PROPOSAL

Cooperative Aerial Manipulation and Load Transportation

Prepared in response to *2026-2027 Delaware NASA/EPSCoR RID Seed Grant Program*

PRINCIPAL INVESTIGATOR

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Abstract

Cooperative aerial manipulation (CAM) uses multiple UAVs to transport payloads exceeding single-vehicle capacities, offering scalable solutions for planetary exploration and disaster relief. However, real-world deployment is limited by dynamic coupling, under-actuation, and reliance on continuous communication or external motion capture. Traditional control structures often restrict systems to low-speed flights by assuming load dynamics are slower than the quadrotor. To overcome these barriers, this research proposes an agile, robust, and energy-efficient CAM framework. The system eliminates payload-mounted sensors, relying exclusively on onboard visual and inertial sensing to estimate vehicle poses and the load's 6-DoF state in real-time. By transitioning to quantized, low-bit inter-vehicle communication, the framework significantly reduces energy consumption. This sensor-light, communication-resilient approach aligns with NASA's ARMD objectives by enabling trusted autonomy and robust performance under off-nominal conditions and wind disturbances.

1 Narrative

1.1 Background and motivation

Figure 1: Illustration of multi-UAV cooperative aerial manipulation and load transportation in planetary exploration scenarios.

The evolution of Unmanned Aerial Vehicles (UAVs) from passive surveillance to active physical interaction has highlighted the payload and actuation limits of single-rotor systems. Cooperative Aerial Manipulation (CAM) addresses these constraints by employing multiple UAVs to collaboratively transport heavy or oversized loads. Cable-suspended configurations are particularly advantageous due to their mechanical simplicity and minimal impact on carrier dynamics, offering significant potential for planetary exploration, construction, and disaster relief. However, real-world deployment is hindered by the complex, non-linear dynamics of multi-agent systems. Current state-of-the-art methods typically rely on cascaded control structures and the principle of time-scale separation, which assumes load dynamics are slower than those of the UAVs. This restriction limits operations to low speeds (e.g., under 1.5 m/s) and low accelerations (under 0.5 m/s²), compromising effectiveness in time-critical missions. Furthermore, centralized coordination models scale poorly and are vulnerable to communication latencies or dropouts. Most existing frameworks also depend on external motion capture or heavy payload-mounted sensors, rendering them impractical for unstructured, GPS-denied, or wind-swept outdoor environments. To achieve robust autonomy, CAM must transition toward sensor-light, decentralized, and communication-resilient architectures. By leveraging onboard visual-inertial estimation and implicit haptic feedback—such as cable tension—multi-UAV teams can operate efficiently without continuous data exchange. Integrating learning-based techniques like Reinforcement Learning (RL) further enables these systems to adapt to unmodeled aerodynamic disturbances and modeling errors. This shift away from rigid analytical models toward adaptive, decentralized control paves the way for agile, high-speed aerial manipulation in unpredictable real-world conditions.

1.2 Related work

Cooperative aerial manipulation and load transportation utilize multiple UAVs to move payloads exceeding the capacity of single multirotors [1, 2]. While scalable for construction and rescue, these systems introduce complex challenges in dynamic coupling and multi-agent coordination [3, 4]. Hardware configurations are generally categorized into four types [1]. Cable-driven systems are mechanically simple but require sophisticated control to manage load swing [5, 6]. Rigidly attached multirotors offer higher lifting capacity but face severe under-actuation, often mitigated by spherical joints [1]. Multi-DoF robotic arms enable precise orientation control at the cost of complex coupled dynamics [7, 8], while heterogeneous ground-air systems combine the strength of UGVs with the vertical mobility of UAVs [1]. Dynamic modeling typically employs two frameworks [1]. The Newton-Euler (N-E) approach models UAVs and payloads as distinct interacting subsystems, ideal for real-time cable or rigid setups [1, 4]. Conversely, the Euler-Lagrange (E-L) formulation treats the assembly as a single coordinate-free system, simplifying the math for highly articulated or heterogeneous configurations [1]. Control strategies are evolving from traditional cascaded structures—which often fail during agile maneuvers due to time-scale separation assumptions—to kinodynamic whole-body motion planners [4, 9]. These planners enable high-speed flight and formation reshaping through narrow gaps [4]. Additionally, researchers are shifting toward decentralized, communication-free coordination where followers track leaders via haptic feedback or visual-inertial odometry [3, 10]. Learning-based advancements further enhance autonomy in unstructured environments [11, 12]. Imitation learning enables the replication of human manipulation, while Deep Learning provides robust perception and state estimation [11, 13]. Multi-Agent Reinforcement Learning (MARL) is particularly effective, allowing agents to coordinate through local observations and maintain stability even during mid-flight vehicle failures [12].

