Biologically Inspired Vision and Control for an Autonomous Flying Vehicle

Matthew A. Garratt

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Declaration

This thesis is an account of research undertaken between February 2000 and October 2007 at The Research School of Biological Sciences, The Australian National University, Canberra, Australia.

Except where acknowledged in the customary manner, the material presented in this thesis is, to the best of my knowledge, original and has not been submitted in whole or part for a degree in any university. The following summarises my own contributions and any contributions made by other people:

Chapter 1: This chapter is all my own work.

Chapter 2: I completed the literature review in this chapter independently.

Chapter 3: The simulation of the Eagle helicopter, including development of all the C-code was implemented by myself. Mr Bilal Ahmed, provided assistance with generating the frequency plots for roll, pitch and vertical motion using the *CIFER*® program. I conducted all of the systems identification experiments and was the pilot for all flights.

Chapter 4: I designed the avionics system architecture for the RMAX and PC104 Eagle helicopters. I selected the PC104 hardware and implemented a variant of the Linux operating system which would boot from a compact flash card on the various flight computers. Electronics design for the inertial systems and autopilots was completed at the UNSW@ADFA workshop under my direction. All of the onboard software on the Eagle and RMAX helicopters was written by myself except for the frame grabber driver and software for computing optic flow, which was provided by Dr Javaan Chahl. I wrote the real-time driver software to interface to the Yamaha Attitude Control System on the RMAX, a multi-port serial card, the NovAtel DGPS system, laser rangefinder, ultrasonic sonar, servos and bluetooth modems. I wrote all of the ground control, telemetry and command and control software. I developed the calibration software for all of the sensors including accelerometers, magnetometers and gyroscopes.

Chapter 5: I developed the beacon algorithm, sensor fusion, controller software and associated simulations. The visual tracking code for the beacon experiments was provided by Dr Chahl. I conducted the flight experiments for the beacon tracking hover and the optic flow damped hover, including operating the ground control computer, tuning control gains and piloting the helicopter in-between closed loop flights.

Chapter 6: All work involving forward flight simulations, controller designs and test flights in this chapter is my own.

Chapter 7: All work involving simulations, network designs, code, techniques and flight test presented on neural networks is my own.

Chapter 8: The designs of the EKF algorithms are all my own. All of the code, simulations, interpretation of results and conclusions presented in this chapter are my own.

Chapter 9: The conclusions and recommendations in this chapter are all my own.

Matthew A. Garratt
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Acknowledgements

I would like to thank Professor Mandyam Srinivasan for taking me on as a research engineer in 1999, which ultimately led me down the path of doing a PhD in this field.

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On a personal note, I would like to recognise the sacrifices made by my wife to get me through this project. During the busiest part of our lives, Lisa did more than her fair share of raising the kids and looking after us all while I worked on this project. I owe her much.

I would like to thank the University of New South Wales for supplying much of the equipment for this project including a differential GPS setup, a mobile field laboratory van, and for helping me to setup an autonomous systems laboratory on the UNSW@ADFA campus.

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Abstract

This thesis makes a number of new contributions to control and sensing for unmanned vehicles. I begin by developing a non-linear simulation of a small unmanned helicopter and then proceed to develop new algorithms for control and sensing using the simulation. The work is field-tested in successful flight trials of biologically inspired vision and neural network control for an unstable rotorcraft. The techniques are more robust and more easily implemented on a small flying vehicle than previously attempted methods.

Experiments from biology suggest that the sensing of image motion or *optic flow* in insects provides a means of determining the range to obstacles and terrain. This biologically inspired approach is applied to control of height in a helicopter, leading to the World's first optic flow based terrain following controller for an unmanned helicopter in forward flight. Another novel optic flow based controller is developed for the control of velocity in hover. Using the measurements of height from other sensors, optic flow is used to provide a measure of the helicopters lateral and longitudinal velocities relative to the ground plane. Feedback of these velocity measurements enables automated hover with a drift of only a few cm per second, which is sufficient to allow a helicopter to land autonomously in gusty conditions with no absolute measurement of position.

New techniques for sensor fusion using Extended Kalman Filtering are developed to estimate attitude and velocity from noisy inertial sensors and optic flow measurements. However, such control and sensor fusion techniques can be computationally intensive, rendering them difficult or impossible to implement on a small unmanned vehicle due to limitations on computing resources. Since neural networks can perform these functions with minimal computing hardware, a new technique of control using neural networks is presented. First a hybrid plant model consisting of exactly known dynamics is combined with a black-box representation of the unknown dynamics. Simulated trajectories are then calculated for the plant using an optimal controller. Finally, a neural network is trained to mimic the optimal controller. Flight test results of control of the heave dynamics of a helicopter confirm the neural network controller's ability to operate in high disturbance conditions and suggest that the neural network outperforms a PD controller. Sensor fusion and control of the lateral and longitudinal dynamics of the helicopter are also shown to be easily achieved using computationally modest neural networks.

