CLIMBING ROBOT FOR STEEL BRIDGE INSPECTION: DESIGN CHALLENGES

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ABSTRACT

Inspection of bridges often requires high risk operations, including work at heights, in confined spaces, in hazardous environments, or sites inaccessible by humans. There is significant motivation for robotic solutions which can carry out these inspection tasks. When inspection robots are deployed in real world inspection scenarios, it is inevitable that unforeseen challenges are encountered.

Since 2011, the New South Wales Roads & Maritime Services (RMS) and the Centre of Excellence for Autonomous Systems (CAS) at the University of Technology Sydney (UTS), have been working together to develop an innovative climbing robot to perform inspection at high risk locations on the Sydney Harbour Bridge. Many engineering challenges have been faced through the development of several prototype climbing robots, and through field trials in the archways of the Sydney Harbour Bridge. This paper will highlight some of the key challenges faced in designing a climbing robot for inspection, and then presents an inchworm inspired robot which answers for many design challenges.

INTRODUCTION

Australia has thousands of steel bridges which form a key infrastructure in supporting urban and rural communities. Periodic inspection of these bridges is vital for the prioritisation of maintenance tasks, extending the service life of the structures, maintaining aesthetics, and preventing costly, unplanned and urgent maintenance activities. By nature, the inspection of bridges often requires high risk operations, including work at heights, in confined spaces, in hazardous environments or sites which are simply inaccessible by humans.

The Sydney Harbour Bridge is a prime example of a complex steel structure with many challenging inspection scenarios. The NSW Roads & Maritime Services (RMS) have identified one inspection area of significant interest. This is the confined spaces which run the length of the two upper and two lower arches. The four arches span 530m over the river and each contains three separate diaphragms. In total, the diaphragms contain 7.2km of confined space to be inspected.

Entry to the confined space is performed outside of handrails while at heights, see Figure 1a. Narrow manholes allow passage to the diaphragms which are no wider than 0.7m in width. The height of each diaphragm varies along the arch from less than 0.7m up to 3m in height. Without internal stairs or ladders and slopes up to 45deg, there is a high risk of slips, trips and falls. The confined space may also expose inspectors to lead paint dust, vehicle exhaust, fuel spills and paint fumes. Partition plates and manholes, seen in Figures 1b, 1c and 1d, occur at regular intervals throughout the diaphragms. This inspection area clearly poses many risks to human inspectors.
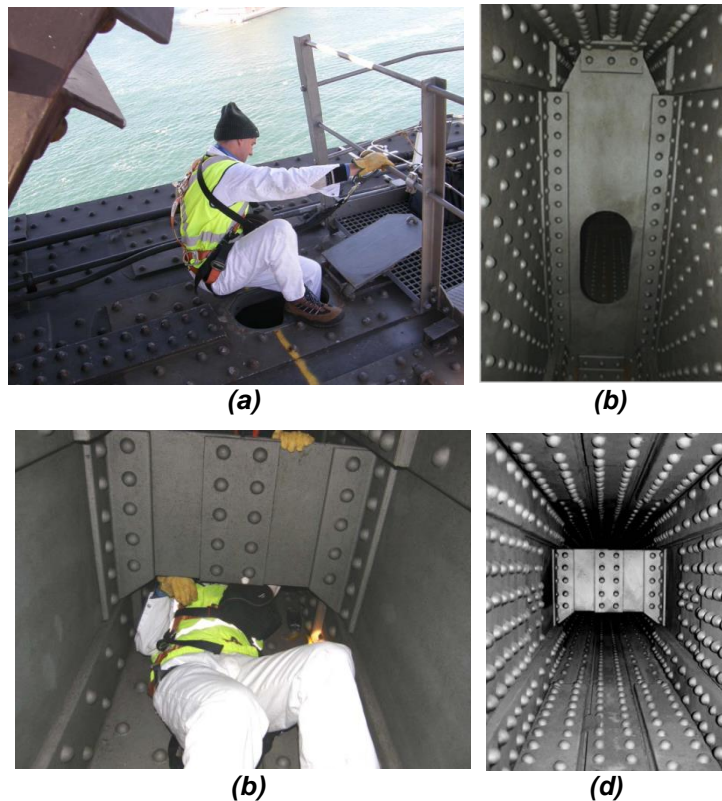
Figure 1: (a) Inspector entering confined space outside of handrails. (b) Example of manhole scenario in diaphragm. (c) Inspector under partition plate in confined space of the arch. (d) Example of partition plate scenario in diaphragm.

