The PenduMAV: A Novel Energy-Efficient MAV Concept for Omnidirectional Aerial Inspection

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***Abstract*— This extended abstract describes a new multirotor aerial vehicle design and discusses its promising application to aerial physical inspection. The proposed omnidirectional MAV concept uses only six inputs while minimizing internal forces at all attitudes, maximizing energy efficiency. We first provide an overview of the state of the art, and then present the concept, highlighting its potential and viability for inspection tasks.**

I. The Landscape of Aerial Inspection With Multirotors

Inspection from the air has emerged as a promising application domain for multirotor aerial vehicles (MAVs), attracting increasing interest from a wide range of industries over the last decade due to the advantages it offers over conventional inspection approaches. In particular, aerial inspection can deliver a step-change improvement in key non-destructive testing (NDT) performance metrics, including inspection speed, measurement accuracy, repeatability, operational safety, and cost-efficiency [1]. Unlike climbing robotic platforms, which typically require continuous mechanical interaction between the robot body and the structure by crawling, rolling, or adhering to its surface, aerial inspection with MAVs can be performed without the vehicle body landing on, sliding along, or being supported by the inspected surface, helping in minimizing any unnecessary mechanical load applied to that surface.

The scope of aerial inspection spans both contact-free and contact-based tasks. Non-contact inspection encompasses visual inspection with for eaxmple RGB cameras or laser scanners mounted on the MAV [2], thermographic inspection using infrared sensors [3], multispectral or hyperspectral imaging [4], and three-dimensional geometric reconstruction via LiDAR or depth cameras [5], [6]. Such sensing techniques are particularly suitable for detecting visible cracks, corrosion, delamination, geometric misalignment, and thermal anomalies without direct physical interaction with the inspected structure. By contrast, contact-based aerial inspection requires the MAV to establish and sustain a controlled contact force and torque with the surface. Typical examples include ultrasonic testing [7], eddy-current inspection, thickness gauging, and tactile probing for barely visible damages or surface-profile reconstruction [8]. In this scenario, the MAV must accurately regulate contact forces and maintain a stable interaction pose throughout task execution. In both categories, the MAV must be able to properly orient the sensor relative to the inspection surface, which is of crucial importance to the success of the inspection task [7].

Conventional quadrotor cannot independently control their attitude and position [9], which prevents the free orientation of a rigidly-attached sensor. To overcome this limitation, an additional mechanism, such as a robotic arm or a gimbal, can be mounted on the platform [10], [11]. However, this comes at the expense of increased weight, cost, and mechanical complexity, together with the added maintenance overhead associated with the extra moving parts. Alternatively, to enable full control of the sensor attitude, omnidirectional MAV designs have been proposed in several works [12]–[14]. These platforms belong to the class of fully actuated aerial vehicles [15], for which attitude and position are separately controllable, allowing the sensor to be oriented such that it matches the inspection surface inclination without sacrificing the ability to independently track a desired position. This is necessary in those inspection tasks that require continuous contact, for example, sliding a tactile sensor along an inclined surface for geometric reconstruction [16]. Two common characteristics of omnidirectional multirotors are that they are often equipped with more actuators than the dimension of the wrench space [17], and that, depending on the vehicle attitude, significant internal forces may arise [18]. This can increase the vehicle's weight, cost and power consumption.

In [19], we propose a novel MAV design with exactly six actuators, equal to the six degrees of freedom of the base pose: four brushless motors driving four propellers, three of which are mounted on rigid links that are connected to the base through passive 2-DoF joints, while the vectoring of the fourth propeller is actively controlled by two servomotors. Moreover, static hovering is shown to be feasible at any base pose in SE(3). This vehicle has no internal forces arising at equilibrium regardless of the base pose, thanks to the links resembling pendula whose configurations at equilibrium become vertical due to the restoring gravity torque acting on the passive joint variables. Finally, the system can be rendered locally asymptotically stable around equilibrium, and the passive joint dynamics are shown to constitute asymptotically stable zero dynamics. We describe the concept in more details in the next section.