1.3 Proposed approach

Cooperative aerial manipulation and load transportation enable multiple UAVs to manage payloads beyond the capacity of a single multirotor. This scalability makes them ideal for critical missions like planetary exploration, construction, and disaster relief. Yet, real-world deployment remains bottlenecked by the complexities of dynamic coupling, under-actuation, and multi-agent coordination. Current frameworks are heavily tethered to continuous wireless communication and rigid analytical models that struggle against aerodynamic disturbances or shifting payload inertias. Moreover, existing force-based cascaded controllers inherently limit systems to low-speed, low-acceleration maneuvers by assuming load dynamics operate slower than the quadrotor. To overcome these barriers, this research proposes an agile, robust, and energy-efficient Cooperative Aerial Manipulation (CAM) framework that will be structured around three core research thrusts:

Thrust 1: Quantized visual-inertial estimation for cooperative navigation Current multi-UAV frameworks are severely bottlenecked by their reliance on continuous wireless communication and external motion capture. To address this, this thrust develops a cooperative navigation scheme utilizing minimal, quantized inter-vehicle communication. By transmitting only essential, discrete data packets instead of continuous streams, the system drastically reduces communication overhead and energy consumption. Furthermore, to eliminate the dependency on external motion capture, this thrust enables decentralized cooperative localization relying exclusively on the UAVs' onboard visual and inertial sensors.

Thrust 2: Visual learning of load dynamics and cable tension Traditional cooperative transport systems rely on complex, payload-mounted trackers or physical force and torque sensors, which introduce parasitic weight and mechanical vulnerability. This thrust eliminates the need for these dedicated physical sensors. Leveraging the onboard visual-inertial suite established in Thrust 1, this research develops a framework to simultaneously estimate the individual UAVs' poses while dynamically inferring the load's full 6-DoF pose, twist, and corresponding cable tension in real-time. To accurately model the highly non-linear dynamics without rigid analytical equations, we will design Deep Neural Networks (DNNs) to approximate complex Jacobians and residuals online and feed them directly into state estimation.

Thrust 3: Reinforcement learning-based control and coordination Traditional cascaded controllers and rigid analytical models restrict UAVs to sluggish maneuvers and frequently fail under aerodynamic disturbances or shifting inertias. To bypass these limitations, this thrust introduces an adaptive impedance control policy driven by RL. This learning-based controller dynamically compensates for wind and modeling errors while optimizing energy efficiency by explicitly penalizing excessive actuator commands during trajectory tracking. To achieve multi-agent coordination without continuous network communication, the framework leverages the real-time cable tension estimates (from Thrust 2) as an implicit haptic feedback channel. To ensure the successful real-world deployment and bridge the simulation-to-reality gap, the training pipeline will incorporate extensive domain randomization to guarantee stability against unpredictable physical and aerodynamic disturbances. This synthesis of RL-based control, quantized communication, and physical haptic feedback empowers the UAV team to maintain formation and execute robust, highly agile transport maneuvers while conserving critical energy.

Ultimately, the integration of these three research thrusts establishes a communication-resilient, energy-efficient, and minimally instrumented framework for Cooperative Aerial Manipulation (CAM). This proposed system directly advances the strategic vision of NASA's Aeronautics Research Mission Directorate (ARMD). By achieving trusted multi-agent autonomy without relying on continuous external infrastructure, this research fulfills the ARMD Research Focus Area (RFA) objective of "enabling robust control, vehicle performance, and mission management under nominal conditions, and contingency management under off-nominal conditions."

2 References

[1] S. C. Barakou, C. S. Tzafestas, and K. P. Valavanis, “A comparative study of real-time implementable cooperative aerial manipulation systems,” *arXiv preprint arXiv:2403.14347*, 2024.

[2] J. Estevez, G. Garate, J. M. Lopez-Guede, and M. Larrea, “Review of aerial transportation of suspended-cable payloads with quadrotors,” *Drones*, 2024.

[3] P. X. Wu, C. C. Yang, and T. H. Cheng, “Cooperative transportation of uavs without inter-uav communication,” *IEEE/ASME Transactions on Mechatronics*, 2023.

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[5] P. Kotaru and K. Sreenath, “Multiple quadrotors carrying a flexible hose: dynamics, differential flatness and control,” *arXiv preprint arXiv:1911.12650*, 2019.

[6] E. Costantini, E. L. De Angelis, and F. Giulietti, “Two-time-scale cooperative uav transportation of a cable-suspended load: A minimal swing approach,” *Drones*, 2025.

