Control of Manipulators on Moving Platforms Under Disturbance

by

Jon Woolfrey

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

at the
Centre for Autonomous Systems
Faculty of Engineering and Information Technology
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Certificate of Original Authorship

I, Jonathan Woolfrey, 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 reference 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

Mobile robots, such as underwater vehicles, drones, and rovers, are now being combined with manipulators to perform a variety of work in the field. But current state of the art in control assumes that disturbances from the environment are minimal. However, the effects of wind, waves, and rough terrain may make it difficult for the vehicle to maintain a steady base for the manipulator. Or, in some cases, the vehicle may lack the control authority to negate disturbances in all directions. In this thesis, predictions of the base motion are used to formulate control strategies that enable a manipulator to proactively counter, and even make use of, these disturbances.

Time series and Fourier series are commonly applied to many predictive control methods in literature. However, there are contradictory results in performance for different applications. To clarify these discrepancies, an objective comparison in prediction performance is made between time series, Fourier series, and Gaussian Process Regression (GPR) using motion data from underwater robots in waves. Analysis of the forecast errors and uncertainties show that GPR can produce better short-term. Furthermore, time series was found to be overconfident in the prediction, whereas Fourier series had the largest uncertainty.

A predictive control method is then presented that enables a manipulator on a free-moving platform to maintain a steady end-effector pose. By using forecasts of the base motion, the manipulator can anticipate and negate this disturbance. Simulations and experiments are conducted, and it is shown that the proposed predictive control can reduce tracking error by 60% compared to a PID feedback controller. Moreover, kinematic constraints can be satisfied whilst simultaneously minimizing task error.

A control strategy is also developed that allows a redundant manipulator to use the inertial forces produced by base disturbance to reduce joint torque. Further improvements are made by predicting changes in gravitational acceleration with respect to the manipulator. It is shown that joint torques can be reduced by 25% compared to a local minimization of the weighted torque norm.

Lastly, a torque minimization method is presented for redundant manipulators handling large external forces. Most literature only addresses the internal dynamics. This thesis presents a method to minimize torque from both an external loading and the internal dynamics. This method can be applied to manipulators on moving platforms, and further enhanced by incorporating the base motion predictions.

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Acronyms & Abbreviations

2D 2-Dimensional

ACFR Australian Center for Field Robotics

ADCP Acoustic Doppler Current Profiler

AGV Autonomous Ground Vehicle

AIC Akaike Information Criterion

AR Autoregression

ARMA Autoregression Moving-Average

AUV Autonomous Underwater Vehicle

BIC Bayes Information Criterion

CAS Centre for Autonomous Systems

DOF Degree(s)-of-Freedom

EJTM External Joint Torque Minimization

EKF Extended Kalman Filter

DLS Damped Least Squares

GP Gaussian Process

GPR Gaussian Process Regression

IMU Inertial Measurement Unit

KF	Kalman Filter
MA	Moving-Average
MKE	Minimum Kinetic Energy
MPC	Model Predictive Control
P	Proportional
PD	Proportional-Derivative
PEEC	Predictive End-Effector Control
PID	Proportional-Integral-Derivative
PJTM	Predictive Joint Torque Minimization
QP	Quadratic Programming
RMSE	Root Mean Squared Error
ROS	Robot Operating System
ROV	Remote Operated Vehicle
SAUVIM	Semi-Autonomous Underwater Vehicle for Intervention Missions
SPIR	Submerged Pile Inspection Robot
UAV	Unmanned Aerial Vehicle
UAVMS	Unmanned Aerial Vehicle-Manipulator System
UTS	University of Technology Sydney
UVMS	Underwater Vehicle-Manipulator System
WLN	Weighted Least Norm