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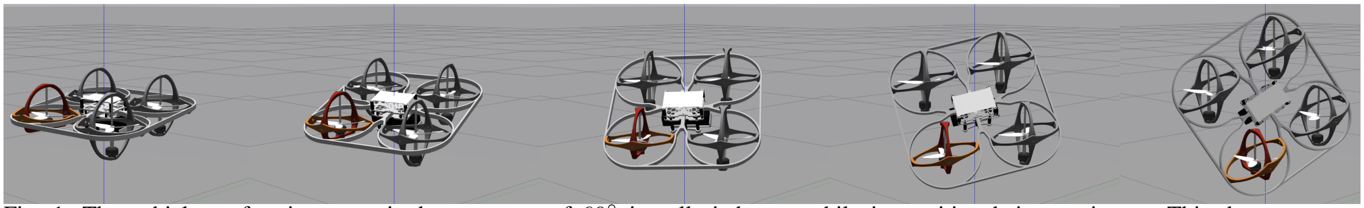

Fig. 1: The vehicle performing an attitude maneuver of 60° in roll-pitch-yaw while its position being stationary. This demonstrates decoupling between attitude and position.

II. Vehicle Concept and Design

The proposed PenduMAV concept, shown in Fig. 2 consists of a main rigid body, referred to as the base, and four smaller propeller-carrying rigid bodies, referred to as links. Each link, together with its rigidly attached motor and propeller, forms an actuation unit connected to the base through a 2-DoF joint. In each unit, the two mutually orthogonal joint axes intersect at the propeller center, which defines the center of rotation of the link. The four actuation units are arranged such that all their centers of rotation lie in the same plane, resulting in a coplanar vehicle architecture, which is favorable, as aerodynamic interference effects between the propellers are largely avoided. Three of the links are designed so that their centers of mass lie below their respective centers of rotation, achieved by placing the motors sufficiently below the propeller blades. As a result, these three units behave as spatial pendula suspended from passive universal joints. By contrast, the fourth unit is designed such that its center of mass coincides with its center of rotation, and it is connected to the base through an actuated universal joint driven by two servomotors, controlling the vectoring of the corresponding propeller.

Videos of Gazebo simulations where the vehicle performs a wide range of maneuvers under realistic conditions are available at `https://www.youtube.com/playlist?list=PL4N8pJgvqASQX6AWEpg3NCZ6QdGBPfbXq`. This verifies that the proposed concept can be realizable in practice.

III. Application to Aerial Inspection

This vehicle can be employed for physical-interaction tasks by mounting a sensor at the end-effector placed in a suitable location of the chassis, as depicted in Fig. 2. A key advantage of this design is that it allows the sensor to track arbitrary trajectories in SE(3) with reduced control effort, as illustrated in the Fig. 3 where, during the 270° roll maneuver, the excess internal forces remain within 2% throughout. This solution outperforms omnidirectional MAVs with fixedly-tilted propellers that provide a similar range of motion but at the expense of generating significant internal forces [18]. Furthermore, it does not have the drawbacks of redundant actuation [17], [20], which can increase weight, cost and battery power consumption.

IV. Conclusion

We presented a design that achieves omnidirectionality with minimal actuation while minimizing internal forces,

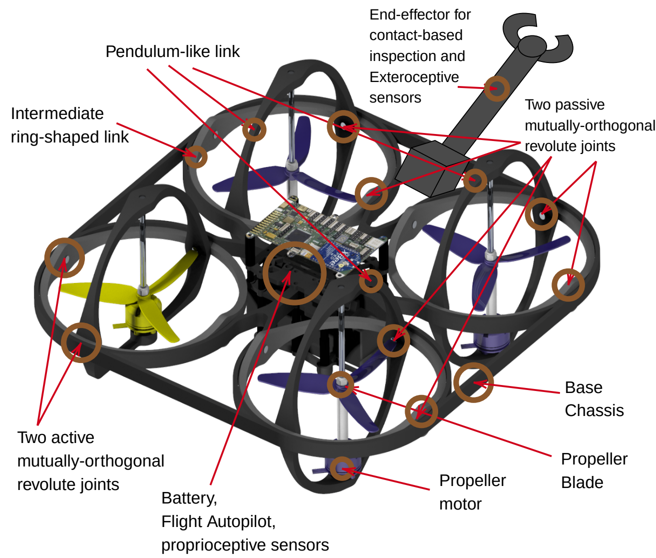

Fig. 2: The PenduMAV: schematics describing the vehicle components.

