Uncertainty Modelling and Motion Planning of an Inchworm Robot Navigating in Complex Structural Environments

by

David Pagano

A thesis submitted in partial fulfillment for the degree of Doctor of Philosophy

in the
Faculty of Engineering and IT
Intelligent Mechatronic Systems Group

July 2018
Declaration of Authorship

I, David Pagano, declare that this thesis titled, 'Uncertainty Modelling and Motion Planning of an Inchworm Robot Navigating in Complex Structural Environments' and the work presented in it are 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: __________________________

Production Note:
Signature removed prior to publication.

Date: 30/12/2018
Abstract

Faculty of Engineering and IT
Intelligent Mechatronic Systems Group

Doctor of Philosophy

by David Pagano
Many ferromagnetic structures require continuous inspection and maintenance routines to ensure longevity, structural integrity and aesthetics. For most structures, routines are performed by teams of personnel, with each individual performing specific tasks. These tasks may be highly hazardous; being performed at height, in confined spaces or in the presence of hazardous materials such as lead-based paints and vehicle fumes. Adopting a robotic solution for inspections would significantly improve occupational health and safety for maintenance personnel, while increasing the quality and reducing the cost.

An inchworm robot has been developed for inspection of confined spaces in the Sydney Harbour Bridge. With a 7 degree of freedom multi-link serial body and magnetic pads for adhesion, the inchworm robot provides a dexterous means for climbing and inspecting particularly difficult-to-access sections of the bridge. However, due to the structure and the adhesion mechanism of the inchworm type robot, deformation of the robot body (i.e. structural uncertainty) and inaccurate landing position of the permanent magnet adhesion pads (i.e. hand position uncertainty) cause imperfect knowledge about the robot state. This prevents safe motion in a real world setting. The combination of these uncertainties present a unique challenge in robot motion planning and collision avoidance which is not considered in the literature.

This thesis first focuses on developing a model for representing the structural and hand position uncertainties. The model describes the uncertainty in the coordinate frame of reference for the joints.

A 3D probabilistic force field (3D-PF²) algorithm is developed to incorporate the uncertainties and allow for smooth, collision-free path planning. A force field surrounds each link to prevent collisions with each force field sized to account for the dimensions of the link and the uncertainty at the joints related to the link. Force fields are used to generate repulsive forces which push the robot away from obstructions while an attractive force pulls the end-effector towards a goal location.

A Line of Sight Tree (LoST) algorithm is developed for longer time-horizon motion planning with the 3D-PF² algorithm used for local motion planning. The LoST algorithm provides waypoints as goal locations for the 3D-PF² algorithm. Waypoints are found in a
manner loosely based on the way a person views a scene whereby their gaze tends towards important regions such as the edges of objects.

Extensive simulations and experiments have been conducted to test the performance of both the 3D-PF$^2$ and the LoST algorithms within a number of environments including the specific application scenario at the Sydney Harbour Bridge.
Acknowledgements

First I would like to thank my supervisor Professor Dikai Liu for all the support he has given me - intellectual, mental and otherwise - throughout the project to allow me to attain the quality of the final thesis.

Thanks to the CROC team including Professor Ken Waldren, Phillip Quin, Gavin Paul, Peter Ward, John Yang for their hours of work into the project from which my work is founded. A special thank you to Phillip for the chats over the years, and to Peter and John for all the help with the experiments.

Thanks to all my friends who have supported me emotionally and mentally throughout this entire process. The list is long and the reasons vast; each of you have helped me in some way, in some cases it may be unknowingly. I am grateful.

And finally I would like to thank my family; Sister, Mother and Father. These last few years haven’t been the greatest but they have been there for me through it all and without them this thesis would not have come to pass.

Nonni and Zia...I miss you all...
## Contents

Declaration of Authorship ......................................................... i

Abstract ......................................................................................... ii

Acknowledgements ........................................................................... v

List of Figures .................................................................................. ix

List of Tables ..................................................................................... xiv

Abbreviations ..................................................................................... xvi

Nomenclature ....................................................................................... xvii

Glossary of Terms ............................................................................. xxiii

1 Introduction ..................................................................................... 1
  1.1 Background ................................................................................. 2
  1.2 Motivation .................................................................................. 5
  1.3 Scope ......................................................................................... 8
  1.4 Contribution ............................................................................... 9
  1.5 Publications ............................................................................... 9
  1.6 Thesis Outline .......................................................................... 10

2 Review of Related Work ................................................................. 12
  2.1 Uncertainty Related to the Inchworm Robot ................................. 12
    2.1.1 Control Uncertainty ............................................................... 13
    2.1.2 Sensor Uncertainty ............................................................... 13
    2.1.3 Imperfect Map Data .............................................................. 14
  2.2 Modelling Uncertainty ............................................................... 14
    2.2.1 Deterministic Modelling ...................................................... 14
    2.2.2 Probabilistic Modelling ...................................................... 22
  2.3 Path Planning ............................................................................. 25
    2.3.1 Non-Probabilistic Path Planners ......................................... 25
## Contents

2.3.2 Planning with Uncertainty .................................. 31
2.4 Discussion on the Related Work ................................ 37

