

Tactile Based Active Perception of Structural Members in Truss Structures

by **Lili Bykerk**

Thesis submitted in fulfilment of the requirements for
the degree of

Doctor of Philosophy

under the supervision of Distinguished Professor Dikai Liu
and Professor Kenneth Waldron

University of Technology Sydney
Faculty of Engineering and Information Technology

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Certificate of Original Authorship

I, Lili Bykerk, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy in the School of Mechanical and Mechatronic Engineering, Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

Abstract

Complex Three-Dimensional (3D) truss structures such as power transmission towers require regular inspection and maintenance during their service life. Developing a robot to climb and explore such complex structures is challenging. Changing lighting conditions can render vision sensors unreliable; therefore, the robot should be endowed with a complementary sensory modality such as touch for accurate perception of the environment, including recognising a structural beam member and its properties of cross-sectional shape, size and the grasping Angle-of-Approach (AoA).

The research presented in this thesis addresses three questions related to grasping and touch based perception of beam members in truss structures. (1) Methods for designing adaptive grippers for grasping a wide variety of structural beam member cross-sectional shapes and sizes; (2) Sensing for data collection and methods for classifying beam member properties; and (3) Efficient methods for selecting the next best grasping action to confidently recognise a beam member.

A stiffness constrained topology optimisation design method is developed and applied in designing a soft gripper for grasping a variety of cross-sectional shapes of beam members. The gripper design is verified through both simulation and experiments. It is found that the gripper is proficient in grasping different shapes and sizes of beam members, with adequate contact points.

A comparative study of commonly used machine learning classifiers is conducted to analyse the effectiveness of recognising a structural beam member and its properties. Using data collected during grasping with a soft gripper, the cross-sectional shape, size and grasping AoA of a beam member are classified. Evaluation of the various classifiers revealed that a Random Forest (RF) classifier with 100 trees achieved high classification accuracies, with short training and classification times.

An information-based method for selecting the next best grasping AoA to confidently recognise a beam member is developed. This method is verified through simulation using grasping data collected with a soft gripper. The results show that this method can correctly recognise a structural beam member and its properties, typically with fewer than four grasping actions. This method can be generally used with many different gripper designs and sensor arrangements.

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Contents

Declaration of Authorship	iii
Abstract	v
Acknowledgements	vii
List of Figures	xiii
List of Tables	xvii
Nomenclature	xxiii
Glossary of Terms	xxvii
1 Introduction	1
1.1 Background and Motivation	4
1.1.1 Motivating Factors	4
1.1.1.1 Scale	4
1.1.1.2 Constraints	5
1.1.1.3 Human Safety Issues	8
1.1.2 Robotic Solutions	8
1.2 Research Questions	11
1.3 Scope	12
1.4 Contributions	14
1.5 Publications	15
1.6 Thesis Outline	15
2 Review of Related Work	17
2.1 Robot Grippers	18
2.1.1 Industrial Robot Grippers	20
2.1.2 Climbing Robot Grippers	23
2.1.3 Underactuated Grippers for Manipulation of Household Objects	24
2.1.3.1 Rigid Underactuated Grippers	26
2.1.3.2 Soft Underactuated Grippers	30

2.2	Sensing Technology for Grippers	34
2.2.1	Proprioception	37
2.2.1.1	Sensing in Rigid Grippers	37
2.2.1.2	Sensing in Soft Grippers	38
2.2.2	Exteroception	41
2.2.2.1	Sensing for Rigid Grippers	42
2.2.2.2	Sensing for Soft Grippers	43
2.3	Object Identification and Recognition Using Touch Based Exploration . . .	46
2.3.1	Human Haptic Perception	47
2.3.2	Robotic Haptic Perception	49
2.3.2.1	Haptic Perception Using Rigid Grippers	50
2.3.2.2	Haptic Perception Using Soft and Hybrid Grippers	52
2.3.2.3	Selecting the Next Best Action for Object Identification and Recognition	54
2.4	Summary	56
3	Stiffness Constrained Topology Optimisation Method	61
3.1	Overview	61
3.2	Design Method	64
3.2.1	Topology Optimisation Method	65
3.2.1.1	Core Topology Optimisation Algorithm	66
3.2.1.2	Stiffness Constrained Topology Optimisation Algorithm . .	67
3.2.2	Optimal Design	69
3.3	Verification of Stiffness Constrained Topology Optimisation Method	71
3.3.1	Gripper Design	71
3.3.2	Simulations	74
3.3.2.1	Simulation 1	77
3.3.2.2	Simulation 2	77
3.3.3	Results	78
3.3.3.1	Simulation 1	78
3.3.3.2	Simulation 2	82
3.4	Verification of a Prototype Soft Gripper	83
3.4.1	Gripper Design	83
3.4.1.1	Gripper #2	83
3.4.1.2	Gripper #4	85
3.4.1.3	Gripper #5	87
3.4.1.4	Gripper #6	88
3.4.2	Simulations and Experiments	93
3.4.2.1	Simulation 1	93
3.4.2.2	Simulation 2	94
3.4.2.3	Experiment 1	94
3.4.2.4	Experiment 2	98
3.4.3	Results	98
3.4.3.1	Simulation 1	98