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Abbreviations

ADC	Analog to Digital Converter
AHRS	Attitude Heading Reference System
ANN	Artificial Neural Network
ARC	Australian Research Council
CAN	Controller Area Network bus protocol
CEP	Circular Error Probability
CIFER®	**C**omprehensive **I**dentification from **F**r**E**quency **R**esponses software
CSIRO	Commonwealth Science and Industrial Research Organisation
CMU	Carnegie Mellon University
COTS	Commercially Available Off-The-Shelf
CPU	Central Processing Unit
DGPS	Differential Global Positioning System
DSTO	Defence Science and Technology Organisation
EKF	Extended Kalman Filter
ESDU	Engineering Sciences Data Unit
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
GPS	Global Positioning System
GUI	Graphical User Interface
HOTO	Hand Over Take Over
I^2A	Optic Flow Image Interpolation Algorithm
I2C	**I**nter **I**ntegrated **C**ircuit Serial Computer Bus
I^3A	Optic Flow Iterative Image Interpolation Algorithm
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LM	Levenberg-Marquardt
LQG	Linear Quadratic Gaussian
LQR	Linear Quadratic Regulator
LRF	Laser Rangefinder
LSB	Least Significant Byte
MAV	Micro Air Vehicle
ms	Milliseconds
MSB	Most Significant Byte
MSE	Mean Square Error
PC	Personal Computer
PCH	Pseudocontrol Hedging
PWM	Pulse Width Modulation
RAM	Random Access Memory

RC	Radio Controlled
RF	Radio Frequency
RDIP	Rotational Dynamics Inversion Processor
ROM	Read Only Memory
RTK	Real Time Kinematic
RTOS	Real Time Operating System
SBC	Single Board Computer
SD	Standard Deviation
TPP	Tip Path Plane
UAV	Unmanned Aerial Vehicle
UHF	Ultra High Frequency
USC	University of Southern California
VBI	Video Blanking Interval
VLSI	Very Large Scale Integration
YACS	Yamaha Attitude Control System
μS	Microseconds

Nomenclature

a	Blade 2D lift curve slope
a_0	Coning angle
a_1	Longitudinal flapping
a_z	Vertical acceleration
A	Rotor disk area
A	Magnitude of magnetometer sine wave during calibration
A_b	Blade area
$\hat{\boldsymbol{A}}_{\boldsymbol{i}}$	Unit vector in direction of i^{th} beacon landmark
A_1	Lateral cyclic
A_{lat}	Lateral cyclic to main rotor pitch ratio
$\boldsymbol{b}$	Earth's magnetic field vector
b_1	Lateral flapping
b_{ij}	Element of rotation matrix $\boldsymbol{B}$ from row i and column j
$\boldsymbol{B}$	3×3 rotation matrix
B_{lon}	Longitudinal cyclic to main rotor pitch ratio
B_1	Longitudinal cyclic
c	Blade chord
c	Lateral flybar flapping
c_x, c_y	Optic flow calibration constants
C_D	Drag coefficient, $D/0.5\rho V^2 S$
C_{D0}	Profile drag coefficient
C_L	Lift coefficient, $L/0.5\rho V^2 S$
C_{lon}	Longitudinal cyclic to flybar pitch ratio
C_P	Power coefficient, $P/\rho A \left(\Omega R\right)^3$
C_{P_0}	Blade profile power coefficient, $P_0/\rho A \left(\Omega R\right)^3$
C_T	Thrust coefficient, $T/\rho A \left(\Omega R\right)^2$
d	Longitudinal flybar flapping
D	Drag
D_{lat}	Lateral cyclic to flybar pitch ratio
e	Rotor blade hinge osffset
e_{eff}	Effective rotor hinge offset
f	Equivalent flat plate area
F_x	Force acting in x-axis direction
F_y	Force acting in y-axis direction
F_z	Force acting in z-axis direction
g	Acceleration due to gravity (scalar)
$\boldsymbol{g}$	Gravity vector
H	Height above ground