In the hierarchy of hazard control the most effective risk management strategy is the elimination of the risk. In order to achieve this, the NSW Roads & Maritime Services and the Centre of Excellence for Autonomous Systems at the University of Technology Sydney, have been working together to develop an innovative climbing robot to inspect the confined spaces in the arches of the Sydney Harbour Bridge. The ultimate goal of the project is to deliver an inspection robot which will aid bridge inspectors in high risk locations.

REQUIREMENTS FOR THE INSPECTION ROBOT

The requirements for the inspection robot are divided into different categories and ordered as follows.

Inspection Outcomes:

- Provide visual feedback to inspector.
- Save visual feedback for processing at a later date.
- Generate 3D maps which can be used with a geographic information system (GIS).
- Provide online condition assessment of inspected surfaces.

Mobility Requirements:

- Perform 360deg plane transitions through manhole scenarios, where the minimum manhole diameter is 0.3m.
- Enter and traverse through confined passages as small as 0.6m by 0.6m.
- Traverse partition plate scenario, where the minimum clearance is 0.3m.
- Traverse in any orientation, including inverted.

- Traverse up to 3m on vertical walls.

- Traverse up to 30m of an archway diaphragm.

- Traverse densely riveted surfaces.

Adhesion Requirements:

- Support entire weight of robot and inspection payload safely.

- In event of power failure adhesion must not detach, and hence cause the robot to fall.

- Cater for surfaces containing up to 2mm in paint, rust, and dirt. See Figure 3.

- Adhesion must be non-destructive to surface and structure.

- No modifications can be made to the structure.

Figure 3: Example of old paint and rust which may peel from surface Brooklyn Bridge.

LITERATURE REVIEW

The advantages provided by robots for performing inspection tasks have been realised for several decades, however their deployment in real world scenarios has been limited. With increasing Occupational Health &Safety (OH&S) standards and technological advancements the demand for inspection robots is rapidly increasing. With the inspection scenario and design requirements in mind, a review on the current state of art climbing robots has been conducted. The review compares the main forms of robot locomotion; these are aerial, wheeled, and legged robots. It also provides a brief overview of adhesion techniques.

Aerial Robots

In recent years unmanned aerial vehicles (UAVs) have recently shown great potential in inspection applications with extended flights times, great stability and higher payloads. However the miniaturisation of UAVs greatly effects these performance characteristics. One such quad rotor UAV with high performance is the AscTec Pelican by Ascending Technologies[1]. The UAV is capable of up to 15mins of autonomous navigation using an on-board lidar for 3D mapping. However with blade tip to tip dimensions of 700mm the UAV cannot pass through the 300mm manholes in the inspection scenario. UAVs smaller than the AscTec Pelican either suffer from significantly shorter flight times or are not capable of autonomous navigation.

Wheeled and Tank Robots

There are numerous wheeled [2–5] and tank robots [6–10] which can perform inspection on steel structures such and ship hulls, power plants and wind turbines. These robots are preferred for faster mobility however are typically limited to smooth and continuous surfaces as their ability to perform plane transitions is restricted. Of the inspection robots identified, two[11,12] have the ability to perform the 90 degree wall transitions, and only Cymag[2] has the ability to perform the required 360 degree plane transition. Unfortunately, its ability to perform transitions is dependent on gravity, and due it its simple construction its inspection capabilities would be very limited.

