been made; a semi-functional system, a platform and a mock-up bridge structure has been developed. Many experiments have been conducted to test and verify the proposed algorithms for 3D map building, collision avoidance and control, and the developed sensor package for sensing and material type identification.

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