Dual-Axis Tilting Quadrotor Aircraft

An investigation into the overactuatedness thereof

Nicholas Von Klemperer

Department of Electrical Engineering
University of Cape Town
Rondebosch, Cape Town
South Africa

September 2016

MSc thesis submitted in fulfilment of the requirements for the degree of Masters of Science in the Department of Electrical Engineering at the University of Cape Town

Keywords: Control, Allocation, Non-linear, Autopilot

Declaration

I, Nicholas Von Klemperer, hereby:

1. grant the University of Cape Town free license to reproduce the above thesis in whole or in part, for the purpose of research;
2. declare that:
   (a) This thesis is my own unaided work, both in concept and execution, and apart from the normal guidance from my supervisor, I have received no assistance except as stated below:
   (b) Neither the substance nor any part of the above thesis has been submitted in the past, or is being, or is to be submitted for a degree at this University or at any other university, except as stated below.
   (c) Unless otherwise stated, any and all illustrations or diagrams demonstrated in this work are productions of my own.
   (d) All the content used to compile this report and complete the investigation revolving around the whole project is collectively hosted on the following GIT repositories:
      - LaTeXreport: `https://github.com/nickvonklemp/Masters-Report`
      - STM32F303 Projects: `https://github.com/nickvonklemp/Code`
      - Design Files & Blue Prints: `https://github.com/Design`
      - Hardware Schematics: `https://github.com/nickvonklemp/visio` &
      - EagleCad Schematics `https://github.com/nickvonklemp/Eagle`
      - MatLab Simulink Code: `https://github.com/nickvonklemp/Simulink`
      - Results & Simulation Data: `https://github.com/nickvonklemp/results`

Nicholas Von Klemperer

Department of Electrical Engineering
University of Cape Town

Sunday 11$^{\text{th}}$ September, 2016

Abstract

Dual-Axis Tilting Quadrotor Aircraft

Nicholas Von Klemperer

Sunday 11^{th} September, 2016

The aim of this project is to design, simulate and control a novel quadrotor platform which can articulate all 6 Degrees of Freedom by vectoring the propellers' directional thrust. To achieve this the structure of the air-frame must redirect those thrust vectors to any desired orientation. This means it has to transform its configuration during flight, redirecting lift actuators whilst still maintaining stable attitude & position control in spite of such relative motion. In view of this required articulation the proposal is to add 2 (degrees) axes of extra actuation to each propeller. As a result each lift propeller can then be pitched or rolled relative to the body frame. This change, to what is an otherwise well understood and highly researched platform, produces an over-actuated control problem. Actuator allocation is the primary contribution of this paper with novel elements of non-linear (*state-space*) attitude control.

The structure of the dissertation first presents the design which the subsequent dynamics and control are derived with respect to. Following that, the kinematics associated with rigid bodies are derived. Any unique effects that could apply to the design like gyroscopic, inertial and aerodynamic responses are investigated and then incorporated into the dynamics. Position and control algorithms are first derived, then simulated and compared based on the plants' dynamics (*which include discretionary effects on the system*). The relative performance of the controllers are evaluated but regular performance metrics for attitude and position control are ill-suited for such a system. Some time is spent discussing the consequence of this and how the controllers are actually evaluated. Finally the design is built and tested using readily available RC components and conclusions drawn on the success or failure of the design.

The purpose of the investigation is the practicality and feasibility of such a design, most importantly whether the complexity of the mechanical design is a decent trade-off for the added degrees of control actuation. The outcome of the build is to ascertain if it's both economically (cost and control effort) feasible to use such a prototype to expand the range of a quadrotors' motion. The design and control treatment presented here are by no means optimal or the most exhaustive solutions, focus is placed on the system as a whole and not just one aspect of it.

