

FACULTY OF ELECTRICAL ENGINEERING AND COMPUTING, UNIVERSITY OF ZAGREB



State-of-the-Art Survey of Manifold Based Control Methods for Unmanned Aerial Vehicles

PhD Qualifying Exam

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Research Area

- Unmanned Aerial Vehicles (UAVs)
- Attitude (ϕ, θ, ψ) and Position (x, y, z) control
- Mathematical model embedded with a manifold structure
- Two frameworks considered:
 - Geometric Mechanics and Control
 - Passive Decomposition



Figure: UAV equipped with a Velodyne LiDAR while performing a wind-turbine inspection.

Why Manifolds? (1)

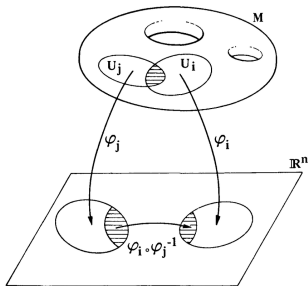


Figure: Manifold \mathcal{M} , Euclidean space \mathbb{R}^n and transport maps φ .¹

¹Vladim Belov, "On Geometry and Symmetries in Classical and Quantum Theories of Gauge Gravity"

- UAV configuration space:

$$\zeta = [x, y, z, \phi, \theta, \psi] \xleftrightarrow{\varphi} T = \begin{bmatrix} R & \mathbf{p} \\ \mathbf{0} & 1 \end{bmatrix} \quad (1)$$

$$\zeta \in \mathbb{R}^6, T \in SE(3), R \in SO(3) \quad (2)$$

- Lie Group

- set of smooth differentiable manifolds
- group multiplication and inversion properties
- e.g. $SO(3)$, $SE(3)$, S^2

Why manifolds? (2)

- Compact model dynamics represented as a Lagrangian / Hamiltonian system
- Coordinate-free approach
- No singularities
- No ambiguities

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Geometric Mechanics

- Introduced by:
 - F. Bullo and A. Lewis, 2005.²
 - T. Lee, 2008.³
 - T. Lee et al. 2018.⁴
- Rotating rigid body dynamics equation:

$$m\ddot{\mathbf{x}} + mg\mathbf{e}_3 = f\mathbf{Re}_3 \quad (3)$$

$$\mathbf{J}\dot{\boldsymbol{\Omega}} + \boldsymbol{\Omega} \times \mathbf{J}\boldsymbol{\Omega} = \mathbf{M} \quad (4)$$

$$\dot{\mathbf{R}} = \mathbf{R}\hat{\boldsymbol{\Omega}} \quad (5)$$

²Andrew D. Lewis Francesco Bullo, Geometric control of mechanical systems: modeling, analysis, and design for simple mechanical control systems, 1st ed., Texts in applied mathematics 49 (Springer, 2005).

³Taeyoung Lee, “Computational geometric mechanics and control of rigid bodies” (2008).

⁴Taeyoung Lee, Melvin Leok, and N. Harris McClamroch, Global formulations of Lagrangian and Hamiltonian dynamics on manifolds : a geometric approach to modeling and analysis, Interaction of mechanics and mathematics series (Springer, 2018).

Geometric Control (1)

- PD control with nonlinear terms
- First developed by T. Lee et al. 2010.⁵
- T. Lee et al. 2011.⁶ - Robust geometric control
- Kotaru et al. 2019.⁷ - L1 Adaptive controller
- S. Lee et al. 2019.⁸ - Parameter tuning optimization

⁵T. Lee, M. Leok, and N. H. McClamroch, "Geometric tracking control of a quadrotor UAV on SE(3)" (2010): 5420–5425.

⁶T. Lee, M. Leok, and N. Harris McClamroch, "Nonlinear Robust Tracking Control of a Quadrotor UAV on SE(3)", ArXiv e-prints (Sept. 2011).

⁷Prasanth Kotaru, Ryan S. Edmonson, and Koushil Sreenath, "Geometric L1 Adaptive Attitude Control for a Quadrotor UAV" (2019).

⁸Seongheon Lee and Hyochoong Bang, "Automatic Gain Tuning Method of a Quad-Rotor Geometric Attitude Controller Using A3C" (2019).

Geometric Control (2)⁹

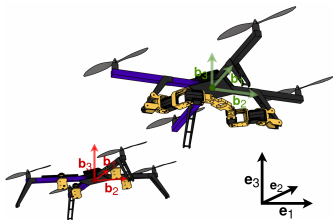
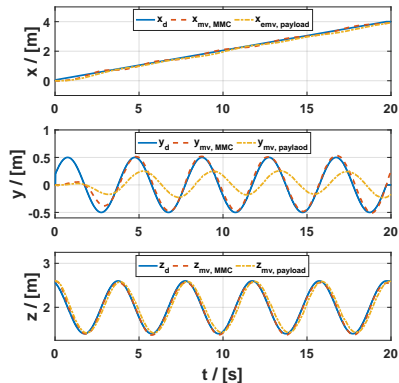


Figure: Two UAVs endowed with variable center of gravity by moving masses and manipulator carried payload (top). Position tracking results (right).⁹



⁹Lovro Markovic et al., "Geometric Tracking Control of Aerial Robots Based on Centroid Vectoring" (June 2019).