3.4.3.2	Simulation 2	98
3.4.3.3	Experiment 1	100
3.4.3.4	Experiment 2	102
3.5	Discussion	106
3.5.1	Verification of Stiffness Constrained Topology Optimisation Method	106
3.5.2	Verification of a Prototype Soft Gripper	109
3.5.2.1	Actuation	110
3.5.2.2	Sensing	111
4	Comparative Study of Machine Learning Classifiers for Beam Member Recognition	113
4.1	Overview	114
4.2	Classification Algorithms	115
4.2.1	k-Nearest Neighbours (k-NN)	118
4.2.2	Linear Discriminant Analysis (LDA)	119
4.2.3	Multiclass Support Vector Machine (SVM)	120
4.2.4	Naïve Bayes	122
4.2.5	Bagged Trees Ensemble (Random Forests (RFs))	124
4.3	Results	126
4.3.1	Target Beam Member Set #2: Beam Members of Unique Cross-sectional Shapes and Sizes	126
4.3.1.1	Random Forests	131
4.3.2	Target Beam Member Set #3: Beam Members of Similar Cross-sectional Shapes and Sizes	135
4.3.2.1	Random Forests	140
4.4	Discussion	142
5	An Information-Based Method for Selecting the Next Best Grasping Angle-of-Approach	147
5.1	Overview	148
5.2	Information-based Method	150
5.2.1	Classifier Training	153
5.3	Results	155
5.3.1	Beam Recognition Using a Single Haptic Glance	155
5.3.1.1	Classification with the RF Classifier Only	155
5.3.1.2	Classification with the Proposed Information-based Method	157
5.3.2	Beam Recognition using Multiple Haptic Glances	159
5.3.3	Case Studies	160
5.3.3.1	Disambiguating Between Beam Members with Differing Cross-sectional Shapes and/or Sizes	160
5.3.3.2	Disambiguating Between Multiple Angles-of-Approach (AoAs) to a Single Cross-sectional Shape and Size of Beam Member	167
5.4	Discussion	172
6	Conclusions	173

6.1	Summary of Contributions	174
6.1.1	A Stiffness Constrained Topology Optimisation Method	174
6.1.2	A Comparative Study of Machine Learning Classifiers for Beam Member Recognition	174
6.1.3	An Information-based Method for Selecting the Next Best Grasping Angle-of-Approach	175
6.2	Discussion of Limitations and Future Work	176
6.2.1	About the Stiffness Constrained Topology Optimisation Method . .	176
6.2.2	Comparative Study of Machine Learning Classifiers for Beam Mem- ber Recognition	179
6.2.3	About the Information-based Method for Selecting the Next Best Grasping Angle-of-Approach	180
Appendices		185
A Grasping Simulation Results		185
A.1	Grasping Structural Beam Members from Target Beam Member Set #1 . .	186
A.1.1	Gripper #1	186
A.1.2	Gripper #2	187
A.1.3	Gripper #3	189
A.1.4	Grasping 250% Scaled Structural Beam Members from Target Beam Member Set #1	190
A.1.4.1	Gripper #6	190
B Classifier Comparison: Results		191
B.1	Target Beam Member Set # 2	192
B.2	Target Beam Member Set # 3	193
Bibliography		195