Acknowledgements

Contents

List of Figures

List of Tables

Appendix A

Standard Quadrotor Dynamics

Appendix B

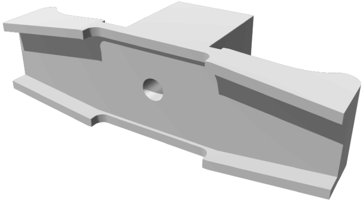
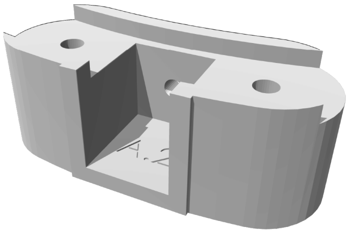
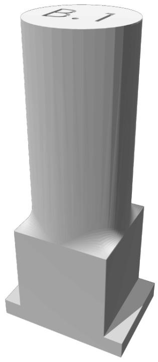
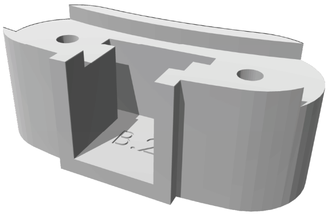
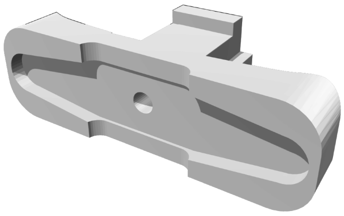
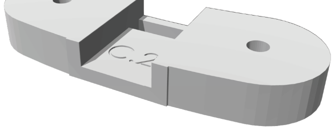
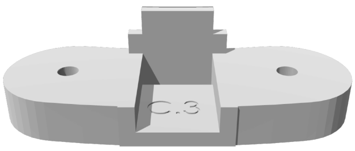
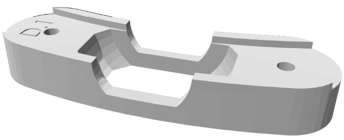
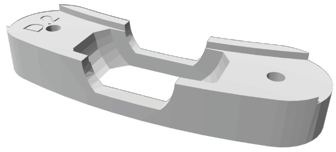
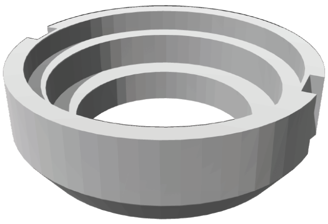
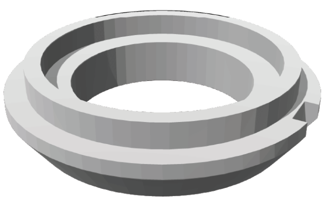
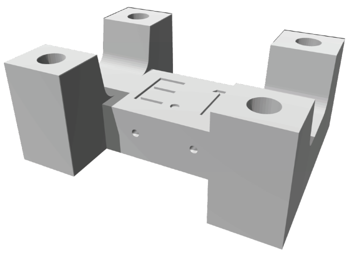
Design Bill of Materials

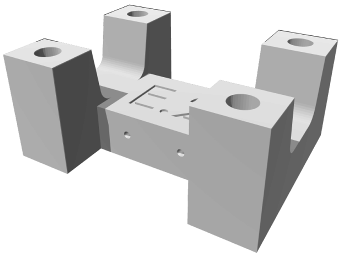
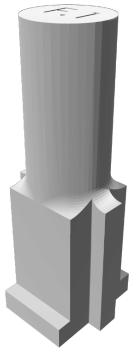
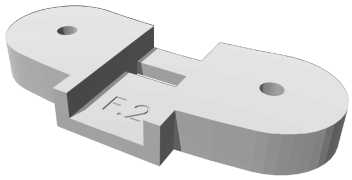
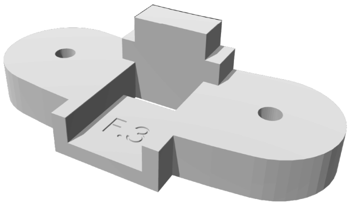
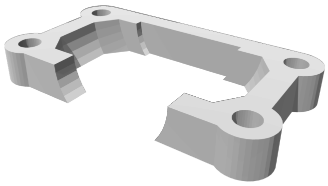
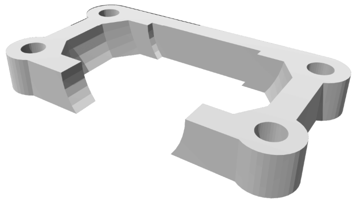
B.1 Parts List

