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.

This document has not been submitted for qualifications at any other academic institution.

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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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To my dear cousin Amy, I miss you immensely.

Contents

List of Figures

List of Tables

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

CO_2 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
$[\cdots]^T$	Transpose
$f(\cdots)$	A scalar valued function
$\mathbf{f}(\cdots)$	A vector valued function
$max(\cdots)$	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.