Nomenclature

	General Formatting Style
$\mathrm{x} \in \mathbb{R}$	A scalar
$\mathbf{x} \in \mathbb{R}^{\mathrm{m}}$	A vector
$\hat{\mathbf{x}} \in \mathbb{R}^{\mathrm{m}}$	A unit vector
$\mathbf{X} \in \mathbb{R}^{\mathrm{m}\times\mathrm{n}}$	A matrix
	Operators
$\|\cdot\|$	Euclidean norm
$*$	Quaternion multiplication
$\mathrm{f}(\cdot) \in \mathbb{R}$	A scalar function
$\mathbf{f}(\cdot) \in \mathbb{R}^{\mathrm{m}}$	A vector function
$\mathbf{F}(\cdot) \in \mathbb{R}^{\mathrm{m}\times\mathrm{n}}$	A matrix function
$S(\cdot) \in \mathbb{R}^{\mathrm{m}\times\mathrm{m}}$	Skew-symmetric matrix operator
	Accents
$\dot{\mathrm{x}}$	First time-derivative $\mathrm{dx/dt}$
$\ddot{\mathrm{x}}$	Second time-derivative $\mathrm{d^2x/dt^2}$
$\hat{\mathrm{x}}$	State estimate of x
	Specific Symbols
$\{\mathrm{F}\}$	A frame of reference in Cartesian space
$\mathbf{J}^{\dagger} \in \mathbb{R}^{\mathrm{n}\times\mathrm{m}}$	Pseudoinverse of a non-square matrix $\mathbf{J} \in \mathbb{R}^{\mathrm{m}\times\mathrm{n}}$, where $\mathrm{m} \neq \mathrm{n}$
$\mathbf{J}^{\dagger}_{\mathrm{W}} \in \mathbb{R}^{\mathrm{n}\times\mathrm{m}}$	Weighted pseudoinverse of a non-square matrix $\mathbf{J} \in \mathbb{R}^{\mathrm{m}\times\mathrm{n}}$

$\mathbf{N}_\mathrm{W} \in \mathbb{R}^{\mathrm{n}\times\mathrm{n}}$	Weighted null space projection matrix for a redundant manipulator.
$\mathbf{p} \in \mathbb{R}^3$	A position or translation vector in Cartesian space
${}^\mathrm{A}\mathbf{p} \in \mathbb{R}^3$	A position or translation vector specified in frame $\{\mathrm{A}\}$
$\mathbf{p}_\mathrm{A}^\mathrm{B} \in \mathbb{R}^3$	A translation vector from frame $\{\mathrm{A}\}$ to frame $\{\mathrm{B}\}$, w.r.t. $\{\mathrm{A}\}$
$\mathbf{q} \in \mathbb{R}^\mathrm{n}$	Joint position vector for a manipulator
$\mathcal{Q} \in \mathbb{H}$	A quaternion
$\mathbf{R}_\mathrm{A}^\mathrm{B} \in \mathbb{SO}(3)$	A rotation matrix from frame $\{\mathrm{A}\}$ to frame $\{\mathrm{B}\}$
$\sigma_\mathrm{x}^2 \in \mathbb{R}$	Variance of a single random variable x.
$\mathbf{\Sigma}_\mathrm{x} \in \mathbb{R}^{\mathrm{n}\times\mathrm{n}}$	Variance-covariance matrix of a set of random variables $\mathbf{x} \in \mathbb{R}^\mathrm{n}$
$\mathbf{T}_\mathrm{A}^\mathrm{B} \in \mathbb{SE}(3)$	A homogeneous transformation matrix from frame $\{\mathrm{A}\}$ to frame $\{\mathrm{B}\}$
$\mathbf{w} \in \mathbb{R}^\mathrm{m}$	A wrench of forces and torques.
$\hat{\mathrm{y}}(\mathrm{t}+\mathrm{i}\mid\mathrm{t}+\mathrm{j})$	A state estimate of y at time $\mathrm{t}+\mathrm{i}$ from time $\mathrm{t}+\mathrm{j}$.

Glossary of Terms

Autonomous	Without human intervention.
Bathymetry	The measurement of depth of water in oceans, seas, or lakes.
End-effector	The extremity of a robot arm designed for interacting with the external environment.
Heave	Vertical motion (z-direction).
Manipulator	A robotic arm design to handle physical objects.
Pitch	Rotation about the y-axis.
Roll	Rotation about the x-axis .
Surge	Forward motion (x-direction).
Sway	Sideways motion (y-direction).
Yaw	Rotation about the z-axis .