Part Name	Amount Used	Unit Weight[g]
Electronics		
SPRacing F3 Deluxe Flight Controller	1	6
OrangeRx 615X 2.4 GHz 6CH Receiver	1	9.8
Signal Converter SBUS-PPM-PWM	1	5.0
STLink-V2 Debugger	1	N/A
RotorStar Super Mini S-BEC 10A	1	30
128x96" OLED Display	1	N/A
XBee-Pro S1	2	N/A
HobbyWing XRotor 15A Opto ESC	4	10.5
OrangeRX RPM Sensor	4	6
HobbyKing Multi-Rotor Power Distribution Board	1	7.6
Motors		
Corona DS-339MG	8	32
Turnigy DST-700KV Brushlesss DC	4	65
Frame Components		
APM Flight Controller Damping Platform	1	16
HobbyKing SK450 Replacement Arm (2 pcs)	2	N/A
SK450 Extended Landing Skid	1	93
Alloy Servo Arm (FUTABA)	8	N/A
10X18X6 Radial Ball Bearing	8	N/A
80g Damping Ball	32	N/A
Plastic Retainers for Damping Balls	32	N/A
3/5mm Aluminum Prop Adapter	4	N/A
6x4.5 Gemfam 3-Blade Propeller	4	N/A
M3 6mm Hex Nylon Spacer	8	N/A
M3 16mm Hex Nylon Spacer	32	N/A
M3 25mm Nylon Screw	128	N/A
M2.5x10mm Socket Head Cap Screw	36	N/A
M2.5x25mm Socket Head Cap Screw	20	N/A
M2.5 A-Lok Nut	16	N/A

Table B.1: Parts List

B.2 3D Printed Parts

Custom Printed CAD Designs		
 **Figure B.1:** Part A.1	 **Figure B.2:** Part A.2	 **Figure B.3:** Part B.1
 **Figure B.4:** Part B.2	 **Figure B.5:** Part C.1	 **Figure B.6:** Part C.2
 **Figure B.7:** Part C.3	 **Figure B.8:** Part D.1	 **Figure B.9:** Part D.2
 **Figure B.10:** Part D.3	 **Figure B.11:** Part D.4	 **Figure B.12:** Part E.1

 Figure B.13: Part E.2	 Figure B.14: Part F.1	 Figure B.15: Part F.2
 Figure B.16: Part F.3	 Figure B.17: Part G.1	 Figure B.18: Part G.2

B.3 Lasercut Components

B.4 Assembly

Appendix C

System ID Test Data

Bibliography

[1] Yazan Al-Rihani. *Development of a dual axis tilt rotorcraft uav: Design, prototyping and control.*, volume 1. Cranfield University: School of Engineering, 2012.

[2] N. Amiri, A. Ramirez-Serrano, and Davies R. Modelling of opposed lateral and longitudinal tilting dual-fan unmanned aerial vehicle. *International Federation of Automatic Control*, pages 2054–2059, September 2011.

[3] APMCopter. Arducopter main page. Website: http://www.arducopter.co.uk/, 6 2016. Arducopter (APM) Official Website.

[4] E. Balasubramanian and R. Vasantharaj. Dynamic modelling and control of quadrotor. *International Journal of Engineering and Technology*, pages 63–39, February 2013.

[5] M. Bangura and R. Mahony. Non-linear dynamic modelling for high performance control of a quadrotor. In *Australasian Conference on Robotics and Automation, Victoria University of Wellington*. Victoria Unversity of Wellington, 12 2012. Published in Conference Proceedings.

[6] Mohd Ariffanan Basri, Abdul R. Husain, and Kumeresan A. Danapalasingam. Intelligent adaptive backstepping control for mimo uncertain non-linear quadrotor helicopter systems. *Institute of Measurement Control Transactions*, pages 1–17, 2014.

[7] BetaFlight. Betaflight fc4 repo, 2016. Forked from the CleanFlight repo.

[8] Charles Blouin and Eric Lanteigne. Pitch control on an oblique active tilting bi-rotor. *International Conference on Unmanned Aircraft Systems*, pages 791–799, May 2014.

[9] R. Bodrany, W. Steyn, and M. Crawford. In-orbit estimation of the inertia matrix and thruster parameters of uosat-12. In *Conference on Small Satellites*, volume 14, pages 1–11. American Institute of Aeronautics and Astronautics, 2000.

[10] Hossein Bolandi, Mohammed Rezaei, Rezo Mohsenipour, Hossein Nemati, and Seed Majid Smailzadeh. Attitude control of a quadrotor with optimized pid. *Intelligent Control and Automation*, pages 335–342, August 2013.

[11] S. Bouabdallah and R. Siegwart. Full control of a quadrotor. *IEEE International Conference on Intelligent Robots and Systems*, pages 153–158, 11 2007. Written for Autonomous Systems Lab at Swiss Federal Institute of Technology.

