

# 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

Supervisor

*prof. dr. sc. Stjepan Bogdan*

Candidate

*mag. ing. Lovro Markovic*

Zagreb, 9.3.2020.

# Table of Contents

---

Introduction

Geometric Control and Mechanics

Passive Decomposition

Conclusion

# Table of Contents

---

Introduction

Geometric Control and Mechanics

Passive Decomposition

Conclusion

## Research Area

- Unmanned Aerial Vehicles (UAVs)
- Attitude ( $\phi, \theta, \psi$ ) 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)

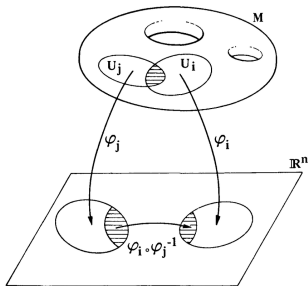


Figure: Manifold  $\mathcal{M}$ , Euclidean space  $\mathbb{R}^n$  and transport maps  $\varphi$ .<sup>1</sup>

- UAV configuration space:

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

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

- Lie Group

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

<sup>1</sup>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

# Table of Contents

---

Introduction

Geometric Control and Mechanics

Passive Decomposition

Conclusion

# Geometric Mechanics

---

- Introduced by:
  - F. Bullo and A. Lewis, 2005.<sup>2</sup>
  - T. Lee, 2008.<sup>3</sup>
  - T. Lee et al. 2018.<sup>4</sup>
- Rotating rigid body dynamics equation:

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

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

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

---

<sup>2</sup>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).

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

<sup>4</sup>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.<sup>5</sup>
- T. Lee et al. 2011.<sup>6</sup> - Robust geometric control
- Kotaru et al. 2019.<sup>7</sup> - L1 Adaptive controller
- S. Lee et al. 2019.<sup>8</sup> - Parameter tuning optimization

---

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

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

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

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

## Geometric Control (2)<sup>9</sup>

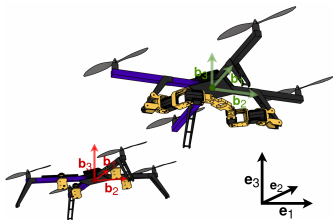
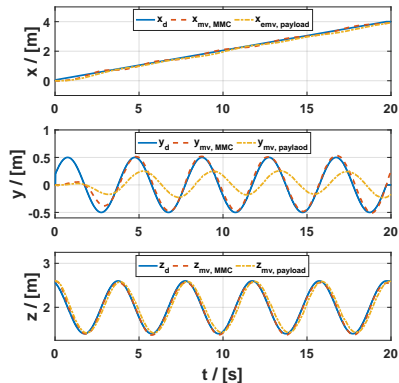


Figure: Two UAVs endowed with variable center of gravity by moving masses and manipulator carried payload (top). Position tracking results (right).<sup>9</sup>



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

# Geometric Control - Transportation Tasks (1)

---

- Introduced by T. Lee and V. Kumar 2013.<sup>10</sup>
- A. Goodarzi and T. Lee 2015.<sup>11</sup> - Multiple quadrotors employed
- A. Goodarzi and T. Lee 2015.<sup>12</sup> and A. Goodarzi et al. 2013.<sup>13</sup> - Adaptive control with unknown mass variations

---

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

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

<sup>12</sup>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.

<sup>13</sup>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)<sup>14</sup>

- 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

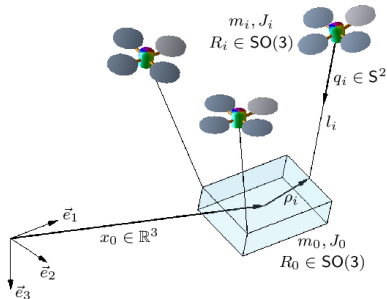


Figure: Payload transportation with multiple UAVs.<sup>14</sup>

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

# Table of Contents

---

Introduction

Geometric Control and Mechanics

Passive Decomposition

Conclusion

# Passive Decomposition

---

- First introduced by D. Lee 2008.<sup>15</sup>
- 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

---

<sup>15</sup>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<sup>16 17</sup>

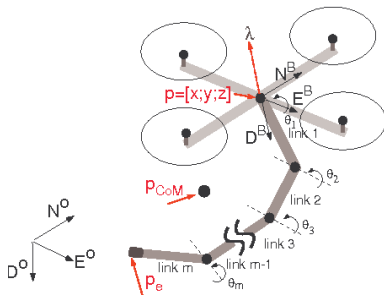


Figure: QM system<sup>15</sup>

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

<sup>16</sup>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.