List of Figures

1.1	Maintenance workers on power transmission towers.	7
1.2	Transmission tower failures in South Australia during storms in 2016.	7
2.1	Bones and joints of the human hand and the Extensor Digitorum Communis.	18
2.2	Young’s modulus for various materials.	19
2.3	Shore Hardness Scale.	20
2.4	The position of soft and rigid manipulators in the 2D design space.	21
2.5	Various industrial robot grippers.	22
2.6	Operational procedure of a granular jamming gripper.	22
2.7	Various parallel climbing robot grippers.	25
2.8	Robot mechanism types and their motions.	26
2.9	Mechanism of the soft gripper designed by Shigeo Hirose.	27
2.10	Various underactuated gripper designs.	28
2.11	The Flexirigid gripper.	28
2.12	Various soft gripper designs.	32
2.13	Design of a soft sensor composed of three sensor layers with embedded microchannels.	40
2.14	Tactile sensors from MEMS barometers: rubber casting process.	45
2.15	BioTac sensor schematic.	45
2.16	TacTip sensor design.	46
3.1	Power transmission tower examples.	62
3.2	Target beam member sets.	63
3.3	3D design domain for soft gripper.	72
3.4	3D gripper design domain with and without stiffness constraints.	73
3.5	Output of topology optimisation with and without stiffness constraints.	75
3.6	Three final gripper topologies.	76
3.7	Polyurethane Shore A 60 stress-strain curves.	76
3.8	Grippers #1 – #3 in two positions during an empty grasp.	79
3.9	Grippers #1 – #3 empty grasp data: output x-y displacements.	80
3.10	Grippers #1 – #3 empty grasp data: input and output forces.	80
3.11	Comparison of grippers #1 – #3 output contact forces and output displacements.	81
3.12	Gripper #2 mould assembly.	84
3.13	CAD model of gripper #2 with mounted linear actuator.	84

3.14	Prototype gripper #2 performing grasping actions.	85
3.15	CAD model comparison of gripper #2 and gripper #4.	85
3.16	Gripper #4 empty grasping results.	86
3.17	Stiffness constrained topology optimisation outputs for gripper #2 and gripper #5.	87
3.18	Gripper #6 prototype design.	90
3.19	Interlink FSR 400 Short details.	91
3.20	FSR connection and performance details.	91
3.21	Gripper #6 FSR arrangement.	92
3.22	Sensor design layout for gripper #6.	93
3.23	CAD model of data collection rig setup with gripper #6.	95
3.24	AoA definitions for target beam member set #2.	96
3.25	AoA definitions for target beam member set #3.	97
3.26	Gripper #6 empty grasp results.	99
3.27	Sum of raw analog FSR readings for each of the AoAs used for data collection for target beam member set #2.	101
3.28	Gripper pose during data collection.	102
3.29	Averaged raw FSR readings for two beam members.	103
3.30	Similar sensor readings for AoAs to multiple target beam members.	104
3.31	Sum of raw analog FSR readings for each of the AoAs used for data collection for target beam member set #3.	105
3.32	Similar sensor readings for AoAs to multiple target beam members.	107
3.33	Gripper points of contact when grasping beam members of similar cross-sectional shape at 180°.	108
3.34	Engineering issues caused by offset of the linear actuation platform.	111
4.1	Classifier training settings for the two target beam member sets.	116
4.2	Example of k-NN classification.	119
4.3	Example of LDA classification.	120
4.4	Example of Multiclass SVM classification.	122
4.5	Example of Naïve Bayes classification.	123
4.6	Example of Trees Ensemble classification.	124
4.7	Simplified representation of RF classification.	124
4.8	Target beam member set #2: comparison of commonly used classifiers evaluated against the four metrics.	127
4.9	Confusion matrix for one trained k-NN classifier for target beam member set #2.	129
4.10	Confusion matrix for one trained k-NN classifier, classifying individual beam member cross-sectional shapes and sizes, not individual AoAs from target beam member set #2.	130
4.11	Target beam member set #2: RF OOB error with increasing number of trees grown in the forest.	133
4.12	RF with 100 trees: Average importance of predictors in feature space for target beam member set #2.	134