Wheeled and tank robots also suffer in harsh environments where rust and paint is susceptible to peeling. Experiments have shown that collecting ferromagnetic dust on wheels rapidly reduce the effective adhesion strength, which may lead to failure of the adhesion[4].

Legged Robots

When faced with wall transitions and complex terrain, legged climbing robots typically perform better due to the added degrees of freedom (DOF) contained in their legs and bodies. Research in ant locomotion has shown the benefits of many DOF legs with overlapping workspaces[13]. The application of this knowledge to robotics is challenging due to constraints on joint sizes, motor torque limitations, and complexity in control and coordination of legs[14]. The inchworm caterpillar is often used for inspiration due to its many DOF contained within a single chain, eliminating the need to coordinate multiple legs. A comparison of numerous inchworm inspired robots [15–21] has shown that despite increased manoeuvrability and reduced control complexity the ability to perform a 360deg plane transition has still not been demonstrated. This is a limitation imposed by the robot configuration; the robot is either too short, joint angles are limited, or joints torques are exceeded. Of these inchworm robots, W-Climbot is the most promising with the ability to perform transitions up to 289deg[18].

Adhesion

There are many forms of adhesion which can be employed with climbing robots including chemical, biological, suction, mechanical, electromagnetic and permanent magnetic. Each form of adhesion provides its own advantages, however the selection of adhesion for a climbing robot is largely dictated by the environment and surface conditions. With the Sydney Harbour Bridge being constructed of Silicon Steel, it is widely agreed that in most instances magnetic adhesion[23] is the best choice. Furthermore, with possible long term build-up of paint, dirt and rust, all other methods that adhere to the exterior surface may lead to detachment by peeling the top surface layer from the structure.

Magnetic adhesion can be categorised as either electromagnet or permanent magnetic; each have their own advantages and disadvantages. With a requirement to be remain active in the event of a power-failure permanent magnet adhesion is necessary. Several[24–26] forms of permanent magnetic adhesion were identified and experimented with however these solutions did not perform well with large air gaps. Hence, research[27] was conducted into an optimal design for a magnetic adhesion.

DESIGN CHALLENGES AND SOLUTIONS

The review on climbing robots highlighted many challenges, in particular identifying the most suitable locomotion, required robot configuration, and the design of safe and reliable adhesion.

Reviewing state of the art inspection robots, an inchworm inspired climbing robot with permanent magnetic adhesion favours most with the operational goals of the inspection robot.

The following sections focus on the challenges in designing the prototype inchworm robot. It also presents new challenges identified through testing in mock environments and in real world conditions at the Sydney Harbour Bridge; these challenges include system management and cable management. In response to these challenges, a next generation inchworm robot, named CROC (Climbing RObot Caterpillar), has been developed.

Robot Configuration

In order to perform the manhole transition, biological inspiration from the inchworm caterpillar seen in Figure 4a has been used. To maximise the step size, Figure 4c shows the use of rotation joints about an 'x' axis at either end of the robot. With rotations at the foot and head of the robot, the body is able to fold as close as possible to the surface during the manhole wrap as shown by the inchworm and inchworm robot in Figures 4b and 4d. By moving the rotation point closer to surface the overall length of the robot is also reduced. This is ideal for inchworm robots, as increases in length greatly affect the torque applied to the joints, particularly in a cantilevered poses as shown in Figure 4c.

While W-Climbot[18] uses only one extra joint with rotation in the 'x' axis, the proposed inchworm robot configuration uses an addition two 'x' axis rotations to achieve the required 360deg plane transition. Traditionally a longer middle link length is used to achieve a larger plane transition angle. However, the additional 'x' rotation allows for a much smaller robot length, at the cost of increased weight and control complexity. Finally, to improve robustness during manhole transitions, three 'z' axis rotations are added between the each 'x' axes rotation.

