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CONTROL ARCHITECTURE AND PATH PLANNING FOR QUADCOPTERS IN FORMATION

by

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Certificate of Original Authorship

I, Van Truong Hoang declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy degree, in the School of Electrical and Data Engineering, 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.

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ABSTRACT

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Unmanned aerial vehicles (UAVs) have found many areas of operation with numerous studies available in the literature. However, increasing demands in applications and the rapid development of technologies have transcended the use of a single UAV to the formation and their coordination. In the literature, UAVs' low-level control, path planning, and formation maintenance have been addressed mainly in separation. This research proposes a control architecture that integrates those three subsystems with a task assessment unit and communication links to accommodate a variety of applications.

At the low level, robustness of the UAV control systems is important for applications which require accurate attitudes, also for safety maintenance and configuration preservation when flying in formation. In operations, UAVs are often subject to nonlinearity, external disturbances, parametric uncertainties and strong coupling, which may downgrade their control performance. Therefore, the first focus is to design robust control schemes to track desired attitudes under various conditions. Accordingly, robust low-level controllers for UAVs are developed, namely the adaptive quasi-continuous and adaptive twisting sliding mode control. They offer a novel technique to adaptively change the control parameters of the so-called sliding modes for the sake of performance improvements.

To deploy multiple-UAV systems, the proposed control architecture includes robust control, path planning, and formation maintenance to create a real-time system that can be used for many engineering purposes. The system coordinates multiple

UAVs in a specific formation to collect data of the inspected objects. The hardware extension on the basis of 3DR Solo drones includes the Internet of Things (IoT) and environmental sensors. Communication links are implemented by employing IoT boards for components of the control architecture to equip them with network and data processing capabilities.

For UAV formation control, a novel multi-objective angle-encoded particle swarm optimisation algorithm is proposed to generate formation trajectories. Here, the algorithm is developed to minimise a cost function incorporating multiple objectives subject to formation constraints that include inspection task completion, shortest paths and safe operation of the drones.

To handle difficulties arising from various inspection surfaces, avoid possible dynamic collisions, and maintain safe motion of the whole UAV formation, the path planning algorithm is incorporated with a reconfigurable capability developed to be integrated to the control architecture. This integration allows for flexible changing of the formation to accommodate additional constraints on collision avoidance, flight altitude, communication range, and visual inspection requirements.

Throughout the dissertation, analytical work developed is validated by extensive simulation, comparisons and experiments to evaluate the proposed approach and confirm its feasibility and effectiveness. Discussions on theoretical aspects and implementation details are included together with some recommendations.

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List of publications

The content of this thesis has been published in the following papers:

Journal papers

J-1. **V. T. Hoang**, M. D. Phung, T. H. Dinh, and Q. P. Ha, "System architecture for real-time surface inspection using multiple UAVs," IEEE Systems Journal, accepted.

J-2. **Van Truong Hoang**, Quang Hieu Pham, "Super-twisting second-order sliding mode for attitude control of quadcopter UAVs," Special Issue On Measurement, Control and Automation, Vietnam Journal of Automation Today, vol. 20, pp. 52-59, 2017.

Conference papers

C-1. **V. T. Hoang**, M. D. Phung, T. H. Dinh, Q. Zhu, and Q. P. Ha, "Reconfigurable multi-UAV formation using angle-encoded PSO," in The 2019 IEEE 15th International Conference on Automation Science and Engineering (CASE 2019), Vancouver, Canada, 22-26 AUG 2019, accepted.

C-2. Qiuchen Zhu, Tran Hiep Dinh, **Van Truong Hoang**, Manh Duong Phung, and Quang Phuc Ha, "Crack detection using enhanced thresholding on UAV based collected images," in Australasian Conference on Robotics and Automation 2018 (ACRA 2018), Canterbury, New Zealand, 4-6 DEC 2018.