[12] Samir Bouabdallah, Andre Noth, and Roland Siegward. Pid vs lq control technqiues applies to an indoor micro quadrotor. *IEEE International Conference on Intelligent Robots and Systems*, pages 2451–2456, 9 2004.

[13] J. Brandt and M. Selig. Propeller performance data at low reynolds numbers. *American Institude of Aeronautics and Astronautics Sciences Meeting, 49th*, pages 1–18, January 2011.

[14] Jian Chen, Aman Behal, and Darren M. Dawson. Adaptive output feedback control for a class of mimo nonlinear systems. In *Proceedings of the American Control Conference*, pages 5300–5306, Minneapolis, Minnesota, US, 6 2006. American Control Conference.

[15] Arindam B. Chowdhury, Anil Kulhare, and Guarav Raina. A generalized control method for tilt-rotor uav stabilization. *IEEE International COnference on Cyber Technology in Automation, Control and Intelligent Systems*, pages 309–314, May 2012.

[16] R.F. de Olivera, F.T. de Salvi, and E.M. Belo. Dynamic modelling, simulation and control of an autonomous quadcopter aircraft. *International Congress of Mechanical Engineering*, pages 1–9, November 2009.

[17] Chen Diao, Bin Xian, Qiang Yin, Wei Zeng, Haotao Li, and Yungao Yang. A nonlinear adaptive control approach for quadrotor uavs. In *Asian Control Conference Proceedings*, volume 8, pages 223–228, Kaohsiung, Taiwan, 5 2011. Asian Control Conference.

[18] DJI Drones. Dji inspire one, 2016.

[19] DJI Drones. Dji phantom, 2016.

[20] Emil Fresk and George Nikolakopoulos. Full quaternion based attitude control for a quadrotor. *European Control Conference*, pages 3864–3869, 6 2013.

[21] Pau. S Gasco. *Development of a Dual Axis Tilt Rotorcraft UAV: Modelling, Simulation and Control*, volume 1. Cranfield University: School of Engineering, 2012.

[22] HiSystems GmbH. Mikrokopter quadroxl, 2016.

[23] Basile Graf. Quaternions and dynamics. Publication for Mathematics - Dynamical Systems, 2 2007.

[24] Gary R. Gress. Lift fans as gyroscopes for controlling compact vtol air vehicles: Overview and development status of oblique active tilting. In *American Helicopter Society Annual Forum*, volume 63, Virginia Beach, 5 2007. American Helicopter Society, American Helicopter Society Inc. Forum Proceedings.

[25] Gary R. Gress. *Passive Stabilization of VTOL Aircraft Having Obliquely Tilting Propellers*. University of Calgary, Department of Mechanical Engineering, Calgary, Alberta, 2014.

[26] Karsten Groekatthfer and Zizung Yoon. Introudction into quaternions for spacecraft attitude representation. *Technical University of Berlin: Department of Astronautics and Aeronatuics*, pages 1–16, May 2012.

[27] N. Guenard, T. Hamel, and V. Moreau. Dynamic modelling and control strategy for an x4-flyer. *International Conference on Control and Automation*, pages 141–146, June 2005.

[28] HobbyKing.com. Hobby king: The ultimate hobby experience, 2016.

[29] G. Hoffmann, H. Huang, S. Waslander, and C. Tomlin. Quadrotor helicopter flight dynamics and control: Theory and experiment. In *Guidance, Navigation and Control Conference and Exhibit*, pages 1–19, Hilton Head, South Carolina, 8 2010. American Institute of Aeronautics and Astronautics, American Institute of Aeronautics and Astronautics. Derivation of advanced aerodynamic affects on STARMAC Quadrotor Prototype.

[30] W. Jia, Z. Ming, Y. Zhiwei, and L. Bin. Adaptive back-stepping lpv control of satellite attitude maneuvers with sum of squares. In *World Congress on Intelligent Control and Automation*, volume 8, pages 1747–1752. IEEE, 7 2010.

[31] Tor A. Johansen and Thor I. Fossen. Control allocation - a survery. *Automatica*, 45:10871103, 11 2012. Prepared for: Department of Engineering Cybernetics - Norwegian University of Science and Technology.

[32] Farid Kendoul, Isabelle Fantoni, and Rogelio Lozano. Modeling and control of a small autonomous aircraft having two tilting rotors. *IEEE Conference on Decision and COntrol*, pages 8144–8149, December 2005.