[7] A. Ollero, M. Tognon, A. Suarez, D. Lee, and A. Franchi, “Past, present, and future of aerial robotic manipulators,” *IEEE Transactions on Robotics*, 2021.

[8] M. J. Fernandez, A. Suarez, A. Ollero, and M. Fumagalli, “Integration of a variable stiffness link for long-reach aerial manipulation,” *arXiv preprint arXiv:2510.15639*, 2025.

[9] L. Xu, H. Lu, J. Wang, H. Oh, and X. G. Guo, “Force-coordination control for aerial collaborative transportation based on lumped disturbance separation and estimation,” *IEEE Transactions on Industrial Electronics*, 2024.

[10] L. Vazquez-Soqui, F. Oliva-Palomo, D. Mercado-Ravell, and P. Castillo, “Sqp-based cable-tension allocation for multi-drone load transport,” *arXiv preprint arXiv:2602.04801*, 2026.

[11] B. Ye, N. Fan, Z. Fan, W. Deng, H. Chen, and Q. Chen, “Flyaware: Inertia-aware aerial manipulation via vision-based estimation and post-grasp adaptation,” *arXiv preprint*, 2026.

[12] S. A. Khursheed, “Cooperative payload transportation by uavs: A model-based deep reinforcement learning (mbdrl) application,” *Master’s Thesis, Virginia Tech*, 2024.

[13] M. Xu, A. Hu, and H. Wang, “Image-based visual impedance force control for contact aerial manipulation,” *IEEE Transactions on Automation Science and Engineering*, 2022.

[14] G. Huang, N. Trawny, A. I. Mourikis, and S. I. Roumeliotis, “On the consistency of multi-robot cooperative localization,” in *Proc. of the Robotics: Science and Systems*, Seattle, WA, Jun. 2009, pp. 65–72.

[15] ——, “Observability-based consistent EKF estimators for multi-robot cooperative localization,” *Autonomous Robots*, vol. 30, no. 1, pp. 99–122, Jan. 2011.

[16] G. Huang, K. Zhou, N. Trawny, and S. I. Roumeliotis, “A bank of maximum a posteriori (MAP) estimators for target tracking,” *IEEE Transactions on Robotics*, vol. 31, no. 1, pp. 85–103, Jan. 2015.

3 Plan for Seeking External Funding

This research aims to develop a proof-of-concept design for agile, robust, and energy-efficient cooperative aerial manipulation framework that operates without payload-mounted sensors or continuous wireless communication by synergizing quantized visual-inertial estimation, real-time visual learning of the load's 6-DoF dynamics and cable tension. Given the broad implications of this technology, it is of considerable interest to various government funding agencies:

- *NSF/NASA EPSCoR Program.* With the preliminary results from this seed project, the PI will be well-equipped to pursue opportunities in the future NSF/NASA EPSCoR program. According to the NASA Strategic Plan, the agency is committed to advancing human and robotic exploration to deepen our understanding of the solar system and the universe. The EPSCoR Research Award is anticipated to call for proposals targeting high-priority research and technology development needs. For instance, as NASA aims to extend human presence to the Moon, Mars, and beyond, precursor robotic missions will explore potential sites and deliver critical data for human explorers. These missions require advanced technologies to cut costs, enhance power efficiency, and increase spacecraft autonomy—priorities that align closely with the PI's expertise in robotic perception and navigation.
- *NASA Planetary Science Research Program and Space Technology Research Grants.* Building on the outcomes of this seed project, the PI will continue collaborating with the NASA JPL Guidance and Control Section, particularly through his former colleague, Nikolas Trawny [14, 15, 16], who spearheaded the Europa Lander Intelligent Landing System. Together, they will develop advanced guidance, navigation, and control (GNC) technologies to enhance NASA's space exploration missions.

4 Relevance to NASA/EPSCoR/RID Mission

Response to NASA missions The integration of the proposed research thrusts establishes a communication-resilient, energy-efficient, and minimally instrumented framework for Cooperative Aerial Manipulation (CAM). This proposed system directly advances the strategic vision of NASA's Aeronautics Research Mission Directorate (ARMD). By achieving trusted multi-agent autonomy without relying on continuous external infrastructure, this research will enable robust control, vehicle performance, and mission management under nominal conditions, and contingency management under off-nominal conditions. Specifically, the quantized communication and dynamic load estimation ensure scalable nominal mission management, while the adaptive RL controller provides critical contingency management against off-nominal aerodynamic disturbances. Furthermore, embedding advanced machine learning—specifically deep learning for spatial perception and RL for adaptive control—into the minimal sensing (visual-inertial) pipeline actively drives ARMD's broader mandate to develop "technologies for vehicle and system-autonomy, robotics, and flight vehicle environment awareness." By bridging the gap between learning-based perception and physical multi-agent control, this project paves the way for the real-world deployment of autonomous aerial systems in complex, unpredictable environments.