$\boldsymbol{H}$	EKF observation matrix
i_s	Main rotor shaft angle
I_b	Blade mass moment of inertia
I_x	Second mass moment of inertia about x-axis
I_y	Second mass moment of inertia about y-axis
I_z	Second mass moment of inertia about z-axis
I_{xy}	Cross-product moment of inertia about xy-axes
I_{yz}	Cross-product moment of inertia about yz-axes
I_{xz}	Cross-product moment of inertia about xz-axes
k	Sensor gain
k_{ind}	Induced power correction factor
k_β	Blade root moment equivalent spring
$\boldsymbol{K}$	EKF gain matrix
$\mathcal{K}$	Slope of gyroscope output per rate of rotation
K_1	Cyclic due to servo command, $dA_1/d\delta_{lat}$
K_d	Derivative feedback gain for a PID controller
K_I	Integral feedback gain for a PID controller
K_p	Proportional feedback gain for a PID controller
K_u	Ultimate proportional feedback gain for marginal stability
L	Lift
L	Rolling moment
L_{mr}	Rolling moment due to main rotor
L_u	Longitudinal turbulence scale length
L_v	Lateral turbulence scale length
L_w	Vertical turbulence scale length
m	Helicopter mass
$\boldsymbol{m}$	Unit vector aligned with magnetometer
m_b	Mass of a rotor blade
M	Pitching moment
M_{mr}	Pitching moment due to main rotor
N	Yawing moment
N	Number of blades
$\boldsymbol{P}$	EKF covariance matrix
$\boldsymbol{q}$	Vector of quaternion parameters $[q_0\, q_1\, q_2\, q_3]^T$
q_0, q_1, q_2, q_3	Quaternion parameters
$\boldsymbol{Q}$	EKF process noise matrix
Q_x	Longitudinal optic flow
Q_y	Lateral optic flow
R	Rotor blade radius
$\boldsymbol{R}$	EKF measurement noise matrix
$\mathcal{R}$	Range computed from optic flow
$\boldsymbol{\mathcal{R}}_\psi$	Rotation matrix due to a rotation about the x-axis
S	Planform area used to non-dimensionalise lift and drag
T	Main rotor thrust
T_{tr}	Tail rotor thrust

u	Longitudinal body-axis velocity
u_{mean}	Mean longitudinal velocity
U	Raw sensor output
v	Lateral body-axis velocity
$\hat{V}$	Air velocity relative to TPP
V_i	Rotor induced velocity
V_n	Freestream velocity normal to TPP
V_R	Velocity of air relative to blade
V_t	Freestream velocity tangential to TPP
w	Vertical body-axis velocity
V_∞	Freestream velocity
V_z	Vertical velocity
X	X position in Earth centred coordinates
$\boldsymbol{\hat{X}_b}$	x body axis unit vector
$\boldsymbol{\hat{X}_g}$	x global axis unit vector
$\mathcal{W}$	Vertical relative velocity between the ground and heliopter
Y	Y position in Earth centred coordinates
$\boldsymbol{\hat{Y}_b}$	y body axis unit vector
$\boldsymbol{\hat{Y}_g}$	y global axis unit vector
z_{mr}	Vertical distance from main rotor hub to centre of gravity
Z	Z position in Earth centred coordinates
Z	Vertical position
$\boldsymbol{\hat{Z}_b}$	z body axis unit vector
$\boldsymbol{\hat{Z}_g}$	z global axis unit vector
$\mathcal{Z}$	Terrain clearance
α	Blade section angle of attack
β	Rotor blade flapping angle
δ_p	Offset error of roll rate gyroscope
δ_q	Offset error of pitch rate gyroscope
δ_r	Offset error of yaw rate gyroscope
δ_x	Offset error of x body axis accelerometer
δ_y	Offset error of y body axis accelerometer
δ_z	Offset error of z body axis accelerometer
δ_{col}	Collective pitch servo command
δ_{lat}	Lateral (roll) servo command
δ_{lon}	Longitudinal (pitch) servo command
δ_{ped}	Yaw servo command
δ_z	Offset error of z body axis accelerometer
ΔT	Time Step
γ	Locke number, $\rho acR^4/I_b$
γ^2	CIFER® correlation factor
$\zeta_{ix}, \zeta_{iy}, \zeta_{iz}$	Sensor alignment coefficients for the i^{th} sensor
θ	Pitch angle
θ	Blade incidence

θ_{max}	Servo rate limit
θ_s	Commanded sinusoidal servo amplitude
θ_0	Blade collective pitch angle
κ	Forward flight profile drag power correction factor
λ	Rotor inflow ratio
λ	Attitude vector correction factor
$\lambda_x, \lambda_y, \lambda_z$	Components of Earth's magnetic field along magnetometer axes
λ_i	Rotor induced inflow ratio, $V_i/\Omega R$
μ	Rotor advance ratio
ρ	Air density
σ	Rotor solidity, A_b/A
σ_u	Longitudinal turbulence intensity factor
σ_v	Lateral turbulence intensity factor
σ_w	Vertical turbulence intensity factor
τ_f	Time constant of main rotor flapping
τ_s	Time constant for flybar flapping
Υ	Sensor offset
ϕ	Roll angle
ϕ	Phase angle of magnetometer sine wave during calibration
Φ	Beacon elevation angle
Φ	EKF fundamental matrix
ψ	Blade azimuth angle measured anti-clockwise from above
ψ	Yaw angle
ψ	Rotation of IMU about an axes during calibration
Ψ	Beacon azimuth angle
Ω	Angular velocity of main rotor
Ω_{cr}	Servo corner frequency due to rate limit