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Vector Distance Transform Maps for Autonomous Mobile Robot Navigation

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Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of
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August 2020

Certificate of Original Authorship

I, Janindu Sithumini Arukgoda declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the 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.

This research is supported by the Australian Government Research Training Program.

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Date: 06 - 08 - 2020

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Abstract

Robot localization, where the position and the orientation of a mobile robot is estimated based on an *a priori* map, is a fundamental problem in autonomous mobile robot navigation. In this thesis, we present how environments can be represented using the vector distance transform for mobile robot localization, and show that it is a superior representation compared to alternatives such as occupancy grid maps and other distance transform variants such as the unsigned distance transform and the signed distance transform.

We propose an approach based on non-linear least squares optimization for robot localization on environments represented by vector distance transform maps, that also captures the uncertainty of the position estimate. We also propose an approach based on extended Kalman filter for robot localization on environments represented by vector distance transform maps. Using simulations, public domain data and real world experiments, the proposed localization approaches are evaluated and compared with existing localization techniques in multiple robot platforms including both ground and aerial robots navigating in 2D and 3D environments using a series of sensors including LiDARs and cameras.

We propose an information filtering based approach for mobile robot localization where a single endpoint range sensor can be used to accurately localize a mobile robot in motion by rotating it in a direction that will improve its position estimate and the corresponding uncertainty. The proposed approach is evaluated using simulations and real world experiments.

Occupancy grid maps, the most popular type of map for robot localization using a range-bearing sensor, are assumed perfect when used for localization. It is a discrete representation of the environment and the probability of occupancy of each cell is independent from its neighbors. Given a set of robot poses and corresponding range-bearing measurements, both incorporated with uncertainty, a representation of environment based on the vector distance transform using non-linear least squares optimization that is both continuous and uncertain is proposed for robot localization. Simulations are used to demonstrate the accuracy of the map and its uncertainties.

Acknowledgements

I would like to thank those who have helped me accomplish this work.

First and foremost, I would like to express my gratitude towards my supervisors, Professor Gamini Dissanayake and Dr. Ravindra Ranasinghe for taking me in as a doctoral student and for guiding me through every step of the way. None of this work would have been possible without your advice, support and guidance.

I would like to thank Professor Tomonari Furukawa, for giving me the opportunity be a part of Team VICTOR that took part in the MBZIRC 2017 competition and for his insight into approaching research problems.

I appreciate the advice and support I received to formulate my research problems and to conduct experiments from Dr. Lakshitha Dantanarayana, Mr. Asok Perera, Mr. James Unicombe, Mr. Maleen Jayasuriya, Dr. Buddhi Wijerathna, and Mr. Nathanael Gandhi. I am thankful for the staff and the students at the Centre for Autonomous Systems at University of Technology Sydney. I have learnt a lot from their knowledge sharing sessions, talks, seminars, and presentations and it has been a privilege to be a part of such a collective.

I would like to thank the members of Team VICTOR for making the time I spent at the Computational Multiphysics Systems Lab at Virginia Tech memorable.

Dr. Chinthana Wimalasuriya, my supervisor at University of Moratuwa, knowingly or unknowingly inspired me to pursue a career in research, and for that, I am grateful to him.

Finally, I am forever indebted to my parents and my wife for supporting me through the years so that I can focus on my work without having to worry about mundane daily tasks. This thesis is dedicated to them.

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Acronyms & Abbreviations

1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
AMCL	Adaptive Monte Carlo Localization
AML	Active Markov Localization
CAS	Centre for Autonomous Systems
EKF	Extended Kalman Filter
GPs	Gaussian Processes
GPS	Global Positioning System
IMU	Inertial Measurement Unit
LRF	Laser Range Finder
NDT	Normal Distribution Transform
OGM	Occupancy Grid Map
PDE	Partial Differential Equation
RTK-GPS	Real-Time Kinematics GPS
SDF	Signed Distance Function
SDT	Signed Distance Transform

SLAM	Simultaneous Localization and Mapping
UAV	unmanned aerial vehicle
UDF	Unsigned Distance Function
UDT	Unsigned Distance Transform
UTS	University of Technology Sydney
UWB	Ultra-wideband
VCD	Vector Chamfer Distance
VDF	Vector Distance Function
VDT	Vector Distance Transform

Nomenclature

	General Notations
t	Time (continuous)
k	Time (discrete step)
DT_u	Unsigned Distance Transform
DT_s	Signed Distance Transform
DT_v	Vector Distance Transform
DT_x	x component of the Vector Distance Transform
DT_y	y component of the Vector Distance Transform
DT_z	z component of the Vector Distance Transform
d_{VCD}	Vector Chamfer Distance
d_{VDT}	Disparity vector between the observation and the Vector Distance Transform
r_i	i^{th} range measurement
σ_r	Standard deviation of range measurement noise
θ_i	i^{th} bearing measurement
Z	Space of all possible observations
z_i	i^{th} observation, $z_i \in Z$
X_o	Observation vector
J	Jacobian matrix
H	Hessian matrix

$\boldsymbol{X_R}$	Robot pose
$\hat{\boldsymbol{X}}_{\boldsymbol{R}}$	Robot pose estimate
P	Robot pose covariance matrix
$g(\cdot,\cdot)$	Motion model
$h(\cdot,\cdot)$	Observation model
$\nabla G_{\square}$	Jacobian of the motion model with respect to $\square$
$\nabla H_{\square}$	Jacobian of the observation model with respect to $\square$
υ	Linear velocity
ω	Angular velocity
ν	Innovation vector
K	Kalman Gain
$\square_{k-1}$	Previous state
$\square_{k\|k-1}$	Predicted current state
$\square_{k}$	Updated current state
$cov(\cdot)$	Covariance matrix
$diag(\cdot)$	Diagonal matrix
$trace(\cdot)$	Trace of a matrix
$\Sigma(\cdot)$	Summation
$\int$	Integral operator
∂	Partial differentiation operator