Contribute to Delaware EPSCoR This research will push the boundaries of current knowledge by addressing a key challenge in the robotics and guidance, navigation, and control (GNC) community, delivering practical solutions underpinned by rigorous mathematical analysis and robust engineering principles. Its transformative potential lies in groundbreaking theoretical advancements in efficient, consistent state estimation for stochastic nonlinear systems. A central aim of the Delaware EPSCoR program is to bolster the state's economy, and this project aligns seamlessly with that goal. By translating the proposed motion tracking and mapping technologies into unmanned vehicles and mobile devices, this research offers significant potential for applications where positioning infrastructure is absent or cost-prohibitive. These innovations will pave the way for a diverse array of novel AI and robotics applications, driving economic growth in Delaware. Furthermore, this project will create distinctive opportunities for University of Delaware (UD) students to engage in impactful robotics and aerospace research.

5 Budget

TITLE: Cooperative Aerial Manipulation and Load Transportation
PI: Guoquan Huang
Sponsor: NASA/EPSCoR RID SEED

				YEAR 1	
		08/01/2026 - 07/31/2027			
PERSONNEL	*% effort*	*months*			
PI salary - Guoquan Huang	0.00%	0.00			
Co-Pi					
Postdoctoral Researcher					
Postdoctoral Fellow					
Graduate Student # 1	61.19%	12.00			18,357
Undergraduate lab assistant(s)					0
Staff					
FRINGE BENEFITS					
Faculty & Professional			39.10% x	0	0
Graduate Student			14.40% x	18,357	2,643
Undergrad			7.90% x	0	0
Salaried Staff			75.10% x		0
TOTAL SALARIES & WAGES					21,000
TRAVEL					
SUPPLIES					
OTHER					
PUBLICATION					
CONSULTANT					
Yale University SUB <25K					
Yale University SUB >25K					
EQUIPMENT					
TUITION				*AY25/26*	
PARTICIPANT SUPPORT					
TOTAL DIRECT COSTS					21,000
Total Direct Costs Eligible for F&A					
INDIRECT COSTS	months	rate		eligible costs	F&A
FY2023	12	60.00% x			0
Totals	**12**			**0**	**0**
TOTAL PROJECT COSTS					**21,000**

Budget justification One graduate student will devote research effort to this project. Salaries budgeted for graduate students are based on standard University of Delaware graduate student stipends in the Mechanical Engineering Department. As per standard University of Delaware policy, the budget includes fringe benefits on graduate student stipends calculated at 14.4%.

6 Biographical Sketch

Professional Preparation

MIT	Cambridge, MA	CSAIL (Marine Robotics)	Postdoc.	2012-14
Univ. of Minnesota	Minneapolis, MN	Computer Science	Ph.D.	2013
Univ. of Minnesota	Minneapolis, MN	Computer Science	M.Sc.	2009
Univ. of Sci. and Tech. Beijing	Beijing, China	Electrical Engineering	B.Eng.	2002

Appointments

09/2025 – present	Professor	University of Delaware, Newark, DE
09/2020 – 08/2025	Associate Professor	University of Delaware, Newark, DE
09/2014 – 08/2020	Assistant Professor	University of Delaware, Newark, DE
10/2012 – 08/2014	Postdoctoral Associate	MIT, Cambridge, MA
09/2005 – 09/2012	Research Assistant	University of Minnesota, Minneapolis, MN
10/2003 – 08/2005	Research Assistant	Hong Kong Polytechnic University, HK

Distinctions

2025	ACM Senior Member, ACM
2025	AI 2000 Most Influential Scholar Award Honorable Mention (Robotics), AI Open Index
2024	Mid-Career Faculty Excellence in Scholarship Award, University of Delaware
2024	Best Paper Award Finalist (Robot Vision), ICRA 2024
2023-25	AI 2000 Scholar (Top 100 in robotics), AI Open Index
2020-25	World Top 2% Scientists, Stanford University
2023	Best Student Paper Award Finalist, RSS 2023
2022	Best Paper Award, Journal of Guidance, Navigation, and Control (GNC) 2022
2022	Outstanding Paper Award (Navigation), ICRA 2022
2021	Best Paper Award Finalist (Robot Vision), ICRA 2021
2020	IEEE Senior Member, IEEE
2019	FPV Drone Racing VIO Competition Champion, IROS 2019
2009	Best Paper Award Finalist, RSS 2009

Related Prior Work

1. N. Merrill, P. Geneva, S. Katragadda, C. Chen, and G. Huang. Fast and Robust Learned Depth-aided Monocular Visual-Inertial Initialization. *International Journal of Robotics Research (IJRR)*, July 2024.