3 Modelling Structural and Hand Position Uncertainty .... 38
  3.1 System Definition ........................................ 39
  3.2 Structural Uncertainty ..................................... 41
    3.2.1 Modelling Structural Uncertainty ....................... 42
  3.3 Hand Position Uncertainty ................................ 47
    3.3.1 Modelling Hand Position Uncertainty ..................... 49
  3.4 Robot Model with Structural and Hand Position Uncertainties ...... 53
  3.5 Parameter Verification ..................................... 55
    3.5.1 Structural Uncertainty Parameters ...................... 56
    3.5.2 Hand Position Uncertainty Parameters ................... 58
  3.6 Discussion ................................................ 59
  3.7 Conclusions ............................................. 61

4 Path Planning with Structural and Hand Position Uncertainty 62
  4.1 Three-Dimensional Force Field (3D-F$^2$) Algorithm ........... 63
    4.1.1 Force Fields ......................................... 64
    4.1.2 Repulsive Forces Due to Potential Collision with the Environment .... 64
    4.1.3 Repulsive Forces Due to Potential Self-Collision .......... 65
    4.1.4 Attractive Force ..................................... 67
    4.1.5 Dynamic Model ....................................... 68
    4.1.6 Force Control Algorithm .............................. 69
  4.2 3-Dimensional Probabilistic Force Field (3D-PF$^2$) Algorithm .... 70
    4.2.1 Force Fields with Structural and Hand Position Uncertainties .... 71
    4.2.2 Repulsive Force Due to Potential Collisions with the Environment .... 77
    4.2.3 Repulsive Force Due to Self-Collision ................ 84
    4.2.4 Attractive Force ..................................... 87
    4.2.5 Dynamic Model ....................................... 89
    4.2.6 Force Control Algorithm .............................. 89
    4.2.7 Local Minima Detection and Termination Criteria .......... 92
    4.2.8 Surface Attachment ................................... 93
  4.3 Simulations and Verification .................................. 95
    4.3.1 Verification of the Attachment Procedure in Simulated Environments 96
    4.3.2 Verification of the 3D-PF$^2$ Algorithm in Simulations .......... 103
    4.3.3 Verification of the 3D-PF$^2$ Algorithm in Experiments .......... 121
    4.3.4 Experimental Verification of the 3D-PF$^2$ Algorithm for Attachment in a Tunnel Environment ......................... 121
    4.3.5 Experimental Verification of the 3D-PF$^2$ Algorithm in the Partition Plate Environment .............................. 123
    4.3.6 Experimental Verification of the 3D-PF$^2$ Algorithm in the Manhole Environment .............................. 126
  4.4 Discussion ................................................ 132
  4.5 Conclusions ............................................. 134
## Contents

5 Line of Sight Tree Algorithm

5.1 Line of Sight Tree Algorithm Architecture

5.1.1 Common Regions

5.1.2 Intermediate Node Identification Algorithm

5.1.3 Safe Robot Workspace

5.1.4 Weighting Criteria

5.1.5 Line of Sight Tree Algorithm Termination Criteria

5.2 Line of Sight Tree Algorithm with the 3D-F\(^2\) Algorithm

5.2.1 Implementation of the Combined LoST and 3D-F\(^2\) Approach

5.2.2 Updating the Line of Sight Tree Algorithm in Real-Time

5.2.3 Additional Weighting Criteria for a Multi-Link Serial Robot

5.3 Line of Sight Tree Algorithm with the 3D-PF\(^2\) Algorithm

5.3.1 Multi-Link Serial Robot Weighting Criteria with Uncertainty

5.3.2 Updating the Line of Sight Algorithm with Uncertainty in the Kinematic Model

5.4 Results

5.4.1 Simulation in Unknown 2D Environments

5.4.2 Simulation with Known 2D and 3D Environments

5.4.3 Verifying the LoST Algorithm in a Steel Bridge Tunnel Application Scenario

5.4.4 Simulations in a Steel Bridge Tunnel Application Scenario using a Deterministic Robot Model

5.4.5 Experiment in an Application Environment with the LoST and 3D-PF\(^2\) Algorithms using a Robot Model with Uncertainty

5.5 Discussion

5.6 Conclusion

6 Conclusion

6.1 Summary of Contributions

6.1.1 A Probabilistic Model with Structural and Hand Position Uncertainties

6.1.2 A 3D Probabilistic Force Field Algorithm

6.1.3 A Line of Sight Tree Algorithm

6.2 Discussion of Limitations and Future Work
List of Figures

1.1 (a) A bridge scenario and related difficult areas; (b) a partition plate with limited space on the top and bottom for access and (c) a partition plate with a small manhole for access. ............................... 3
1.2 A 7DOF inchworm robot for steel bridge inspection. .................. 5
1.3 The inchworm robot deforming due to the weight of the permanent magnet adhesion system. The deformation of the inchworm robot is superimposed with an image of the robot in an upright position which is not affected by deformation. The variation between these two images shows the deformation. Covers are attached to the robot for protection. ....................... 6
1.4 The hand position error due to the strength of the permanent magnets in the adhesion system (a) on the floor and (b) on the wall (pad detached from the surface for clarity). The arrows show the direction of the hand position error from the intended goal location. .................. 7