<sup>17</sup>Nebi 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.<sup>18</sup> - General formation and internal control laws
- M E. Guerrero et al. 2015.<sup>19</sup> - An Interconnection and Damping Assignment - Passivity Based Control (IDA-PBC) for payload swing suppression
- P. Prajapati et al. 2019.<sup>20</sup> - Master-slave transportation strategy with human-in-the-loop

---

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

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

<sup>20</sup>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.<sup>21</sup> - Manipulator passivity preservation control (PPC)
- Q. Delamare 2019.<sup>22</sup> - Exploiting physical contact to achieve flight maneuvers
- M. Schuster et al. 2019.<sup>23</sup> - Energy efficient approach to maximum in-flight wrench generation

---

<sup>21</sup>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.

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

<sup>23</sup>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.<sup>24</sup> - Passivity based control of a fully actuated UAV for aerial physical interaction near hovering



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

<sup>24</sup>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. Igarashi et al. 2009.<sup>25</sup>
  - Passivity based motion coordination of rigid bodies by exchanging information over connected graphs
- H. Yang and D. Lee 2015.<sup>26</sup>
  - A hierarchical cooperative control framework
  - Endowment of a common grasped object with desired behavior (e.g., trajectory tracking, compliant interaction, etc.)

---

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

<sup>26</sup>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.<sup>27</sup>
  - 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.<sup>28</sup>
  - Semi-autonomous haptic teleoperation control architecture for multiple UAVs

---

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

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

# Table of Contents

---

Introduction

Geometric Control and Mechanics

Passive Decomposition

Conclusion

## Future Work (1)

---

- ENCORE project <sup>29</sup>
- 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

---

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

## Future Work (2)

- Autonomous wind-turbine blade inspection using presented control frameworks

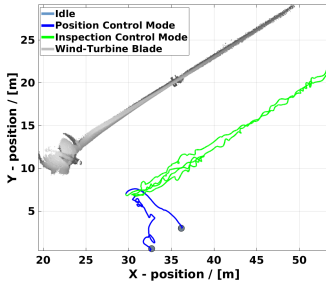


Figure: Inspection trajectory and a wind-turbine model.

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

L. Markovic, A. Ivanovic, M. Car, M. Orsag and S. Bogdan  
University of Zagreb, LARICS

# 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



## References (1)

---



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.







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



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

## References (2)

---

-  Goodarzi, Farhad A., Daewon Lee, and Taeyoung Lee. "Geometric Stabilization of Quadrotor UAV with a Payload Connected by Flexible Cable". (2013). [arXiv: 1309.6717 \[math.OC\]](#).
-  Goodarzi, Farhad A. 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. Print.
-  ——. "Stabilization of a Rigid Body Payload with Multiple Cooperative Quadrotors". (2015). Print.
-  Guerrero, M. E., et al. "Passivity based control for a quadrotor UAV transporting a cable-suspended payload with minimum swing". (2015): 6718–6723. Print.

## References (3)

---



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



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



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



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

## References (4)

---



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



Lee, T., M. Leok, and N. Harris McClamroch. "Nonlinear Robust Tracking Control of a Quadrotor UAV on  $SE(3)$ ". [ArXiv e-prints](#) (Sept. 2011). [arXiv: 1109.4457 \[math.OC\]](#).



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



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

## References (5)

---



—. “Geometric control of multiple quadrotor UAVs transporting a cable-suspended rigid body”. *53rd IEEE Conference on Decision and Control* (2014): 6155–6160. Print.



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



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

## References (6)

---



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.



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



Rashad, R., 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. Print.

## References (7)

---



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



Schuster, Micha, et al. "Comparison of design approaches of fully actuated aerial robots based on maximum wrench generation and minimum energy consumption". [IFAC-PapersOnLine 52.15 \(2019\). 8th IFAC Symposium on Mechatronic Systems MECHATRONICS 2019: 603 –608. Print](#).



Spyrakos-Papastavridis, E., 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. Print](#).

## References (8)

---



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](#).



Yang, H. and D. Lee. “Hierarchical cooperative control framework of multiple quadrotor-manipulator systems”. (2015): 4656–4662. [Print](#).



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