UNIVERSITY OF TECHNOLOGY, SYDNEY

Design of a Biologically Inspired Climbing Robot and an Adhesion Mechanism for Reliable and Versatile Climbing in Complex Steel Structures

by

Peter Kenneth Ward

A thesis submitted in partial fulfillment for the
Degree of Masters of Engineering by Research

in the
Faculty of Engineering and IT
Intelligent Mechatronic Systems Group

July 2016

Declaration of Authorship

I, Peter Kenneth Ward , declare that this thesis titled, 'Design of a Biologically Inspired Climbing Robot and an Adhesion Mechanism for Reliable and Versatile Climbing in Complex Steel Structures' and the work presented in it is my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed: ____________________

Date: 22/07/2016

UNIVERSITY OF TECHNOLOGY, SYDNEY

Abstract

Faculty of Engineering and IT

Intelligent Mechatronic Systems Group

Masters of Engineering by Research

by Peter Kenneth Ward

Steel infrastructure is the backbone of modern day society, however it requires regular inspection and maintenance to ensure integrity and prolong the life of services. The inspection of steel infrastructure such as steel bridges, often requires inspection at heights, in confined spaces, in hazardous environments or in areas which simply cannot be accessed by humans. With more stringent Work Health and Safety requirements, the ability to carry out comprehensive inspection becomes more challenging, to the extent that particular locations can no longer be inspected. There is significant motivation for climbing robots to carry out the inspection of such locations; however very few solutions have been successfully deployed.

The difficulty in deploying a climbing robot is largely attributed to robot configurations which lack versatility and adhesion systems which lack reliability. Inspired biologically from the inchworm caterpillar, a climbing robot is developed to addresses these two issues. This research presents the kinematic design of a climbing robot and the design of a novel magnetic adhesion mechanism which overcomes the challenges faced by the current state-of-the-art climbing robots.

The inchworm inspired climbing robot has a unique kinematic design consisting of 7 Degrees of Freedom to achieve its versatile climbing ability. This unique configuration allows the robot to navigate complex structures and pass through narrow obstacles, such as manholes.

This research presents an optimisation model for developing robust and reliable adhesion systems which consist of multiple adhesion modules. The optimisation model maximises particular adhesion performance criteria, whilst minimising weight. The model allows for tailored designs depending on the means of adhesion being used.

In verifying the optimisation model, a novel adhesion mechanism is developed with the means of attaching and detaching a permanent magnet to a steel surface. The adhesion module consists of a quarter gear segment to rotate the magnet between attached and detached states. Using the novel adhesion mechanism, an adhesion system is developed based on the optimisation model and verified through testing.

The inchworm inspired robot configuration and the novel magnetic adhesion system enable the practical deployment of the robot. The Climbing RObot Caterpillar (CROC) has undergone extensive testing in simulated environments, mock-up environments and has been deployed for the real world inspection of complex steel structures. Over 50 site trials have been conducted over a three year period inside the hollow archways of the Sydney Harbour Bridge. CROC extends the state of the art, being the first of its kind deployed with the capability of autonomous inspection in complex steel structures.

Acknowledgements

Firstly, I would like to express my sincere gratitude to my supervisor Prof. Dikai Liu who introduced me to this field of research and allowed me to join the Climbing Robot team. Since taking me on as an intern, he has provided continuous guidance and motivation for my personal development through my studies and work related experience.

Besides my supervisor, I would like to thank the rest of the Climbing Robot project team, Prof. Kenneth Waldron, Prof. Gamini 'Dissa' Dissanayake, Dr. Gavin Paul, Chia-Han 'John' Yang, Phillip Quin, David Pagano and Liyang Liu. Also to Jack Liang and the many interns and capstone students who have assisted me during the project. Thank you for your insightful comments, encouragement, patience and support in broadening my research knowledge from various perspectives. Also, for the trials and tribulations, with many sleepless nights, even weeks, leading to the eventual success of the project. My sincere thanks also goes to the rest of the research staff and students at the Centre for Autonomous Systems. There has always been someone to lend a hand.

I would like to thank Laurent Matkovic, Peter Mann, Waruna Kaluarachchi, Philip Brooks and Palitha Manamperi from the NSW Roads and Maritime Services, who have supported us and beleived in us throughout the project. It has been fantastic to work in collaboration with them.

A very special thank you to the FEIT Workshop, Laurence Stonard, John Funnel, Scott Graham, Peter Bracken, Siegfried Holler, Ron Smith and Bill Firth (RIP), for supporting me throughout my research. With each iteration of the robot, they have taught me many valuable technical skills. Also to Peter Waterson for his valuable knowledge on magnets and John Hazelton for his time in proof reading my thesis.

I am thankful to all my friends who have made my time in Sydney enjoyable, particularly my past colleagues Greg Peters and Freek De Bruijn who also shared many insightful discussions during our coffee breaks.

Last but not the least, I would like to thank my family and friends. My parents Anthea and Trevor Ward have driven my curiosity and passion for learning, inventing and never giving up. Without their encouragement, I may not have undertaken this research and without their proof reading, my thesis would not read as well. Also to my brother Martin Ward, my grandparents and relatives who have supported me throughout the undertaking of this thesis and my life in general. Finally to Sandra Palm for your patience over the past four years, I promise I will start cooking and cleaning again.

Contents

List of Figures

List of Tables

Abbreviations

CAD	Computer Aided Design
CAS	Centre for Autonomous Systems
CROC	Climbing Robot Caterpillar
DOF	Degrees Of Freedom
EPM	Electro Permanent Magnet
FEA	Finite Element Analysis
HD	High Definition
MAV	Micro Aerial Vehicle
MFEA	Magnetic Static Finite Element Analysis
NDT	Non-Destructive Testing
NSW	New South Wales (Australia)
PEM	Permanent Electro Magnet
RGB	Red Green Blue
RMS	Roads and Maritime Service New South Wales
UTS	University of Technology, Sydney
UAV	Unmanned Aerial Vehicle
WHS	Work Health and Safety

Glossary of Terms

Actuator	On a robot, the actuators are devices responsible for controlled motion of the system. They may be powered by electrical energy, hydraulic fluids, or pneumatic pressure.
Degrees of Freedom	The Degrees of Freedom (DOF) in a robotic system, is the number of unique ways in which the system can move, whether the movements are translations or angular motions.
Environment	Includes all characteristic of the 3D surroundings in which the robot is operates.
Electro-mechanical servo	A type of actuator consisting of an electric motor, typically a gear train and control board. Normally can be controlled given a specific position, velocity, acceleration or torque.
Joints	In robotics, joints are objects which have at least one degree of freedom and represent the relationship between different reference frames. Joints by be of revolute, prismatic, translation or spherical type. They may also be passive or actively controlled. Actuators typically referred to as joints.

Manipulator	An articulated robotic arm consisting of several actuators. The manipulators end-effector allows it to manipulate objects in 3D space.
Map	Model of the geometry and material-type of surfaces in the surrounding environment.
Obstacle	An object within the robot's environment which it must overcome by climbing around, over or through.
Planning	The act of generating a path (and motion) course which the robot can then follow to get between two poses.
Pose	The position the robot or manipulator takes given a set of joint angles.
Unstructured	A real-world environment that has not been set up to facilitate ease of robot movements. These environments contain many uncertainties.
Workspace	The set of points which can be reached by the end-effector of a robot manipulator.