[33] P. Krishnamurthy and F. Khorrami. Adaptive backstepping and theta-d based controllers for a tilt-rotor aircraft. *Mediterranean Conference on Control and Automation*, pages 540–545, June 2011.

[34] Raymond Kristiansen and Per J. Nicklasson. Satellite attitude control by quaternion-based backstepping. *American Control Coference*, N/A:907–912, 6 2005. Published by Department of Computer Science, Electrical Engineering and Space Technology; Narvik University College.

[35] Jack B. Kuipers. *Quaternions and Rotation Sequences: A Prier with Aplication to Orbital Aerospace and Virtual Reality*, pages 127–143. Princeton University Press, September 2002. Used for Quaternion and Rotation Matrix reference.

[36] Peter Lambert. Nakazawa, banton and jin, bai x. Technical Report N/A, Computer and Electrical Engineering: University of Victoria, Victoria, Canada, 12 2013.

[37] Prof Allan J. Laub. The moore-penrose pseudo inverse. UCLA Math33A Course Content, UCLA, Los Angeles, 3 2008. Course Notes cited from `http://www.math.ucla.edu/~laub/33a.2.12s/mppseudoinverse.pdf`.

[38] Jang-Ho Lee, Byoung-Mun Min, and Eung-Tai Kim. Autopilot design of tilt-rotor uav using particle swarm optimization method. *International COnference on Control, Automation and Systems*, pages 1629–1633, October 2007.

[39] LibrePilot. Openpilot/librepilot wiki. Website: http://opwiki.readthedocs.io/en/latest/index.html, 5 2016. Information wiki page for LibrePilot/OpenPilot firmware.

[40] Hyon Lim, Jaemann Park, Daewon Lee, and H.J. Kim. Build your own quadrotor. *IEEE ROBOTICS & AUTOMATION MAGAZINE*, pages 33–45, 9 2012. Publication on Opensource Autopilot systems.

[41] SteadiDrone PTY LTD. Steadidrone home, 2016.

[42] Teppo Luukkonen. Modelling and control of a quadcopter. Master's thesis, Aalto University: School of Science, Eepso, Finland, 8 2011. Independent research project in applied mathematics.

[43] Tarek Madani and Abdelaziz Benallegue. Backstepping control for a quadrotor helicopter. *International COnference on Intelligent Robots and Systems*, pages 3255–3260, October 2006.

[44] I. Mandre. Rigid body dynamics using euler's equations, rungekutta and quaternions, 2 2006.

[45] Carlos J. Mantas and Jose M. Puche. Artificial neural networks are zero-order tsk fuzzy systems. In *IEE Transactions on Fuzzy Systems*, volume 16, pages 630–644, 6 2008.

[46] Christopher G. Mayhew, Ricardo G. Sanfelice, and Andrew R. Teel. On quaternion based attitude control and the unwinding phenomenon. *American Control Conference*, pages 299–304, June 2011.

[47] Ashfaq A. Mian and Wang Daoboo. Modelling and backstepping-based nonlinear control of a 6dof quadrotor helicopter. *Chinese Journal of Aeronautics*, 21:261–268, 3 2008. Simulated Backstepping Control.

[48] Svein Rivli Napsholm. Prototype of a tiltrotor helicopter. Master's thesis, Norwegian University of Science and Technology: Department of Engineering Cybernetics, Norway, 1 2013.

[49] A. Nemati and M. Kumar. Modeling and control of a single axis tilting quadcopter. *American Control Conference*, pages 3077–3082, June 2014.

[50] Kenzo Nonami, Farid Kendoul, Satoshi Suzuki, Wei Wang, and Daisuke Nakazawa. *Autonomous Flying Robots: Unmanned Aerial Vehicles and Micro Aerial Vehicles*, chapter 2, pages 44–48. Springer Japan, 1 edition, 2010. References to Cyclic-Pitch Control relevant subsections.

[51] Gustavo P. Oliveira. Quadcopter civil applications. Master's thesis, Informatics and Computer Engineering: University of Portugal, Portugal, 2 2014.

[52] Christos Papachristos, Kostas Alexis, and Anthony Tzes. Design and experimental attitude control of an unmanned tilt-rotor aerial vehicle. *International Conference on Advanced Robotics*, pages 465–470, June 2011.

