Stable Path Planning for Reconfigurable Robots Over Uneven Terrains

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Declaration

I, **Mohammad Norouzi**, certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Abstract

Autonomous mobile robots are required to find safe and feasible routes in the environment when operating over challenging terrains. The most influential tip-over stability measures are based on two criteria; the robot's centre of mass (CM) and the support polygon defined by the convex area spanned between the ground contact points. The force angle (FA) stability margin is employed in this work given its widespread use and simple geometric interpretation.

A method to compute the contact points between a tracked robot and rugged terrain and predict robot's stability axes on 3D meshed maps reconstructed from 3D point clouds using the open dynamics engine (ODE) is presented. The validity and the need for stability computations based on the proposed contact points prediction algorithm is established through experiments over two common indoor obstacles i.e. ramps and stairs.

An analytical strategy to generate stable paths for reconfigurable robots whilst also meeting additional navigational objectives is hereby proposed. The suggested solution looks at minimizing the length of the traversed path and the energy expenditure in changing postures, and also accounts for additional constraints in terms of sensor visibility and traction.

A statistical analysis of stability prediction to account for the uncertainties associated with the actual robot's dynamic model, its localisation in the ground, and the terrain models is introduced. Probability density function (PDF) of contact points, CM and the FA stability measure are numerically estimated, with simulation results performed on the ODE simulator based on uncertain parameters. Two techniques are presented: a conventional standard Monte Carlo (SMC) scheme, and a structured unscented transform (UT) which results in significant improvement in computational efficiency.

A novel probabilistic stability criterion derived from the cumulative distribution of the FA margin is introduced that allows a safety constraint to be dynamically updated by available sensor data as it becomes available. The advantages of planning with probabilistic stability is demonstrated using a grid based A* algorithm as well as a sampling based RRT planner. The validity of the proposed approach is evaluated with a multi-tracked robot fitted with a manipulator arm and a range camera using two challenging 3D terrains data sets: one obtained whilst operating the robot in a mock-up urban search and rescue arena, and a second one from a publicly available on-line data from a quasi-outdoor rover testing facility.

This thesis is dedicated to my wife; *Minoo* for her love, patience, understanding, support and encouragement to finish this dissertation.

To *Aileen*, who
I adore her smile,
I cherish her hugs,
I admire her heart,
but most of all ...
I love that she is **my daughter.**

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LIST OF ABBREVIATIONS & SYMBOLS

List of Abbreviations & Symbols

α	Heuristic factor for A* algorithm
βnom_i	The nominal β for the given ith tip-over axis $\mathbf{a_i}$
β	The normalised value of the force angle stability measure
β_μ	Mean of β
β_σ	Variance of β
β_{min}	The minimum stability margin
γ	Weighting factor for stability/reconfiguration or distance
$\mathbf{a_i}$	The ith tip-over axis
$\mathbf{f_i}$	The component of effective net force $\mathbf{f_r}$ which acts about the tip-over axis $\mathbf{a_i}$
$\mathbf{f_r}$	The effective net force
$\mathbf{l_i}$	The tip-over axis normal
$\phi_a nom$	Nominal arm angle
ϕ_a	Robot's arm angle
$\phi_f nom$	Nominal flippers angle
ϕ_f	Robot's flippers angle
$\mathcal{T}$	RRT tree
θ_i	The angle between $\mathbf{f_i}$ and the tip-over axis normal $\mathbf{l_i}$

LIST OF ABBREVIATIONS & SYMBOLS

L_a	Length of arm
L_f	Average length of flippers's CM
m_b	Total mass of robot's main body
m_f	Flippers's mass
m_h	Sensor head's mass
m_{tot}	Total mass of robot
n	Number of out-most contact points
nrj	Number of the robot's joints
nwp	Number of way-points in the trajectory
SC_{min}	Minimum safety confidence
U_c	The reconfiguration cost
Ud	Accumulated grid distance cost
Ue_i	The energy consumption cost
Up_i	The desired position cost
Us	Normalised stability cost
$\mathbf{g}$	**g**ravitational acceleration
$\mathbf{P}$	candidate points
$\mathbf{TP}$	touched points
ASP	**A**ltered **S**upporting **P**olygon
CAS	**C**entre for **A**utonomous **S**ystems
CDF	**C**umulative **D**istribution **F**unction
CM	**C**entre of **M**ass

DEM	**D**igital **E**levation **M**ap
DS	**D**iagonal **S**tep-field
ERC	**E**nergy **R**econfiguration **C**
ESM	**E**nergy **S**tability **M**argins
FA	**F**orce **A**ngle stability measure
HS	**H**ill **S**tep-field
IMU	**I**nertial **M**easurement **U**nits
INS	**I**nertial **N**avigation **S**ystem
ISP	**I**deal **S**upport **P**olygon
ITM	**I**rregular **T**riangulation **M**eshes
LQG-MP	**L**inear-**Q**uadratic **G**aussian **M**otion **P**lanning
LRF	**L**aser **R**ange **F**inders
MHS	**M**oment **H**eight **S**tability measure
ODE	**O**pen **D**ynamics **E**ngine
OSHV	**O**ptimum **S**table **H**igh **V**isibility
PDF	**P**robability **D**ensity **F**unction
PRM	**P**robabilistic **R**oad**M**ap
ROS	**R**obot **O**perating **S**ystem
RRT	**R**apidly exploring **R**andom **T**ree
SC	**S**afety **C**onfidence
SMC	**S**tandard **M**onte **C**arlo
SRM	**S**tochastic **R**esponse **S**urface **M**ethod

LIST OF ABBREVIATIONS & SYMBOLS

SRR	**S**ample **R**eturn **R**over
SSM	**S**tatic **S**tability **M**argin
USAR	**U**rban **S**earch **A**nd **R**escue
UT	**U**nscented **T**ransform
UTIAS	**U**niversity of **T**oronto **I**nstitute for **A**erospace **S**tudies
UTS	**U**niversity of **T**echnology, **S**ydney
VSP	**V**ariable **S**upport **P**olygon
ZMP	**Z**ero **M**oment **P**oint