For a given inchworm robot configuration, research was also conducted to optimise the design parameters for an inchworm robot configuration. See "A method for optimal design of an inchworm climbing robot"[22] for more information.
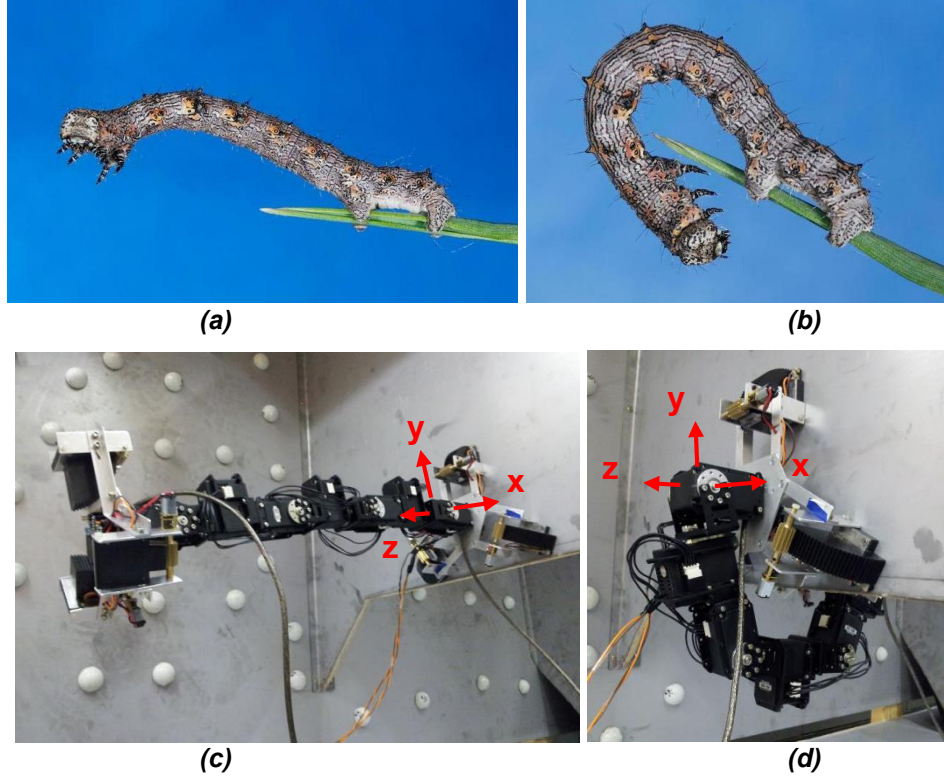

Figure 4: (a) Inchworm caterpillar in cantilevered pose. (b) Inchworm caterpillar performing desired 360deg plane transition. (c) Inchworm inspired robot in cantilevered pose. (d) Inchworm inspired robot performing 360deg plane transition.

This 7 DOF inchworm robot is the only climbing robot known to the authors which can perform the 360 degree plane transition in any orientation with respect to gravity. The inchworm robot caters for all required design scenarios, including manhole transitions with plate thicknesses varying from 0 to 40mm. The limitation for the plate thickness is due to the length between joints 3 and 5, however the plate thickness is not expected to exceed 20mm. The inchworm robot has been demonstrated in a mock up environment with the ability to traverse the manhole scenario, as shown in the time lapse seen in Figure 5.
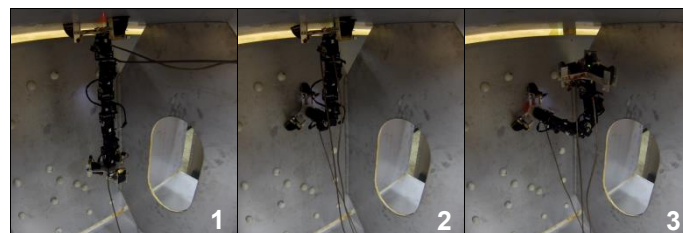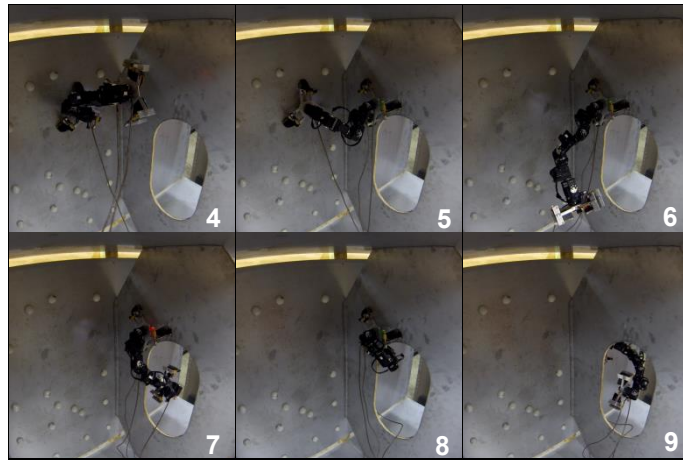
Figure 5: Time lapse of inchworm robot performing manhole transition in a mock up environment of manhole scenario.