3.1 (a) Representation of the inchworm robot. (b) Multi-link serial robot representation of the inchworm robot. ......................... 40
3.2 Uncertainty in links due to a) gravitational forces and b) impulses or dynamic motions. .................................................. 41
3.3 (a) The coordinate frame of a link, i, (b) deformation along the y-axis, (c) deformation along the z-axis, (d) deformation about the x-axis, (e) deformation about the y-axis, (f) deformation about the z-axis. ................. 43
3.4 Visualisation of inchworm robot in cantilever with two toes aligned with gravity. ................................................................. 44
3.5 (a) Robot with joints directly above each other. (b) Robot in a wrapped pose with the base and end-effector above each other. ............... 45
3.6 The mean and variance of the structural uncertainty for a multi-link serial robot in an arbitrary pose. .................................. 47
3.7 (a) Uncertainty in the hand pad location due to stepping on a rivet (side view). (b) Uncertainty in the hand pad location due to the hand position uncertainty shown with dotted outlines (top-down view). .......... 48
3.8 A representation of a multi-link serial manipulator with hand position uncertainty. .................................................. 50
3.9 Different distances relating to different growth factors. At the preparatory approach distance the growth factor is zero, while at the surface approach distance the growth factor is at a maximum. ....................... 52
3.10 (a) The variance at a maximum growth factor (b) and with a growth factor of 0.5. The red circle at the hand pad represents the maximum variance with the cyan discs showing the variance at each link’s coordinate frame of reference. ........................................ 53

3.11 Visualisation of the (a) structural uncertainty and (b) the hand position uncertainty at a growth factor of 0.5. (c) The coordinate frame resulting from structural uncertainty. (d) The maximum variance represented as ellipsoids at the model’s coordinate frame of reference. .................... 55

3.12 The inchworm robot in case 1 (a) deforming due to the weight of the permanent magnet adhesion system orientated with two magnet housings pointing in the positive z-direction and (b) superimposed on a non-deformed inchworm robot. Covers are attached to the robot for protection. ....................... 57

3.13 The inchworm robot in case 2 (a) deforming due to the weight of the permanent magnet adhesion system orientated with the two magnet housings pointing in the negative z-direction and (b) superimposed on a non-deformed inchworm robot. Covers are attached to the robot for protection. ....................... 57

3.14 The inchworm robot in case 3 (a) deforming due to the weight of the permanent magnet adhesion system orientated with the magnet housing orientated perpendicular to the z-axis and (b) superimposed on a non-deformed inchworm robot. Covers are attached to the robot for protection. ....................... 58

3.15 The hand position variance due to the permanent magnets in the adhesion system with the hand pad attaching to (a) the floor, (b) the wall and (c) the ceiling (pad detached from the surface for clarity). .................... 59

4.1 Basic 3D-F$^2$ Algorithm flowchart. .................................................. 63

4.2 Blue ellipsoids surrounding links of the multi-link serial robot to represent the force fields. ................................................................. 65

4.3 A repulsive force acting on an inchworm robot. ................................. 66

4.4 The attractive force acting on the inchworm robot. ............................ 67

4.5 Basic 3D-PF$^2$ algorithm flowchart. Green objects are modified based on the model described in Chapter 3, purple have added algorithms and blue are unchanged. .................................. 71

4.6 (a) The variance in a link at its coordinate frame of reference, $i$, and its proceeding coordinate frame of reference, $i + 1$ (b) The resulting variance force field surrounding a link to include the variance. .................... 73

4.7 (a) The link components superimposed on the link with the variance at a link’s joint and the proceeding joint. Black circles show the link vertices, $V$ (b) The proportionate variance at each vertex, $\sigma_V$ (c) The resulting force field surrounding the link. The red asterisks at the end of the proportionate variances are the points supplied to the Khachiyan Algorithm. (d) The resulting force field and link shown for clarity. .................... 75

4.8 (a) A link’s component with vertices shown as red asterisks. (b) The vertices transformed relative to the unit sphere shown as red asterisks. The furthest vertex from the origin is found. (c) The final minimum force field encompassing the link’s component. .................... 78
4.9 (a) The variance force field, $\hat{D}_i$. (b) The maximum variance force field, $\hat{D}_{i,\text{max}V}$, at a maximum variance factor of 90%. (c) The minimum variance force field, $\hat{D}_{i,\text{min}V}$ at a minimum variance factor of 10%. (d) The minimum force field, $\hat{D}_{i,\text{min}}$ ................................. 79

4.10 Transformed voxels relative to the unit sphere. Red voxels are within the minimum variance unit sphere, blue voxels are between the minimum variance unit sphere and maximum variance sphere, green voxels are outside the maximum variance sphere. .................................................. 80

4.11 The closest point, $\mathcal{P}_{ii+1}$ on a link, $\mathcal{P}_i$ to $\mathcal{P}_{i+1}$ to a given voxel, $\mathcal{P}_{\text{cls}}$. ............................... 82

4.12 The repulsive force versus unit sphere distances at varying error factors. Each of the blue and red lines show the amplitude of the generated repulsive forces for maximum variance spheres with radii of 1.1 and 1.3 respectively. . 82

4.13 Multiple repulsive forces acting on a link. Green dots are voxels, the red and blue ellipsoids are the minimum and maximum variance force fields respectively, the red line is the link, the blue vectors are the repulsive forces with their related voxels coloured magenta. ........................................ 83

4.14 Self-collision avoidance between two links. .............................. 84

4.15 (a) Wireframe representation of the multi-link serial robot with the translational attractive force vector shown at a start pose and (b) at the goal location. ................................. 88