[53] Parth N. Patel, Malav A. Patel, Rahul M. Faldu, and Yash R. Dave. Quadcopter for agricultural surveilance. In *Advance in Electronic and Electrical Engineering*, volume 3, India, 2013.

[54] J. Peraire and S. Widnall. 3d rigid body dynamics: Euler angles. Lecture notes for Dynamics Course, 2009. Dynamics course notes, fall 2007.

[55] D. Peters. Eigth amendment of the civil aviation regulations. Goverment Gazette Notice, 5 2015. In Amendment to the Civil Aviation Act, 2009 (Act No.13 of 2009).

[56] Jean-Baptiste Pomet and Laurent Praly. Adaptive nonlinear regulation: Estimation from the lyupanov equation. In *IEEE Transactions on Automatic Control*, volume 37, pages 729–740. IEEE, 6 1992.

[57] P. Pounds, R. Mahony, P. Hynes, and J. Roberts. Design of a four-rotor aerial robot. *Australasian Conference on Robotics and Automation*, pages 145–150, November 2002.

[58] Beard Randal. Quadrotor dynamics and control. Report, Brigham Young University, 2 2008. Part of the Electrical and Computer Engineering Commons.

[59] O. Rawashdeh, H.C. Yang, R. AbouSleiman, and B. Sababha. Microraptor: A low cost autonomous quadrotor system. *International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, pages 1–8, August 2009.

[60] Anastasia Razinkove, Igor Gaponov, and Hyun-Chan Cho. Adaptive control over quadcopter uav under disturbances. *International Conference on Control, Automation and Systems*, pages 386–390, October 2014.

[61] M.K. Rwigema. Propeller blade element momentum theory with vortex wake deflection. *International Congress of the Aeronautical Sciences, 27th*, pages 1–9, January 2010.

[62] M. Ryll, H. Bulthoff, and P. Robuffo Giordano. Modelling and control of a quadrotor uav with tilting propellers. *IEEE International Conference on Robotics and Automation*, pages 4606–4613, May 2012.

[63] M. Ryll, H. Bulthoff, and P. Robuffo Giordano. First flight tests of a quadrotor uav with tilting propellers. *IEEE International Conference on Robotics and Automation*, pages 295–302, May 2013.

[64] A. Sanchez, J. Escareo, O. Garcia, and R. Lozano. Autonomous hovering of a noncyclic tiltrotor uav: Modeling, control and implementation. *The International Federation of Automatic Control*, pages 803–808, July 2008.

[65] Puneet Singla, Daniele Mortari, and John L. Junkins. How to avoid singularity when using euler angles? *Advances in the Astronautical Sciences*, pages 1409–1426, January 2005.

[66] Abdelhamid Tayebi and Stephen McGilvray. Attitude stabilization of a vtol quadrotor aircraft. *IEEE Transactions on Control Systems Technology*, pages 562–571, May 2006.

[67] John Ting-Yung Wen and Kenneth Kreutz-Delgado. The attitude control problem. *IEEE Transactions on Automatic Control*, pages 1148–1162, October 1991.

[68] P. Tsiotras, M. Corless, and J.m Longuski. A novel approach to the attitude control of axisymmetric spacecraft. *Automatica*, 31:1099–1112, 3 1995. Control Automatica, Printed in Great Britan.

[69] Ultimaker, 2016.

[70] E. van Kampen and M. M. van Paassen. Ae4301: Automatic flight control system design. Delft Centre for Systems and Control; MSc Notes, 1 2008. Course Notes cited from: `http://aerostudents.com/master/advancedFlightControl.php`.

[71] Ronny Votel and Doug Sinclair. Comparison of control moment gyros and reaction wheels for small earth-observing satellites. In *Conference on Small Satellites*, volume 26, pages 1–7. Utah State University, 8 2012. Open access on AIAA conference website.

[72] Tao Wang, Tao Zhao, Du Hao, and Mingxi Wang. Transformable aerial vehicle, 09 2014.

[73] X. Xiaozhu, L. Zaozhen, and C. Weining. Intelligent adaptive backstepping controller design based on the adaptive particle swarm optimization. *Chinese Control and Decision Conference*, pages 13–17, September 2009.

[74] Song Xin and Zou Zaojian. A fuzzy sliding mode controller with adaptive disturance approximation for an underwater robot. In *International Asia Conference on Informatics in Control, Automation and Robotics*, volume 2, pages 50–53, 10 2010.