4.13	Target beam member set #3: comparison of commonly used classifiers evaluated against the four metrics.	135
4.14	Confusion matrix for one trained k-NN classifier for target beam member set #3.	137
4.15	Confusion matrix for one trained k-NN classifier, classifying individual beam member cross-sectional shapes and sizes, not individual AoAs from target beam member set #3.	138
4.16	Target beam member set #3: RF OOB error with increasing number of trees grown in the forest.	141
4.17	RF with 100 trees: Average importance of predictors in feature space for target beam member set #3.	143
5.1	Flow chart of the information-based method.	151
5.2	Classifier training settings for the information based method.	154
5.3	Confusion matrix from the RF classifier trained with 100 trees on 90% of the complete dataset (training set) for target beam member set #3. Results shown are the classifications of the remaining 10% of the complete data including symmetrical AoAs (test set) using input data from FSRs only.	156
5.4	Confusion matrix from the RF classifier trained with 100 trees on 90% of the complete dataset (training set) for target beam member set #3. Results shown are the classifications of the remaining 10% of the reduced data not including symmetrical AoAs (test set) using input data from FSRs only.	157
5.5	Information-based method (with $\tau = 15\%$) for grasping at the initial AoA of 180° to the 50×50 "T" beam member.	162
5.6	Information vs. candidate AoA shifts for the original perceived AoA of $\pm 180^\circ$ to the 50×50 "T" shaped beam member.	165
5.7	Information-based method (with $\tau = 18\%$) for grasping at the initial AoA of 180° to the 50×50 "T" beam member.	166
5.8	Information-based method implemented with $\tau = 15\%$ for grasping at the initial AoA of -40° to the 50×50 "L" beam member.	169
5.9	Information-based method process for an initial grasping AoA of -100° to the 50×50 "L" shaped beam member.	171
6.1	An example of a multi fingered hand design domain.	178
A.1	Gripper #1 grasping each of the beam members in target beam member set #1.	186
A.2	Gripper #2 grasping each of the beam members in target beam member set #1.	187
A.3	Gripper #2 grasping "L" shaped beam member from target beam member set #1 at various AoAs and positions.	188
A.4	Gripper #3 grasping each of the beam members in target beam member set #1.	189
A.5	Gripper #6 grasping each of the scaled (250%) sizes of beam members in target beam member set #1.	190

List of Tables

1.1	Transpower NZ unpainted tower life expectancy.	5
2.1	Climbing robot grippers and their target grasping objects.	23
2.2	Various underactuated discrete mechanism gripper designs.	29
2.3	Various underactuated discrete, serpentine & continuum mechanism gripper designs.	33
2.4	Exploratory Procedures.	49
3.1	Individual gripper design domain settings summary; grippers #1 – #3. . . .	74
3.2	Input and output forces and input-to-output force ratios for grippers #1 – #3 at 85 mm linear input displacement.	81
3.3	Individual gripper design domain settings summary; grippers #2 and #5. . .	87
3.4	Target beam member sets and their structural beam member shapes, sizes and AoAs for data collection.	94
4.1	Data set descriptions for target beam member sets #2 and #3.	117
4.2	Target beam member set #2 classification accuracy and OOB error for between 10 and 100 trees grown in the RF using the FSR only data set. . .	132
4.3	Target beam member set #3 classification accuracy and OOB error for between 10 and 100 trees grown in the RF using the FSR only data set. . .	142
5.1	Averaged RF results over 1000 classifier training rounds for the information-based method—grasping AoAs for target beam member set #3.	157
5.2	Results of beam member recognition using the information-based method across the 324 unique AoAs with varying threshold values.	159
5.3	Information-based method calculation process, for an initial haptic glance performed at -40° to the 50×50 “L” beam.	168
B.1	Commonly used classifier results—grasping AoAs for target beam member set #2, not including repeated AoAs from symmetrical beam members. . .	192
B.2	RF results—grasping AoAs for target beam member set #2, not including repeated AoAs from symmetrical beam members.	192
B.3	Commonly used classifier results—grasping AoAs for target beam member set #2, including repeated AoAs from symmetrical beam members.	192
B.4	RF results—grasping AoAs for target beam member set #2, including repeated AoAs from symmetrical beam members.	192

B.5	Commonly used classifier results—grasping AoAs for target beam member set #3, not including repeated AoAs from symmetrical beam members.	193
B.6	RF results—grasping AoAs for target beam member set #3, not including repeated AoAs from symmetrical beam members.	193
B.7	Commonly used classifier results—grasping AoAs for target beam member set #3, including repeated AoAs from symmetrical beam members.	193
B.8	RF results—grasping AoAs for target beam member set #3, including repeated AoAs from symmetrical beam members.	193

Acronyms & Abbreviations

2D	Two-Dimensional
3D	Three-Dimensional
ANN	Artificial Neural Network
AoA	Angle-of-Approach
AoAs	Angles-of-Approach
BN	Bayesian Network
CAS	Centre for Autonomous Systems
CAD	Computer Aided Design
CC	Constant Curvature
CCD	Charge-Coupled Device
CCW	Counterclockwise
COTS	Commercially Available Off-The-Shelf
CO₂	Carbon Dioxide
CPR	Cardiopulmonary Resuscitation
CW	Clockwise
DES	Dielectric Elastomer Sensor
DOF	Degrees Of Freedom