4.16 The (a) position and (b) rotation components of the attractive force with different $K_s$ constants over different distances (Equations 4.56 and 4.57 respectively). Here $K_{\text{att.T}}$ is 1 and $K_{\text{att.R}}$ is 0.15. ......................... 90

4.17 Different stages of surface attachment. From the preparatory approach distance ($d_e = d_a$) the end-effector is guided through the surface approach distance ($d_e = d_b$) to the goal location ($d_e = 0$). ......................... 94

4.18 (a) Case 1: An obstacle near the surface goal location. As the variance increases, the size of the force fields also increase. This increases the chances of repulsive forces being generated from potential collision with the floor. (b) Case 2: Three additional obstacles are placed near the body of the robot. The deterministic representation of the inchworm robot is shown as is the goal location, $P_g$. The goal orientation, $R_g$, is not shown as it is pointing towards the surface. The goal region is shown as a circle centred at the goal location. ........................................ 96

4.19 Case 1: Graphs of forces, the distance to the goal and the end-effector’s distance to the goal normal at varying allowed maximum hand position variance values. ........................................ 97

4.20 Case 1: Attachment figures. ........................................ 98

4.21 Case 2: Graphs of forces, the distance to the goal and the end-effector’s distance to the goal normal at varying allowed maximum hand position variance values. ........................................ 99

4.22 Case 2: Attachment figures. ........................................ 100
4.23 Case 1: Partition plate environment from the front (a) and from the side (b). The deterministic representation of the inchworm robot at the initial pose; the goal location position, \( \mathbf{P}_g \), and orientation, \( \mathbf{R}_g \), are shown. The deterministic representation considers all allowed maximum mean and variance values to be zero. ...................................................... 105

4.24 Case 2: Manhole environment from the front (a) and from the side (b). The deterministic representation of the inchworm robot at the initial pose; the goal location position, \( \mathbf{P}_g \), and orientation, \( \mathbf{R}_g \), are shown. The deterministic representation considers all allowed maximum mean and variance values to be zero. .......................... 105

4.25 Case 1: Graphs of forces and the distance to the goal at various allowed maximum structural translations, rotations and variances for the partition plate simulation (part 1). ........................................ 111

4.26 Case 1: Graphs of forces and the distance to the goal at various allowed maximum structural translations, rotations and variances for the partition plate simulation (part 2). ........................................ 112

4.27 Results of the partition plate simulation with an allowed maximum structural translation at 0.0m and rotation at 0.0° .............................. 113

4.28 Results of the partition plate simulation with an allowed maximum structural translation at 0.075m and rotation at -15.0° .............................. 113

4.29 Results of the partition plate simulation with an allowed maximum structural translation at 0.05m and rotation at -15.0° .............................. 114

4.30 Results of the partition plate simulation with an allowed maximum structural translation at 0.075m and rotation at -5.0° .............................. 114

4.31 Results of the partition plate simulation with an allowed maximum structural translation at 0.125m and rotation at -25.0° .............................. 115

4.32 Results of the partition plate simulation with an allowed maximum structural translation at 0.075m and rotation at -15.0° .............................. 115

4.33 Case 2: Graphs of forces and the distance to the goal at various allowed maximum structural translation, rotation and variance values for the manhole simulation (part 1). ........................................ 116

4.34 Case 2: Graphs of forces and the distance to the goal at various allowed maximum structural translation, rotation and variance values for the manhole simulation (part 2). ........................................ 117

4.35 Results of the manhole simulation with an allowed maximum structural translation at 0.0m and rotation at 0.0° .............................. 118

4.36 Results of the manhole simulation with an allowed maximum structural translation at 0.05m and rotation at -10.0° .............................. 118

4.37 Results of the manhole simulation with an allowed maximum structural translation at 0.025m and rotation at -5.0° .............................. 119

4.38 Results of the manhole simulation with an allowed maximum structural translation at 0.125m and rotation at -25.0° .............................. 119

4.39 Results of the manhole simulation with an allowed maximum structural translation at 0.075m and rotation at -15.0° .............................. 120