C-3. **V. T. Hoang**, M. D. Phung, T. H. Dinh, and Q. P. Ha, "Angle-encoded swarm optimization for UAV formation path planning," in The 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2018), Madrid, Spain, 1-5 OCT 2018. IEEE, pp. 5239-5244.

C-4. **V. T. Hoang**, M. D. Phung, and Q. P. Ha, "Adaptive twisting sliding mode control for quadrotor unmanned aerial vehicles," in Control Conference (ASCC), The 11th Asian, Gold Coast, Australia, 17 - 20 DEC 2017. IEEE, pp. 671-676.

C-5. Manh Duong Phung, **Van Truong Hoang**, Tran Hiep Dinh, and Quang Ha, "Automatic crack detection in built infrastructure using unmanned aerial vehicles," in Proceedings of the 2017 International Symposium on Automation and Robotics in Construction (ISARC 2017), Taipei, Taiwan. 28 JUN-1 JUL 2017, pp. 823-829.

C-6. **Van Truong Hoang**, Ansu Man Singh, Manh Duong Phung, and Quang Ha, "Adaptive second-order sliding mode control of UAVs for civil applications," in Proceedings of the 2017 International Symposium on Automation and Robotics in Construction (ISARC 2017), Taipei, Taiwan. 28 JUN-1 JUL 2017, pp. 816-822.

C-7. Ansu Man Singh, **Van Truong Hoang**, and Quang Ha, "Fast terminal sliding mode control for gantry cranes," in Proceedings of the 2016 International Symposium on Automation and Robotics in Construction (ISARC 2016), Auburn, USA, 18-21 JUL 2016, pp. 437-443.

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Abbreviation

1-SMC	First-order sliding mode control
2-SMC	Second-order sliding mode control
2-D	Two-dimensional
3-D	Three-dimensional
ANN	Artificial neural network
APF	Artificial potential field
AdTSM	Adaptive twisting sliding mode
AQCSM	Adaptive quasi-continuous sliding mode
ATSM	Accelerated twisting sliding mode
CGLA	Geometric learning algorithm
COG	Center of gravity
IP	Internet protocol
IWP	Intermediate waypoint
GA	Genetic algorithm
GCS	Ground control stations
GPS	Global positioning system
GST	Google satellite map
HALE	High altitude long endurance
HOSM	Higher-order sliding modes
IoT	Internet of things
LIDAR	Light detection and ranging
L-F	Leader-follower
LQG	Linear quadratic gaussian

LQR	Linear quadratic regulator
MALE	Medium altitude long endurance
MAV	Micro UAV
MPC	Model predictive control
MUAV	Miniature UAV
NAV	Nano UAV
PD	Proportional-derivative
PID	Proportional-integral-derivative
PRM	Probabilistic roadmap method
PSO	Particle swarm optimisation
QCSM	Quasi-continuous sliding mode
RCU	Remote computational units
RRT	Rapidly exploring random tree
RTK	Real-time kinematic
RTP	Real-time transport protocol
SOSM	Second-order sliding modes
STSM	Super-twisting sliding mode
SUAV	Small UAV
TCP	Transmission control protocol
TUAV	Tactical UAV
UAV	Unmanned aerial vehicle
UDP	User datagram protocol
UGV	Unmanned ground vehicle
VRB	Virtual rigid body
VS	Virtual structure
VTOL	Vertical take-off and landing
θ-PSO	Angle-encoded particle swarm optimisation