To improve the manoeuvrability of the inchworm robot configuration an offset between joints 1 and 2, and between 6 and 7, has been added in CROC. This offset provides even closer compliance with the surface. With no reduction in maximum step size, the new robot configuration caters manhole plate thicknesses of up to 97mm.
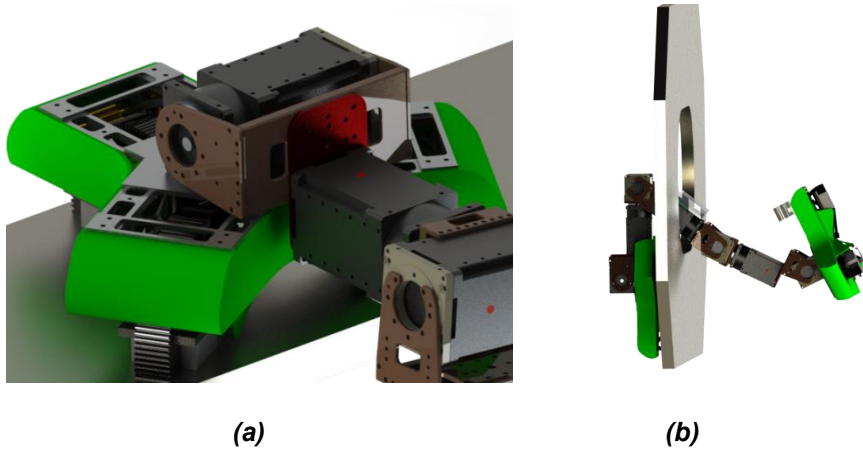

(a)   *(b)*

Figure 6: (a) Offset between joint 1 and joint 2 improves manhole wrap performance. (b) Robot is able to extend further through manhole for inspection before performing transition.

Adhesion

Research into an optimal design for magnetic adhesion has led to a patent pending adhesion system[28]. High grade neodymium magnets are peeled from the surface through the mechanical advantage of gears and leverage. The magnetic foot pad comprises three independently controlled magnetic toes, each with force sensors to provide feedback of current adhesion state.