4.40 Results of the manhole simulation with an allowed maximum structural translation at 0.10m and rotation at -20.0° .............................. 120
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.41</td>
<td>The tunnel environment used to verify the surface attachment.</td>
<td>122</td>
</tr>
<tr>
<td>4.42</td>
<td>Graph of the generated forces, distance to the goal and the end-effector’s</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td>distance to the goal normal for the landing experiment.</td>
<td></td>
</tr>
<tr>
<td>4.43</td>
<td>The inchworm robot landing experiment.</td>
<td>124</td>
</tr>
<tr>
<td>4.44</td>
<td>Graph of the generated forces, distance to the goal and the end-effector’s</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>distance to the goal normal for the partition plate experiment.</td>
<td></td>
</tr>
<tr>
<td>4.45</td>
<td>The inchworm robot partition plate experiment.</td>
<td>127</td>
</tr>
<tr>
<td>4.46</td>
<td>The final inchworm robot pose for the partition plate experiment.</td>
<td>128</td>
</tr>
<tr>
<td>4.47</td>
<td>Graph of the generated forces, distance to the goal and the end-effector’s</td>
<td>129</td>
</tr>
<tr>
<td></td>
<td>distance to the goal normal for the manhole experiment.</td>
<td></td>
</tr>
<tr>
<td>4.48</td>
<td>The inchworm robot manhole experiment.</td>
<td>130</td>
</tr>
<tr>
<td>4.49</td>
<td>The final inchworm robot pose for the manhole experiment.</td>
<td>131</td>
</tr>
<tr>
<td>5.1</td>
<td>Basic LoST Algorithm flowchart.</td>
<td>136</td>
</tr>
<tr>
<td>5.2</td>
<td>LoST algorithm in a simple 2D environment with accompanying LoS tree.</td>
<td>139</td>
</tr>
<tr>
<td>5.3</td>
<td>Common Regions.</td>
<td>142</td>
</tr>
<tr>
<td>5.4</td>
<td>Ray casting from an intermediate node.</td>
<td>144</td>
</tr>
<tr>
<td>5.5</td>
<td>RANSAC used for intermediate node generation in 3D environments.</td>
<td>144</td>
</tr>
<tr>
<td>5.6</td>
<td>Insufficient ray cast distance.</td>
<td>145</td>
</tr>
<tr>
<td>5.7</td>
<td>Generating safe workspaces.</td>
<td>147</td>
</tr>
<tr>
<td>5.8</td>
<td>Basic flow of the combined LoST and 3D-F$^2$ approach.</td>
<td>152</td>
</tr>
<tr>
<td>5.9</td>
<td>Basic flow of the combined LoST and 3D-PF$^2$ approach.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>The green object is modified based on the algorithm described in Section</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.2.1, the purple object has been added and blue objects are unchanged.</td>
<td></td>
</tr>
<tr>
<td>5.10</td>
<td>An example randomly generated unknown 2D environment with 40 random</td>
<td>155</td>
</tr>
<tr>
<td></td>
<td>obstacles.</td>
<td></td>
</tr>
<tr>
<td>5.11</td>
<td>LoS tree and path in an example 2D environment.</td>
<td>159</td>
</tr>
<tr>
<td>5.12</td>
<td>LoS tree and path in an example 3D environment.</td>
<td>160</td>
</tr>
<tr>
<td>5.13</td>
<td>LoST and RRT paths in a simulated steel bridge tunnel environment.</td>
<td>161</td>
</tr>
<tr>
<td>5.14</td>
<td>Inchworm robot moving through a simulated partition plate environment.</td>
<td>169</td>
</tr>
<tr>
<td>5.15</td>
<td>Simulation scan data taken from the initial pose.</td>
<td>171</td>
</tr>
<tr>
<td>5.16</td>
<td>The inchworm robot at the initial pose as seen from the base side. The cyan</td>
<td>172</td>
</tr>
<tr>
<td></td>
<td>line is the initial robot pose.</td>
<td></td>
</tr>
<tr>
<td>5.17</td>
<td>The inchworm robot LoST experiment.</td>
<td>173</td>
</tr>
<tr>
<td>5.18</td>
<td>The inchworm robot at the final pose as seen from the goal side. The cyan</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>line is the initial robot pose, and the magenta lines show the final pose.</td>
<td>176</td>
</tr>
<tr>
<td>5.19</td>
<td>Graph of the generated forces and distance to the goal for the manhole</td>
<td>176</td>
</tr>
<tr>
<td></td>
<td>experiment.</td>
<td></td>
</tr>
<tr>
<td>5.20</td>
<td>Two example environments with unreachable goal nodes due to undetectable</td>
<td>177</td>
</tr>
<tr>
<td></td>
<td>gaps.</td>
<td></td>
</tr>
</tbody>
</table>
# List of Tables

3.1 Measured structural deformation mean and variance for the inchworm robot at difference base orientations ........................................ 57

3.2 Measured hand position variance for the inchworm robot at difference hand position attachment surfaces ........................................ 59

4.1 Case 1: Obstacle near surface goal location .................................. 101

4.2 Case 2: Obstacle near surface goal location .................................. 101

4.3 Case 1: Results of partition plate environment collected based on allowed maximum variance ................................................... 104

4.4 Case 2: Results of manhole environment collected based on allowed maximum variance ................................................... 104

4.5 Case 1: Results of partition plate simulation with various allowed maximum translations, rotations and variances ....................... 104

4.6 Case 2: Results of manhole simulation with various allowed maximum translations, rotations and variances ............................. 106

4.7 Table of allowed maximum structural and hand position uncertainty values used during experiments. ............................................. 121

5.1 Unknown environment with 40 random obstacles - averaged over 100 runs ................................................................. 158

5.2 2D environments with 20 random obstacles - averaged over 100 runs. LoST algorithm run at various maximum index levels .................. 162

5.3 2D environments with 40 random obstacles - averaged over 100 runs. LoST algorithm run at various maximum index levels .................. 162

5.4 2D environments with 60 random obstacles - averaged over 100 runs. LoST algorithm run at various maximum index levels .................. 162

5.5 2D environments with 80 random obstacles - averaged over 100 runs. LoST algorithm run at various maximum index levels .................. 163

5.6 2D environments with 100 random obstacles - averaged over 100 runs. LoST algorithm run at various maximum index levels .................. 163

5.7 2D environments with 120 random obstacles - averaged over 100 runs. LoST algorithm run at various maximum index levels .................. 163

