ROBUST REGION REACHING AND TRACKING CONTROL OF AN AUTONOMOUS UNDERWATER VEHICLE

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by

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To my parents

Certificate

This is to certify that the thesis titled **"Robust Region Reaching and Tracking Control of an Autonomous Underwater Vehicle"** submitted by **Koena Mukherjee** to the **Indian Institute of Technology Delhi**, for the award of the degree of **Doctor of Philosophy** in Electrical Engineering, is a record of the original, bonafide research work carried out by her under our supervision. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

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Abstract

The vast expanse of ocean on earth has permeated interest in researchers to develop autonomous underwater vehicle (AUV) as a tool to study and utilize marine life more appropriately. An underwater vehicle provides a way for interaction and possible manipulation in hazardous and uncertain ocean environment. The focus of this dissertation is to design robust controllers for an AUV, which can navigate in presence of obstacles, input time delay, parametric uncertainty, environmental disturbances, etc.

Presently, most research work focuses on set point regulation and tracking of an AUV based on different mission scenario. This research work utilizes potential field based method to develop a new region reaching/tracking based controller with application to an AUV. Assuming position measurement is available to the controller, an auxiliary velocity signal is generated to eliminate the requirement of velocity measurement. Further, the region reaching based controller design is modified appropriately to avoid static obstacles.

A region tracking controller is developed for an AUV with application to pipeline inspection like scenario. In addition, uncertain restoring forces are estimated using adaptive law and compensated in the closed loop dynamics. To facilitate the design of this controller and analysis, a high pass filter is introduced which obviates the use of velocity sensor.

Leveraging the result obtained during region tracking controller design, a robust controller is designed for an AUV with constant input delay. A rigorous stability analysis using Lyapunov-Krasovskii functional is performed to prove Uniformly Ultimately Bounded (UUB) stability of the closed loop system.

Since environmental disturbances such as waves, currents generally affect an AUV

operation, a nonlinear disturbance observer (DO) structure is proposed to estimate the disturbance. An exo-system is used to generate the disturbance with unknown amplitude and phase. The observer estimates the state of the exo-system and the disturbance is canceled out in the composite closed loop dynamics. Extending the previous results obtained for DO, a new DO is presented to estimate periodic disturbances with unknown amplitude, phase and frequency. The unknown frequency is estimated using adaptive control technique and bounds of the unknown quantities are used to achieve asymptotic stability of the composite closed loop dynamics.

Lyapunov based stability analyses and simulations are provided to demonstrate the performance of each of the controller and observer designed throughout the dissertation.

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Abbreviations and Nomenclature

Abbreviation/Symbol	Description
AUV	Autonomous Underwater Vehicle
ROV	Remotely Operated Vehicle
DOF	Degrees of Freedom
UUB	Uniformly Ultimately Bounded
UVMS	Underwater Vehicle Manipulator Systems
DO	Disturbance Observer
LIP	Linear-In-Parameter
APF	Artificial Potential Field
$\eta_1 = [x, y, z]^T$	Cartesian position coordinate
$\eta_2 = [\phi, \theta, \psi]^T$	Orientation in Euler angle notation
$\epsilon = [\epsilon_0, \epsilon_1, \epsilon_2, \epsilon_3]^T$	Quaternion
$\eta = [\eta_1^T, \eta_2^T]^T$	Pose Vector
η^T	Transpose of a vector
R	Rotation matrix
x_d, y_d, z_d	Desired Cartesian position coordinate
ϕ_d, θ_d, ψ_d	Desired orientation in Euler angle notation
$e_x = x - x_d$	x-position error
$e_1 = [e_x, e_y, e_z]^T$	Positional error
$e_2 = [e_\phi, e_\theta, e_\psi]^T$	Orientation error
$e = [e_1^T, e_2^T]^T$	Pose error
e_R	Region tracking error
Ra	Attractive region
Rr	Repulsive region
τ_c	Controller input
τ_d	Delay in input
d	Disturbance
M	Mass matrix
C	Coriolis and Centrifugal matrix
D	Damping matrix
$g(\eta)$	Gravitational force matrix
V	Lyapunov function
I_n	Identity Matrix of dimension $n \times n$
$\mathscr{L}_\infty$	∞-norm
$\mathscr{L}_2$	2-norm
$Tanh(X)$	$[\tanh(x_1), .. \tanh(x_n)]^T$
$Cosh(X)$	$[cosh(x_1), ..cosh(x_n)]^T$
$L_N Cosh(X)$	$[ln \cosh(x_1), ..ln \cosh(x_n)]^T$
$\lambda_{min}\{P\}/\lambda_{max}\{P\}$	Minimum/Maximum Eigenvalue of matrix P