There are several variables used to determine the adhesion strength of the magnetic foot pad. These include the number of magnets used, dimensions of the magnet, magnet grade, magnet configuration, and the radius of the foot pad. The magnetic foot pad has been designed for worst case torque loading of the robot in a cantilevered position, which was expected to be 7.8Nm. The foot pad was verified at site with a 2.4x factor of safety supporting 18.4Nm. In the event of a power cut the magnetic foot pad remains firmly attached with no change in adhesion strength.
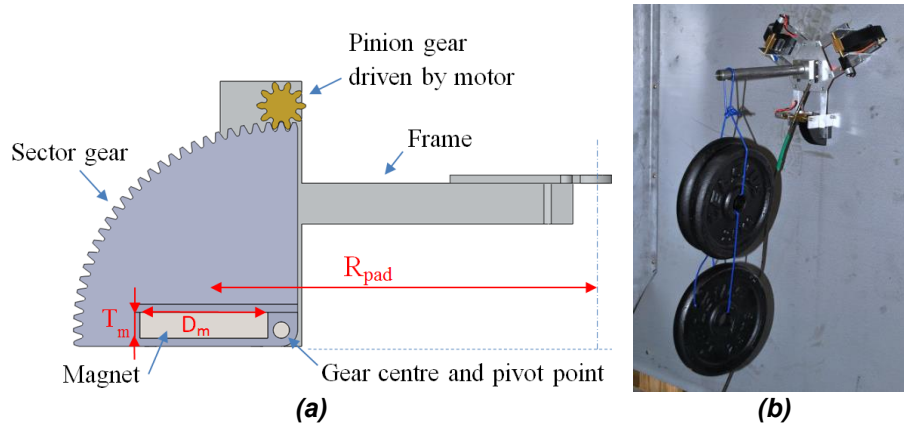
Figure 7: (a) Components of a single magnetic toe. (b) Testing magnetic adhesion system, loaded to 18.4Nm.

Control

The climbing robot, being 7DOF, poses many challenges in control. For a user to manipulate each of the seven motors would be very time consuming and challenging to visualise the required set of joint angles to move from one position to the next whilst avoiding collisions with the robot and the environment. Significant research has been conducted into autonomous control of the climbing robot[29,30], including autonomous exploration and map building, localisation, and planning.

A PrimeSense depth camera, an inexpensive 3D sensor, is used to capture 3D point clouds of the environment. Figure 8 shows the inchworm climbing robot about to perform exploration and mapping in front of the partition plate. The depth camera is mounted to the head of the robot to allow more data to be collected with a larger robot workspace.

Several algorithms have been experimented with at different locations on the Sydney Harbour Bridge. However these mapping techniques rely on very accurate joint angles and localisation of the sensor with respect to the base of the robot. Errors in the joint angles and flexibility throughout the robot body cause inaccuracies when constructing the 3D map of the environment. Figure 9a shows how flexibility in the robot causes distortions in the construction of the 3D map.

Another mapping technique, Reconstruct Me, gathers more data and uses a smoothing process. This process has also been tested on the inchworm climbing robot in front of the partition plate, as seen in Figure 9b. While the reconstructions appear better quality, they also exhibit walls which warp. Furthermore the process is very computationally expensive, meaning a powerful computer must be used and movements must be very slow and smooth. The flexibility of the robot induces vibrations through the body. Vibrations and rapid movements both cause the algorithm to lose track of features in the environment, which in turn prevents the mapping process. To combat these errors CROC has been designed using high performance motors (Dynamixel PRO H54) with better angle resolution and higher torques. The links and brackets supporting the motors are also stronger.
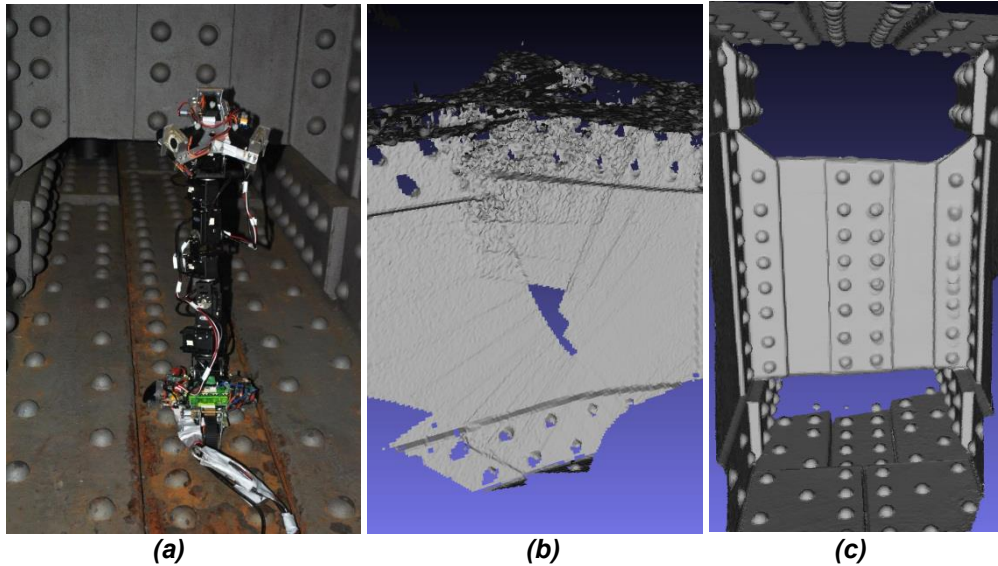
Figure 9: (a) Inchworm climbing robot standing in front of partition plate performing exploration. Depth sensor mounted to head of robot. (b) Reconstruction of environment using efficient mapping algorithm. (c) Reconstruction of environment using ReconstructMe