2. Z. Huai, and G. Huang. A Consistent Parallel Estimation Framework for Visual-Inertial SLAM. *IEEE Transactions on Robotics (T-RO)*, July 2024.

3. Y. Yang, P. Geneva, and G. Huang. Multi-Visual-Inertial System: Analysis, Calibration and Estimation. *International Journal of Robotics Research (IJRR)*, January 2024.

4. Y. Yang, P. Geneva, X. Zuo, and G. Huang. Online Self-Calibration for Visual-Inertial Navigation Systems: Models, Analysis and Degeneracy. *IEEE Transactions on Robotics (TRO)*, May 2023.

5. C. Burgul, W. Lee, P. Geneva, and Guoquan Huang. Online Determination of Legged Kinematics. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2024.

6. N. Merrill, P. Geneva, S. Katragadda, C. Chen, and G. Huang. Fast Monocular Visual-Inertial Initialization Leveraging Learned Single-View Depth. *Robotics: Science and Systems (RSS)*, 2023.

7. C. Chen, P. Geneva, Y. Peng, W. Lee, and G. Huang Monocular Visual-Inertial Odometry with Planar Regularitie. *IEEE International Conference on Robotics and Automation (ICRA)*, 2023.

8. K. Baxevani, I. Yadav, Y. Yang, M. Sebok, H. Tanner, and G. Huang. Resilient Ground Vehicle Autonomous Navigation in GPS-denied Environments. *Guidance, Navigation and Control (GNC)*, November 2022.

9. J. Lv, X. Zuo, K. Hu, J. Xu, G. Huang, and Y. Liu. Observability-Aware Intrinsic and Extrinsic Calibration of LiDAR-IMU Systems. *IEEE Transactions on Robotics (TRO)*, June 2022.

10. W. Lee, Y. Yang, P. Geneva, and G. Huang. Tightly-coupled GNSS-aided Visual-Inertial Localization. *IEEE International Conference on Robotics and Automation (ICRA)*, 2022.

11. N. Merrill, Y. Guo, X. Huang, X. Zuo, S. Leutenegger, L. Ren, and G. Huang. Symmetry and Uncertainty-Aware Object SLAM for 6DoF Object Pose Estimation. *Conference on Computer Vision and Pattern Recognition (CVPR)*, 2022.

12. W. Lee, Y. Yang, and G. Huang. Efficient Multi-sensor Aided Inertial Navigation with Online Calibration. *IEEE International Conference on Robotics and Automation (ICRA)*, 2021.

13. K. Eckenhoff, P. Geneva, and G. Huang. MIMC-VINS: A Versatile and Resilient Multi-IMU Multi-Camera Visual-Inertial Navigation System. *IEEE Transactions on Robotics (TRO)*, 2021.

14. P. Geneva, K. Eckenhoff, W. Lee, Y. Yang, and G. Huang. OpenVINS: An Open Platform for Visual-Inertial Research. *International Conference on Robotics and Automation (ICRA)*, 2020.

Synergistic Activities

1. *Panelist and Reviewer* for US National Science Foundation, Israeli Science Foundation, Dutch Research Council, Canada Foundation for Innovation.

2. State of Delaware Homeland Security Advisory Council, Unmanned Aerial Vehicle (UAV) Subcommittee and Task Force Group, 2014-2019.

3. *Guess Editor* for: IEEE Transactions on Robotics (T-RO) Special Issue on Visual SLAM; Sensors Special Issue on State Estimation for Mobile Robotics.

4. *Associate Editor* for: IEEE Transactions on Robotics (2021-present), IET Cyber-Systems and Robotics (2018-present), IEEE Robotics and Automation Letters (2019-2022), IEEE International Conference on Robotics and Automation (ICRA) (2015-2022), and IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (2017-2022).

5. *Program Chair* for IEEE International Conference on Mobility: Operations, Services, and Technologies (MOST) 2025.

6. *Organizers* for SLAM for AR Competition at ISMAR 2019, VINS Workshops at IROS 2019 and ICRA 2020, and MM-SpatialAI Workshop at ICRA 2026.

7. *Technical Mentor* for FIRST Tech Challenge (Team Green Lemons – PA FTC State Championship).