5.8 3D environments with 20 random obstacles - averaged over 100 runs. LoST algorithm run at various maximum index levels .................. 164

5.9 3D environments with 40 random obstacles - averaged over 100 runs. LoST algorithm run at various maximum index levels .................. 164
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.10</td>
<td>3D environments with 60 random obstacles - averaged over 100 runs. LoST</td>
<td>164</td>
</tr>
<tr>
<td></td>
<td>algorithm run at various maximum index levels</td>
<td></td>
</tr>
<tr>
<td>5.11</td>
<td>3D environments with 80 random obstacles - averaged over 100 runs. LoST</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>algorithm run at various maximum index levels</td>
<td></td>
</tr>
<tr>
<td>5.12</td>
<td>3D environments with 100 random obstacles - averaged over 100 runs. LoST</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>algorithm run at various maximum index levels</td>
<td></td>
</tr>
<tr>
<td>5.13</td>
<td>3D environments with 120 random obstacles - averaged over 100 runs. LoST</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>algorithm run at various maximum index levels</td>
<td></td>
</tr>
<tr>
<td>5.14</td>
<td>3D complex partitioned tunnel - averaged over 100 runs</td>
<td>169</td>
</tr>
<tr>
<td>5.15</td>
<td>Table of allowed maximum structural uncertainty values used during experi-</td>
<td>173</td>
</tr>
<tr>
<td></td>
<td>ments.</td>
<td></td>
</tr>
</tbody>
</table>
# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D-F&lt;sup&gt;2&lt;/sup&gt;</td>
<td>3 Dimensional Force Field</td>
</tr>
<tr>
<td>3D-PF&lt;sup&gt;2&lt;/sup&gt;</td>
<td>3 Dimensional Probabilistic Force Field</td>
</tr>
<tr>
<td>COG</td>
<td>Centre of Gravity</td>
</tr>
<tr>
<td>DOF</td>
<td>Degrees of Freedom</td>
</tr>
<tr>
<td>EKF</td>
<td>Extended Kalman Filter</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>IMU</td>
<td>Inertial Measurement Unit</td>
</tr>
<tr>
<td>HMI</td>
<td>Human-Machine Interface</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
</tr>
<tr>
<td>LOS</td>
<td>Line of Sight</td>
</tr>
<tr>
<td>LoST</td>
<td>Line of Sight Tree</td>
</tr>
<tr>
<td>LQG</td>
<td>Linear-quadratic Gaussian</td>
</tr>
<tr>
<td>MDP</td>
<td>Markov Decision Process</td>
</tr>
<tr>
<td>NSW</td>
<td>New South Wales (Australia)</td>
</tr>
<tr>
<td>PF</td>
<td>Potential Field</td>
</tr>
<tr>
<td>POMDP</td>
<td>Partially Observable Markov Decision Process</td>
</tr>
<tr>
<td>PRM</td>
<td>Probabilistic Roadmap</td>
</tr>
<tr>
<td>RANSAC</td>
<td>Random sample consensus</td>
</tr>
<tr>
<td>RGB-D</td>
<td>Red, green, blue and depth</td>
</tr>
<tr>
<td>RRT</td>
<td>Rapidly-exploring Random Tree</td>
</tr>
<tr>
<td>SLAM</td>
<td>Simultaneous Localisation and Mapping</td>
</tr>
<tr>
<td>UTS</td>
<td>University of Technology Sydney</td>
</tr>
<tr>
<td>VFF</td>
<td>Virtual Force Field</td>
</tr>
</tbody>
</table>
Nomenclature

**General Formatting Style**

- $f(\cdots)$ A scalar valued function
- $\mathbf{f}(\cdots)$ A vector valued function
- $[\cdots]^T$ Transpose
- $|\cdot|$ Absolute value
- $\|\cdot\|$ Vector length and normalised vector

**Local and Global Variables**

- $\psi_G$ The global coordinate frame
- $\psi_R$ Coordinate frame of reference of a link
- $i, j, k$ Variables signifying the index of and counts associated with joints and links

**Specific Symbol Usage**

- $i^{-1}T_i$ A homogeneous transformation matrix (4 by 4)
- $a$ A DH parameter describing the distance along the x-axis
- $d$ A DH parameter describing the distance along the z-axis
- $\alpha$ A DH parameter describing the rotation about the z-axis
- $\mathbf{R}$ A rotation matrix (3 by 3)
- $\mathbf{R}_n, \mathbf{R}_a, \mathbf{R}_o$ The normal, approach and orientation vectors of a rotation matrix (3 by 1)
- $n_x, n_y, n_z$ Components of normal vector
- $a_x, a_y, a_z$ Components of approach vector
- $o_x, o_y, o_z$ Components of orientation vector
Nomenclature

\( \mathbf{P} \) A position vector (3 by 1)
\( x, y, z \) Components of the position vector along a x-, y- and z-axis
\( \mathbf{P}_{xy} \) A position vector along the xy-plane (2 by 1)
\( n \) Number of joints in the multi-link serial robot
\( \mathbf{q} \) A joint position matrix \((n \times 1)\)
\( q \) A component of the joint position matrix

\( 0^\mathbf{P}_g \) Goal location position vector (3 by 1)
\( 0^\mathbf{R}_g \) Goal location orientation vector (3 by 1)