System Management

The first inchworm climbing robot prototype required a powerful remote server computer for all control computations. CROC uses distributed computing for better control management and efficiency. The management of systems is split into eleven autonomous systems; these include the seven motor controllers, two foot pad controllers, one on-board robot controller, and one remote robot server.

Each motor controller and foot pad controller contains their own embedded system with unique identifiers. They act as slaves on a RS485 network to the on-board robot controller which issues commands and requests state information. The state information for the motors includes joint angles, temperature, current, and errors. The foot pad state information includes magnetic adhesion state and angle of magnets. Upon a attach command the foot pad moves the magnet until a contact sensor confirms attachment.

The on-board robot controller passes motor and foot pad state information to the remote robot server. The robot controller also captures and passes on point cloud data from a low cost 3D sensor at the head of the robot. This data is used by the remote server to build 3D maps.

The remote server uses the 3D information to construct maps of the environment and perform local and global planning. These planning techniques are computationally expensive and hence a miniature pc with an Intel i7-4770R is used. After determining a suitable path a set of robot positions are issued to the robot controller which handles control of the robot joints.

The distribution of computing allows for a more cost efficient system with better performance than the centralised computing in initial prototypes. Furthermore initial limitations in data bandwidth over the primary tether are mitigated with initial processing of data from motors, foot pads, RGB camera and the 3D sensor.

Cable Management

While biological creatures do not have tethers for power and data, the inchworm robots are not capable of supporting the extra weight of batteries on board. This poses several cable management challenges when design the climbing robot system. These can be split into two distinct parts. Firstly, the primary tether between the robot and the remote robot server, secondly the on-board robot wiring.

Primary Tether

Managing the primary tether while performing climbing motions is challenging for numerous reasons; the base of the robot changes with each step, the robot has a very large workspace, the robot may be at any orientation in space, it is difficult to track tether, performing a flip gait may cause tangling. Other challenges include potential data limitation and power loss experienced with long cable lengths.

The primary tether for the inchworm prototype is connected to the foot of the robot. However, this has been found to pose several limitations. These limitations include restricting exploration ability to one foot, restricting ability to perform a more efficient flipping gait, and increased loads at one end of the robot. To resolve these problems the primary tether has been relocated to the centre of the robot as seen in Figure 10b. The wiring connects to a robot controller via a slip ring which allows for continuous rotation and reduces torque applied to the robot body. The slipring is offset from the centre of the robot to allow clearance between the robot and the footpad during a flip gait.

While the climbing robot is intended to inspect over 30m of passage, the initial prototype was limited to 10m due to data transmission constraints. With the distributed computing method, the robot controller on CROC can now communicate to the robot server with up to 100m of tether, and supports wireless communication. The primary tether to the robot also delivers the 24V power to the motors and the on board controller. To prevent excessive power loss across the tether, remote voltage sensing is used to adjust the remote power supply unit accordingly.