ECOC	Error-Correcting Output Codes
EGaIn	Eutectic Gallium-Indium
EP	Exploratory Procedure
e-3DP	Embedded 3D Printing
FEA	Finite Element Analysis
FSR	Force Sensitive Resistor
KLD	Kullback Leibler Divergence
k-NN	k-Nearest Neighbours
LDA	Linear Discriminant Analysis
LVDT	Linear Variable Differential Transformer
MEMS	Microelectromechanical Systems
NZ	New Zealand
OC	Optimality Criteria
OOB	Out-of-bag
PAM	Pneumatic Artificial Muscle
PCC	Piecewise Constant Curvature
PDMS	Polydimethylsiloxane
PPE	Personal Protective Equipment
PCB	Printed Circuit Board
RF	Random Forest
RVDT	Rotational Variable Differential Transformer
SA	South Australia

SIMP Solid Isotropic Material with Penalisation

SVM Support Vector Machine

TEPCO Tokyo Electric Power Company

ToMBot Tower Maintenance Robot

UK United Kingdom

USA United States of America

UTS University of Technology Sydney

WHS Workplace Health and Safety

Nomenclature

General Notations

$[\dots]^T$	Transpose
$f(\dots)$	A scalar valued function
$\mathbf{f}(\dots)$	A vector valued function
$\max(\dots)$	Maximum value

Stiffness Constrained Topology Optimisation Method

$\tilde{\mathbf{x}}_{\text{stiffer}}$	The density of elements in the regions of the design domain to stiffen
$\tilde{\mathbf{x}}_{\text{rest}}$	The density of elements in the remainder of the design domain
α	A user defined stiffness multiplier
N_i	The neighbourhood of an element
x_i	An element in the design domain
x_e	The design variable
v_i	Volume of an element in the design domain
\bar{v}	The prescribed volume limit of the design domain
H_{ij}	A weight factor
\mathbf{L}	A unit length vector with all zeros at all degrees of freedom except at the output point where it is one
n	The number of elements used to discretise the design domain
\mathbf{F}	A vector of nodal forces
$\mathbf{U}(\tilde{\mathbf{x}})$	A vector of nodal displacements
$\mathbf{K}(\tilde{\mathbf{x}})$	Global stiffness matrix

Information-based Method

Bm	Number of beam members
N_{AoA}	Number of Angles-of-Approach (AoAs)
N_{ba}	Number of beam-angle pairs
N_g	Number of grasps performed for data collection
N_{grasps}	Number of grasps executed for beam member identification
β	Angle shift increments
F	Force Sensitive Resistor (FSR) data
I_a	Information for a candidate Angle-of-Approach (AoA)
N_{FSR}	Number of individual FSR sensors
N_{enc}	Number of encoder readings
n	Number of predicted beam member AoAs after a haptic glance
μ_i	Average of FSR data for a given sensor number and AoA
σ_i^2	Variance of FSR data for a given sensor number and AoA
τ	Threshold value above which to count the Random Forest (RF) classifier votes as valid

Glossary of Terms

Autonomous	Without human intervention.
Compliance Match	The principle that contacting materials should share similar mechanical rigidity in order to evenly distribute internal load and minimise interfacial stress concentrations.
Effector	An organ or cell that acts in response to a stimulus.
Extensor Digitorum Communis	A muscle of the posterior forearm present in humans and other animals. It extends the medial four digits of the hand.
Exteroception	By which one perceives the outside world.
Haptic Glance	A brief, spatially constrained contact that involves little or no movement of the fingers.
Haptic Perception	The ability to identify something by active exploration of surfaces by a moving subject.
Interphalangeal Joint	Hinge joints between the phalanges of the fingers that provide flexion towards the palm of the hand.
Metacarpophalangeal Joint	Hinge joints between the metacarpal bones and the proximal phalanges of the digits.
Modulus of Elasticity	A quantity that measures an object or substance's resistance to being deformed elastically when a stress is applied to it.

Papillae	A small rounded protuberance on a part or organ of the body. Associated with nerve endings, they are able to relay sensory information.
Phalanges	Finger or toe bones.
Proprioception	The ability to sense the position, location, orientation and movement of the body and its parts.
Tactile Pattern	A distribution of tactile sensor readings collected during grasping.