Nomenclature and Notation

	General Formatting Style
$[\dot{\cdot}]$	The time derivative of a variable
$[\cdot]^T$	Transpose of a vector or a matrix
$\|\cdot\|$	The norm of a vector
$\text{sign}(\cdot)$	The signum function
	Specific Symbol Usage
$\{E\}$	Earth fixed inertial coordinate frame
$\{B\}$	A quadcopter's body coordinate frame
$\{F\}$	A formation coordinate frame
$\{O\}$	A inertia frame of the formation
c	Force-to-torque coefficient of a quadcopter
c_1, c_2	PSO gain coefficients
C_j	Coordinates of the jth IWP
C_k	Centers coordinate of the kth obstacle
c_x	$cos(x)$
d	Disturbance vector
d_{com}	Communication range
d_i	Distance between the UAV_i and the formation centroid
d_k^S	Safe distance of the kth obstacle
d_θ	Pitch disturbance
d_ϕ	Roll disturbance
d_ψ	Yaw disturbance
e	A vector containing control error

F	Sum of aerodynamic forces affecting the quadcopter
F_i	Lift force generated by the ith motor/propeller
g	Gravitational acceleration
g_{ij}	A PSO global-best position
H	Transformation matrix
I	Inertia matrix of a quadcopter
J	The overall cost function
J_1	A cost component corresponding to a path length
J_2	A cost component corresponding to a violation
J_3	A cost component corresponding to a flying altitude
J_F	A cost function for path planning algorithm
J_R	A cost component corresponding to an intermediate waypoint
K	Number of obstacles
L_i	The total number of segments of the path T_{Fi}
M_j	Number of intermediate waypoints
p	Roll angular velocity of a quadcopter
P_n^*	Flying path for the UAVn
P_F	Position of the formation's centroid
p_{ij}	A PSO local-best positions
P_F^j	A set of waypoints of the formation at the jth intermediate waypoint
P_n^j	A set of waypoints of the UAVn at the jth intermediate waypoint
q	Pitch angular velocity of a quadcopter
R	Rotation matrix
r	Yaw angular velocity of a quadcopter
r_1, r_2	PSO pseudorandom scalars
r_F	Radius of the formation
r_k	Radius of the kth obstacle

r_Q	Radius of a quadcopter including propellers
$r_{l,k}^S$	Safe radius from the lth path segment to the kth obstacle
r_n^S	Safe radius of the nth UAV
$S(\omega)$	A skew-symmetric matrix
s_x	$sin(x)$
T_F^*	Reference trajectory of the formation centroid
T_{Fi}	The formation path at ith iteration
T_n	Reference trajectory for the nth UAV
u	A vector of control input
u_D	Discontinuous control component
u_{eq}	Equivalent control component
u_T	A twisting sliding controller
u_z	Altitude control input
u_θ	Pitch control input
u_ϕ	Roll control input
u_ψ	Yaw control input
V_0	Lyapunov function of the sliding surface
v_{ij}	Velocity of the ith particle in dimension j
V_l	Violation cost of the lth segment
V_n	Velocity profile for the nth UAV
$V_{\sigma,\alpha}$	Global Lyapunov function
X	State of a dynamic system
x_{ij}	Position of the ith particle in dimension j
x_{max}	Upper restriction of the search space
x_{min}	Lower restriction of the search space
z_k^{max}	Maximum altitude of the kth obstacle
α	A vector containing adaptive gains

α_i	An adaptive gain of the state i
$\alpha_{M,i}$	A maximum possible value of the adaptive gain
$\alpha_{m,i}$	A threshold of the adaptive gain
$\Delta\theta_{ij}$	phase angle increment of the ith particle in dimension j
Θ	Orientation vector of a quadcopter
θ	Pitch angle
θ_{ij}	Phase angle of the ith particle in dimension j
Λ_g	θ-PSO global best positions
Λ_i	θ-PSO personal best positions
σ	A vector containing the sliding surface components
τ	A torque component caused by thrust forces
τ_a	A torque component caused by the aerodynamic friction
τ_b	A torque component caused by body gyroscopic effects
τ_p	A torque component caused by propeller gyroscopic effects
τ_θ	Pitch torque
τ_ϕ	Roll torque
τ_ψ	Yaw torque
ϕ	Roll angle
ψ	Yaw angle
ω	A vector containing the three angular rates
Ω_r	Overall residual propeller angular speed