\( l_c \) Distance between the base and the end-effector
\( E_c \) Allowed maximum structural translational deformation
\( \gamma_c \) Allowed maximum structural rotational deformation
\( d_{xy} \) Maximum distance along the xy-plane between a joint’s and a preceding joint’s coordinate frames of reference
\( \beta_c \) Joint distance ratio
\( G_c(\cdots) \) Function relating allowed maximum translational deformation to the joint distance ratio
\( F_c(\cdots) \) Function relating allowed maximum rotational deformation to the joint distance ratio
\( \mu_{E,i} \) Estimate of the mean structural translational deformation at a joint
\( \mu_{\gamma,i} \) Estimate of the mean structural rotational deformation at a joint
\( \sigma_{E,i} \) Structural translational variance
\( \sigma_{E,i} \) A matrix describing the structural translational variance in 3D (3 by 3)

\( \mu_{x.h}, \mu_{y.h} \) Hand position mean along the x- and y-axis
\( J_c(\cdots) \) Function relating the hand position variance to the joint position ratio
\( d_a, d_b, d_e \) Preparatory approach, surface approach and end-effector distances to the surface goal location
$K_g$  The growth factor

$\sigma_h$  Hand position variance

$\sigma_h$  A matrix describing the hand position variance in 3D (3 by 3)

$\sigma$  A matrix describing the variance at the joint (3 by 3)

$T$  A homogeneous transformation matrix with uncertainty (4 by 4)

$R$  A rotation matrix with uncertainty (3 by 3)

$P$  A position vector with uncertainty (3 by 1)

$I$  Mass-inertia matrix of the robot links

$\beta$  Damping coefficient matrix of the robot joints

$k_{sp}$  Stiffness coefficient matrix of the robot joints

$\Gamma$  A torque-force matrix defining in joint space (n by 1)

$\tau$  Joint torque-force of a joint, a component in $\Gamma$

$\dot{q}$  A joint velocity matrix (n by 1)

$\ddot{q}$  A joint acceleration matrix (n by 1)

$H$  A force transformation matrix

$h$  Component of the force transformation matrix, $H$

$M$  A rotation skew-symmetric matrix

$L$  Configuration matrix of a joint

$l_{r,x}, l_{r,y}, l_{r,z}$  Rotational components of the configuration matrix of a joint

$l_{t,x}, l_{t,y}, l_{t,z}$  Translational components of the configuration matrix of a joint

$\mathcal{H}$  A probabilistic force transformation matrix

$\mathcal{M}$  A probabilistic rotation skew-symmetric matrix

$\hat{h}$  Component of the probabilistic force transformation matrix, $H$

$S$  A skew-symmetric matrix (3 by 3)

$F$  A 6DOF spatial force acting on the multi-link serial manipulator

$f$  The positional component of the spatial force

$\omega$  The rotational component of the spatial force
Nomenclature

\( \mathcal{F} \) A 6DOF spatial force acting on the probabilistic multi-link serial manipulator

\( f \) The positional component of the probabilistic spatial force

\( w \) The rotational component of the probabilistic spatial force

\( P_{\text{att}} \) The point the attractive force is applied

\( K_{\text{att}} \) Coefficient of an attractive force amplitude

\( K_{s} \) A constant for defining a transient state of the attractive force

\( K_{\text{zero}} \) A small non-zero positive constant

\( K_{P} \) Ellipsoid coverage constant

\( K_{f} \) Coefficient of a repulsive force amplitude

\( K_{de} \) The environmental repulsive force distance factor

\( K_{ds} \) The self repulsive force distance factor

\( d_{0} \) Distance between the closest points between two links

\( E_{r} \) Force field error factor

\( \hat{D} \) The variance force field

\( \hat{D}_{\text{min}} \) The minimum force field

\( \hat{D}_{\text{min}V} \) The minimum variance force field

\( \hat{D}_{\text{max}V} \) The maximum variance force field

\( R_{ff} \) A rotation matrix for a force field (3 by 3)

\( r \) A matrix describing the radius of a force field (3 by 1)

\( c \) A matrix describing the centre of a force field (3 by 1)

\( \xi_{\text{min}}, \xi_{\text{max}} \) The minimum and maximum variance factors

\( V \) A matrix of a component’s vertices

\( \sigma_{V} \) A matrix of the variance of a component’s vertices

\( P_{\sigma_{V}} \) A matrix of points representing the variance of a component’s vertices

