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)

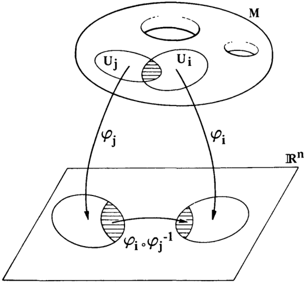

Figure: Manifold $\mathcal{M}$, Euclidean space $\mathbb{R}^n$ and transport maps φ.[1]

- UAV configuration space:

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

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

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

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

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:

$$m\ddot{\mathbf{x}} + mg\mathbf{e}_3 = f\mathsf{R}\mathbf{e}_3 \tag{3}$$

$$\mathsf{J}\dot{\boldsymbol{\Omega}} + \boldsymbol{\Omega} \times \mathsf{J}\boldsymbol{\Omega} = \mathbf{M} \tag{4}$$

$$\dot{\mathsf{R}} = \mathsf{R}\widehat{\boldsymbol{\Omega}} \tag{5}$$

[2] Andrew 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).

[3] Taeyoung Lee, "Computational geometric mechanics and control of rigid bodies" (2008).

[4] Taeyoung 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 Aadaptive controller
- S. Lee et al. 2019.[8] - Parameter tuning optimization

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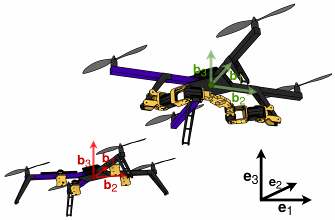
[5] T. Lee, M. Leok, and N. H. McClamroch, "Geometric tracking control of a quadrotor UAV on SE(3)" (2010): 5420–5425.

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

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

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

Geometric Control (2)[9]



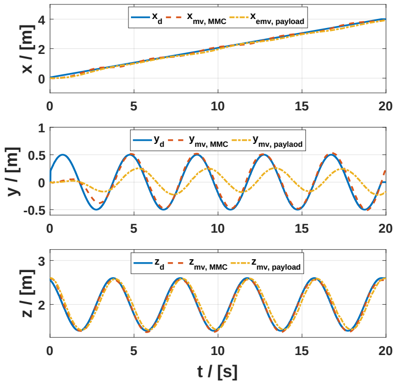


Figure: Two UAVs endowed with variable center of gravity by moving masses and manipulator carried payload (top). Position tracking results (right).[9]

[9] Lovro 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

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

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

[12] Farhad 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.

[13] Farhad 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 $\mathsf{SE}(3) \times \mathsf{S}^2$
- Payload position and attitude tracking problem

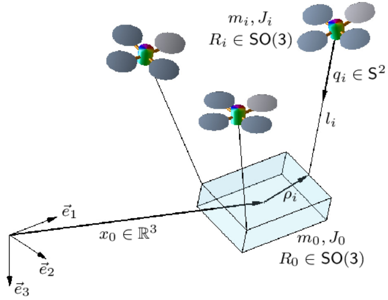


Figure: Payload transportation with multiple UAVs.[14]

[14] Taeyoung 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

[15] Dongjun 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]

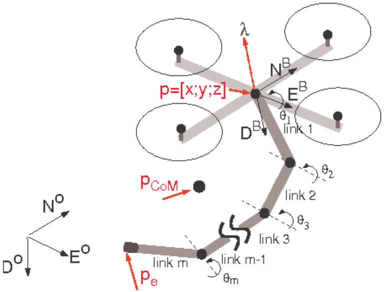

Figure: QM system[15]

- Decoupled quadrotor-manipulator(QM) system:
  - center-of-mass dynamics in E(3)
  - Robotic manipulator Lagrange dynamics
- End-effector control law:
  - Backstepping-like controller[16]
  - PID cascade[17]

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

[17] Nebi Bulut, Ali Turgut, and Kutluk Arikan, "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

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

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

[20] P. 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

[21] E. 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.

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

[23] Micha 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

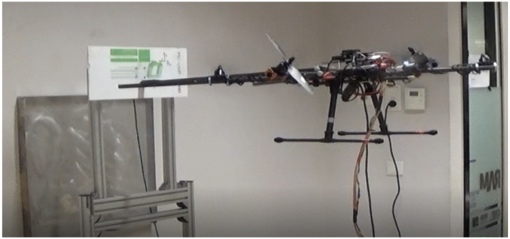

Figure: A fully-actuated hexarotor UAV applying force to a vertical surface.

[24] R. 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. Iarashi 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.)

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

[26] H. 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

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

[28] D. 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)

- Autonomous wind-turbine blade inspection using presented control frameworks

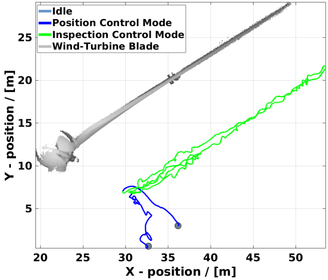
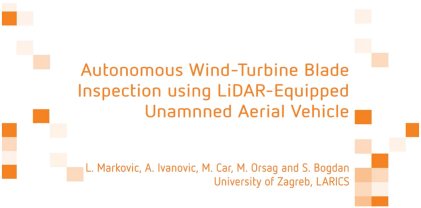


Figure: Inspection trajectory and a wind-turbine model.



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

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- Goodarzi, Farhad A., Daewon Lee, and Taeyoung Lee. “Geometric Stabilization of Quadrotor UAV with a Payload Connected by Flexible Cable”. (2013). arXiv: 1309.6717 [math.OC].
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- ——. “Stabilization of a Rigid Body Payload with Multiple Cooperative Quadrotors”. (2015). Print.
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Meissen, Chris, et al. “Passivity-based Formation Control for UAVs with a Suspended Load”. *IFAC-PapersOnLine* 50.1 (2017). 20th IFAC World Congress: 13150 –13155. Print.

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