Gemetric Control - Transportation Tasks (1)

- Introduced by T. Lee and V. Kumar 2013.¹⁰
- A. Goodarzi and T. Lee 2015.¹¹ - Multiple quadrotors employed
- A. Goodarzi and T. Lee 2015.¹² and A. Goodarzi et al. 2013.¹³ - Adaptive control with unknown mass variations

¹⁰K. Sreenath, T. Lee, and V. Kumar, "Geometric control and differential flatness of a quadrotor UAV with a cable-suspended load" (2013): 2269–2274.

¹¹Farhad A. Goodarzi and Taeyoung Lee, "Stabilization of a Rigid Body Payload with Multiple Cooperative Quadrotors" (2015).

¹²Farhad A. Goodarzi and Taeyoung Lee, "Dynamics and control of quadrotor UAVs transporting a rigid body connected via flexible cables", 2015 American Control Conference (ACC) (2015): 4677–4682.

¹³Farhad A. Goodarzi, Daewon Lee, and Taeyoung Lee, "Geometric Stabilization of Quadrotor UAV with a Payload Connected by Flexible Cable" (2013).

Geometric Control - Transportation Tasks (2)¹⁴

- Multiple quadrotor UAVs carrying a rigid body payload via cables
- Cable configuration lies in S^2 - spherical Lie group
- Complete system configuration lies in $SE(3) \times S^2$
- Payload position and attitude tracking problem

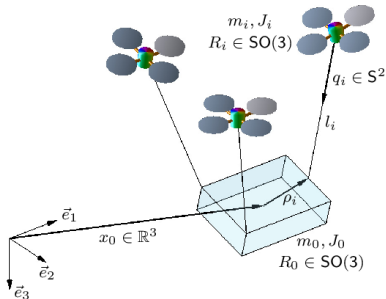


Figure: Payload transportation with multiple UAVs.¹⁴

¹⁴Taeyoung Lee, "Geometric control of multiple quadrotor UAVs transporting a cable-suspended rigid body", 53rd IEEE Conference on Decision and Control (2014): 6155–6160.

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Passive Decomposition

- First introduced by D. Lee 2008.¹⁵
- Proposed system dynamics split:
 - Shape - internal configuration of each robot
 - Locked - current overall behavior of multiple robot systems
 - Coupled - interaction between locked and shape dynamics
- Passive decomposition
 - Applying a control law to cancel the dynamics coupling terms without energy generation
 - Enforces energetic passivity

¹⁵Dongjun Lee, "Passive Decomposition of Multiple Nonholonomic Mechanical Systems under Motion Coordination Requirements", IFAC Proceedings Volumes 41.2 (2008): 4367–4373.

Passive Decomposition - QM systems^{16 17}

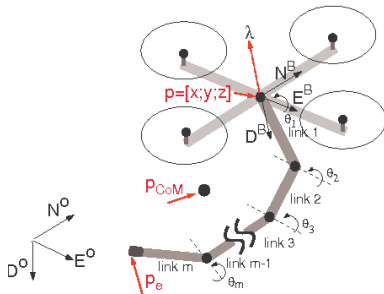


Figure: QM system¹⁵

- Decoupled quadrotor-manipulator(QM) system:
 - center-of-mass dynamics in $E(3)$
 - Robotic manipulator Lagrange dynamics
- End-effector control law:
 - Backstepping-like controller¹⁶
 - PID cascade¹⁷

¹⁶Hyunsoo Yang and Dongjun Lee, "Dynamics and control of quadrotor with robotic manipulator", 2014 IEEE International Conference on Robotics and Automation (ICRA) (2014): 5544–5549.

¹⁷Nebi Bulut, Ali Turgut, and Kutluk Arian, "Decoupled Cascaded PID Control of an Aerial Manipulation System", Hittite Journal of Science and Engineering 6.4 (2019): 251–259.

Passivity Based Control - Payload Transportation

- C. Meissen et al. 2017.¹⁸ - General formation and internal control laws
- M E. Guerrero et al. 2015.¹⁹ - An Interconnection and Damping Assignment - Passivity Based Control (IDA-PBC) for payload swing suppression
- P. Prajapati et al. 2019.²⁰ - Master-slave transportation strategy with human-in-the-loop

¹⁸Chris Meissen et al., "Passivity-based Formation Control for UAVs with a Suspended Load", IFAC-PapersOnLine 50.1 (2017): 13150 –13155.