Robot Wiring

The challenges of wiring a manipulator are multiplied when many degrees of freedom and high manoeuvrability is required. During testing of the first inchworm prototype cables were prone to being disconnected in extreme positions. Furthermore the cables were susceptible to being pinch between joints. Several solutions were experimented with.

Enclosing the motors within through bore slip rings was considered on joints to eliminate in wiring issues entirely and provides the joints with the ability to perform continuous rotations. However, the minimum outside diameter for such slip ring significantly reduce the usable workspace of the robot and prevents the robot from performing the manhole transition.

Another method was trialled using an enclosed drag chain and strain relief helped to prevent cables being disconnected or pinched between joints. However this solution caused limitations on the robot workspace with reduced joint angles. Removing the drag chain housing, as seen in Figure 10a and 10b, allowed for greater workspace however it was not reliable enough during testing. During tests, the drag chain was prone to collisions with the robot the robot or environment causing drag chain links to disengage.

Due to the very large workspace of the 7DOF inchworm, a cable management solution which is compliant during collisions with the both robot and the environment was necessary. High class flexible robot cable from IGUS, designed for twisting and torsional loads are now used. By modularising robot wiring different lengths of the robot cable can be experimented with to achieve the desired robot workspace.
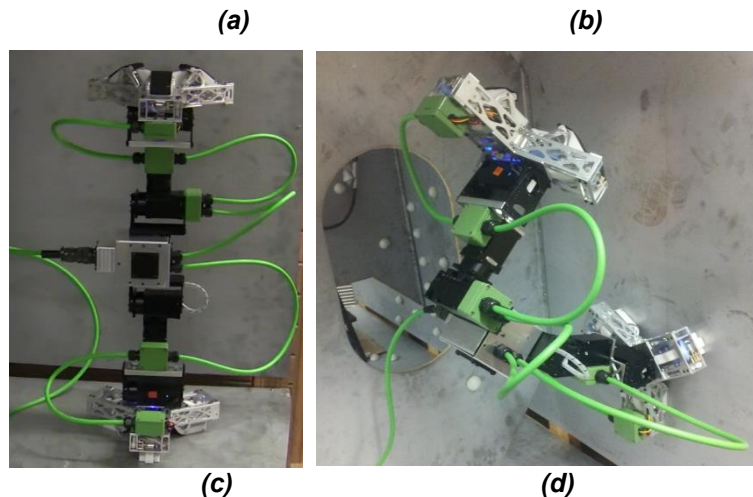
Figure 10: (a) Use of drag chain to prevent cables being caught in-between joints. (b) CROC with drag chains. (c) CROC with class 6 IGUS robot cable. (d) Primary tether attached to centre of inchworm allows free movement of head and foot.

CONCLUSIONS AND REMARKS

Inspection robots are being driven by rapid technological advancements and more stringent OH&S standards in the workplace. Their deployment in real world scenarios however are limited by many engineering challenges. This paper has focused on some of the engineering challenges faced during the design of the inspection robot. These challenges are common throughout literature, and have also been identified through the development and testing of prototype climbing robots in mock up environments and in real world scenarios.

Solutions to some of the more challenging design aspects of a climbing inspection robot have been proposed. Although there are many issues yet to be resolved including portability, ergonomics, and a friendly user interface, CROC is the result of many hours understanding and evaluating design challenges for a robotic inspection solution. CROC is in early stages of testing under ideal conditions of the mock up environment. The true performance of CROC will be evaluated in the next field testing at Sydney Harbour Bridge, and many more design challenges are inevitable. Despite the challenges, there are many more benefits for inspection robots including:

- Mitigating safety, economic, environmental risks by inspecting areas previously inaccessible or no longer safe to inspect.

- Increased efficiency by using multiple inspection robots.

- Increase quality by employing multiple inspection techniques i.e. visual, ultrasonic, magnetic particle, eddy current. Furthermore, the ability to construct 3D maps to track quality and inspection progress.

- Ability to perform maintenance tasks at inspection time

ACKNOWLEDGEMENTS

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