\( \hat{V} \) A component’s vertices relative to a unit sphere

\( \psi_{\hat{D}} \) A matrix used to create a unit sphere

\( \xi_{\text{dist}} \) Furthest distance to a vertex within the unit sphere

\( r_{\text{min}} \) The radius of the minimum force field
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{minV}$</td>
<td>The radius of the minimum variance force field</td>
</tr>
<tr>
<td>$r_{maxV}$</td>
<td>The radius of the maximum variance force field</td>
</tr>
<tr>
<td>$P_{obs}$</td>
<td>The environment voxels</td>
</tr>
<tr>
<td>$\hat{P}_{obs}$</td>
<td>The environmental voxels transformed relative to a unit sphere</td>
</tr>
<tr>
<td>$\hat{P}_{dist}$</td>
<td>The distance from the origin of the unit sphere to the transformed environmental voxels</td>
</tr>
<tr>
<td>$\hat{r}_l$</td>
<td>The radius of the maximum variance unit sphere</td>
</tr>
<tr>
<td>$d_{cls}$</td>
<td>The distance penetrated into a force field</td>
</tr>
<tr>
<td>$k_{sample}$</td>
<td>Local minima detection sample period</td>
</tr>
<tr>
<td>$k_q$</td>
<td>Insignificant motion detection threshold</td>
</tr>
<tr>
<td>$\dot{k}_q$</td>
<td>Insignificant velocity detection threshold</td>
</tr>
<tr>
<td>$k_{q,set}$</td>
<td>Repeated motion threshold</td>
</tr>
<tr>
<td>$N_0$</td>
<td>The start node</td>
</tr>
<tr>
<td>$N_g$</td>
<td>The goal node</td>
</tr>
<tr>
<td>$N, N_{CR}$</td>
<td>An intermediate node and a common region centre</td>
</tr>
<tr>
<td>$u$</td>
<td>Current nodes index</td>
</tr>
<tr>
<td>$v$</td>
<td>Parent node index</td>
</tr>
<tr>
<td>$P_{mid}$</td>
<td>A discontinuous minpoint</td>
</tr>
<tr>
<td>$P_{min}, P_{max}$</td>
<td>The end point of the shorter and longer discontinuous pair</td>
</tr>
<tr>
<td>$l_{min}, l_{max}$</td>
<td>The shorter and longer lengths of a discontinuous pair</td>
</tr>
<tr>
<td>$\theta_{min}$</td>
<td>The minimum angle</td>
</tr>
<tr>
<td>$Z_{off}$</td>
<td>Number of rays in the minimum angle</td>
</tr>
<tr>
<td>$\theta_{res}$</td>
<td>The angle between rays</td>
</tr>
<tr>
<td>$c$</td>
<td>The radius of a robot’s workspace</td>
</tr>
<tr>
<td>$L$</td>
<td>A matrix of ray distances</td>
</tr>
<tr>
<td>$\delta$</td>
<td>A ray’s offset angle</td>
</tr>
<tr>
<td>$\theta$</td>
<td>A matrix of angles between the each ray and the offset ray</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$m$</td>
<td>Weighting criteria set</td>
</tr>
<tr>
<td>$d_m$</td>
<td>The distance for a weighting criteria set</td>
</tr>
<tr>
<td>$K_m$</td>
<td>Normalised distance for a weighting criteria set</td>
</tr>
<tr>
<td>$\alpha_m$</td>
<td>The weighting factor for a weighting criteria set</td>
</tr>
<tr>
<td>$w$</td>
<td>The final weight for an intermediate node or common region centre</td>
</tr>
</tbody>
</table>
## Glossary of Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>The foot pad of the robot that is currently fixed to the surface.</td>
</tr>
<tr>
<td>Common Region</td>
<td>Where visible regions of the end node and an intermediate node overlap. Termination criteria.</td>
</tr>
<tr>
<td>Common Region Centre</td>
<td>The midpoint of the common region.</td>
</tr>
<tr>
<td>End Node</td>
<td>Ending position of the inchworm robot end-effector.</td>
</tr>
<tr>
<td>Environment</td>
<td>A 3D structure in which a manipulator is positioned. Assumed to have some structural characteristics such as planar surfaces.</td>
</tr>
<tr>
<td>Ferromagnetic</td>
<td>Made of metals to which magnets are attracted.</td>
</tr>
<tr>
<td>Hand position uncertainty</td>
<td>The deviation in the end-effector position when attaching to the surface caused by the magnetic force.</td>
</tr>
<tr>
<td>Hybrid Planner</td>
<td>Path planner which comprises of two or more individual path planners working in tandem.</td>
</tr>
<tr>
<td>Inchworm Robot</td>
<td>A 7DOF serial robot which uses magnets to adhere to ferromagnetic surfaces.</td>
</tr>
<tr>
<td>Intermediate Nodes</td>
<td>Points within Cartesian space which serve as subgoals with the LoST algorithm.</td>
</tr>
<tr>
<td>Line of sight</td>
<td>The visibility of the surroundings from a point which is not impeded by obstacles.</td>
</tr>
<tr>
<td>Maximum index level</td>
<td>Maximum number of iterations down a single branch of the line of sight tree the line of sight algorithm searches.</td>
</tr>
</tbody>
</table>
Multi-link serial robot  A series of actuated joints and connected links describing a robot from a base to an end-effector.

Node  Possible robot position in Cartesian space.

Obstacle  An object which a manipulator can potentially collide with.

Planning  The act of generating a path (and motion) which the robot can then follow between two poses.

Pose  The joint configuration of a robot.

Ray Casting  Process which uses rays to determine intersection points with obstacles.

Start Node  The start position of the inchworm robot end-effector.

Start Pose  The start pose of the inchworm robot.

Structural uncertainty  The deformation caused by gravitational loads on the inchworm robot.

Surface Normal  A 3D vector perpendicular to a surface.

Visible Region  Area surrounding a node which is visible and determined through line of sight.

Voxel  Volumetric Pixel which represents a 3D cube-like volume in Cartesian space.

Waypoint  Either a common region centre or intermediate node used as a goal for the 3D-PF\(^2\) algorithm to manoeuvre to.