¹⁹M. E. Guerrero et al., "Passivity based control for a quadrotor UAV transporting a cable-suspended payload with minimum swing" (2015): 6718–6723.

²⁰P. Prajapati, S. Parekh, and V. Vashista, "Collaborative Transportation of Cable-Suspended Payload using Two Quadcopters with Human in the loop" (2019): 1–6.

Passivity Based Control - Aerial Compliance (1)

- E. Spyrakos et al. 2019.²¹ - Manipulator passivity preservation control (PPC)
- Q. Delamare 2019.²² - Exploiting physical contact to achieve flight maneuvers
- M. Schuster et al. 2019.²³ - Energy efficient approach to maximum in-flight wrench generation

²¹E. Spyrakos-Papastavridis, P. R. N. Childs, and J. S. Dai, "Passivity Preservation for Variable Impedance Control of Compliant Robots", IEEE/ASME Transactions on Mechatronics (2019): 1–1.

²²Quentin Delamare, "Algorithms for estimation and control of quadrotors in physical interaction with their environment", *Theses, Univ Rennes, Inria, CNRS, IRISA, France, 2019.*

²³Micha Schuster et al., "Comparison of design approaches of fully actuated aerial robots based on maximum wrench generation and minimum energy consumption", IFAC-PapersOnLine 52.15 (2019): 603 –608.

Passivity Based Control - Aerial Compliance (2)

- R. Rashad et al. 2019.²⁴ - Passivity based control of a fully actuated UAV for aerial physical interaction near hovering by



Figure: A fully-actuated hexarotor UAV applying force to a vertical surface.

²⁴R. Rashad, F. Califano, and S. Stramigioli, "Port-Hamiltonian Passivity-Based Control on $SE(3)$ of a Fully Actuated UAV for Aerial Physical Interaction Near-Hovering", IEEE Robotics and Automation Letters 4.4 (2019): 4378–4385.

Passivity Based Control - Notable Mentions (1)

- Y. Igarashi et al. 2009.²⁵
 - Passivity based motion coordination of rigid bodies by exchanging information over connected graphs
- H. Yang and D. Lee 2015.²⁶
 - A hierarchical cooperative control framework
 - Endowment of a common grasped object with desired behavior (e.g., trajectory tracking, compliant interaction, etc.)

²⁵Y. Igarashi et al., "Passivity-Based Attitude Synchronization in $SE(3)$ ", IEEE Transactions on Control Systems Technology 17.5 (Sept. 2009): 1119–1134.

²⁶H. Yang and D. Lee, "Hierarchical cooperative control framework of multiple quadrotor-manipulator systems" (2015): 4656–4662.

Passivity Based Control - Notable Mentions (2)

- P. Robuffo Giordano et al. 2011.²⁷
 - Experimental validation of a decentralized passivity-based control strategy for teleoperating a group UAVs
 - Master UAV (human-in-the-loop) controls the group motion and receives feedback about the remote slave motion status
- D. Lee et al. 2013.²⁸
 - Semi-autonomous haptic teleoperation control architecture for multiple UAVs

²⁷P. Robuffo Giordano et al., “Experiments of passivity-based bilateral aerial teleoperation of a group of UAVs with decentralized velocity synchronization” (2011): 163–170.

²⁸D. Lee et al., “Semiautonomous Haptic Teleoperation Control Architecture of Multiple Unmanned Aerial Vehicles”, IEEE/ASME Transactions on Mechatronics 18.4 (2013): 1334–1345.

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Future Work (1)

- ENCORE project ²⁹
- Formation flight for building inspection
- Simultaneous exploration and physical interaction with architectural structures
- Applying passivity-based control in a real-world environment
- Goal: compliant multi-agent control method immune to communication unreliability while achieving energetic passivity

²⁹"Encore project", <http://encorebim.eu/> Accessed: 2019-09-10

Future Work (2)

- Implement autonomous wind-turbine blade inspection using presented control frameworks

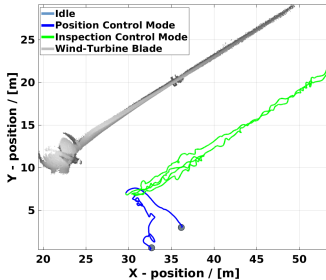


Figure: Inspection trajectory and a wind-turbine model.

Autonomous Wind-Turbine Blade
Inspection using LiDAR-Equipped
Unmanned Aerial Vehicle

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Conclusion

- An overview of geometric and passivity based control methods
- General frameworks - many application opportunities
- Geometric control - trajectory tracking in various configurations
- Passive-decomposition
 - powerful framework with multitude of utilization opportunities
 - trajectory tracking, environment interaction, compliant behavior, haptic user control, formation control etc.
- Current state-of-the-art presented for both frameworks

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-  ——. "Stabilization of a Rigid Body Payload with Multiple Cooperative Quadrotors". (2015). Print.
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