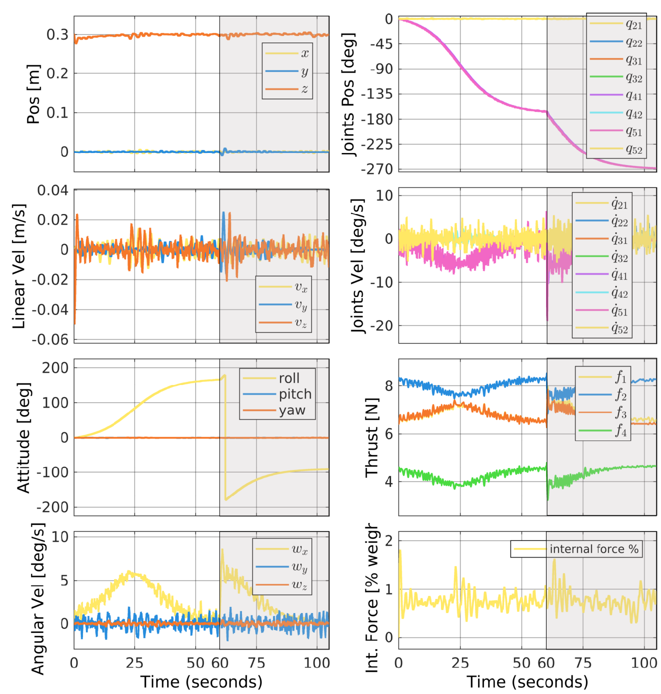

Fig. 3: Simulation results of PenduMAV rotating around roll by 270° in two steps: 170° before 60s and 270° afterward, while keeping its position fixed. Notice that the internal forces remain below 2% of the weight during the whole maneuver despite the large change in the attitude.

thus enhancing its potential for highly energy-efficient omnidirectional interaction. The design also exhibits favorable scaling properties, as the hovering load is shared almost uniformly among the propellers, preventing the actively tilting unit from being excessively loaded. The main scaling issues are the same as those commonly faced by multirotor systems, such as propeller sizing and battery design, rather than being specific to the proposed MAV architecture. Future work will concentrate on the long-term realization, implementation, and experimental validation of the mechanical concept in contact-based physical interaction scenarios.

REFERENCES

[1] P. Nooralishahi, C. Ibarra-Castanedo, S. Deane, F. López, S. Pant, M. Genest, N. P. Avdelidis, and X. P. V. Maldague, "Drone-based non-destructive inspection of industrial sites: A review and case studies," *Drones*, vol. 5, no. 4, 2021. [Online]. Available: https://www.mdpi.com/2504-446X/5/4/106

[2] J. Quenzel, M. Nieuwenhuisen, D. Droeschel, M. Beul, S. Houben, and S. Behnke, "Autonomous mav-based indoor chimney inspection with 3d laser localization and textured surface reconstruction," *Journal of Intelligent & Robotic Systems*, vol. 93, no. 1, pp. 317–335, 2019.

[3] S. Gallardo-Saavedra, L. Hernández-Callejo, and O. Duque-Perez, "Technological review of the instrumentation used in aerial thermographic inspection of photovoltaic plants," *Renewable and Sustainable Energy Reviews*, vol. 93, pp. 566–579, 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032118303708

[4] E. A. Bolch, E. L. Hestir, and S. Khanna, "Performance and feasibility of drone-mounted imaging spectroscopy for invasive aquatic vegetation detection," *Remote Sensing*, vol. 13, no. 4, p. 582, 2021.

[5] M. Memari, P. Shakya, M. Shekaramiz, A. C. Seibi, and M. A. S. Masoum, "Review on the advancements in wind turbine blade inspection: Integrating drone and deep learning technologies for enhanced defect detection," *IEEE Access*, vol. 12, pp. 33 236–33 282, 2024.

[6] L. Yoder and S. Scherer, "Autonomous exploration for infrastructure modeling with a micro aerial vehicle," in *Field and Service Robotics: Results of the 10th International Conference*. Springer, 2016, pp. 427–440.

[7] C. M. G. D. W. G. Dayi Zhang, Robert Watson and G. Pierce, "Implementation and evaluation of an autonomous airborne ultrasound inspection system," *Nondestructive Testing and Evaluation*, vol. 37, no. 1, pp. 1–21, 2022. [Online]. Available: https://doi.org/10.1080/10589759.2021.1889546

[8] M. Schuster, A. Bredenbeck, M. Beitelschmidt, and S. Hamaza, "Tactile odometry in aerial physical interaction," in *2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2024, pp. 8103–8110.

[9] R. Mahony, V. Kumar, and P. Corke, "Multirotor aerial vehicles: Modeling, estimation, and control of quadrotor," *IEEE Robotics Automation Magazine*, vol. 19, no. 3, pp. 20–32, 2012.

[10] H. Yang and D. Lee, "Dynamics and control of quadrotor with robotic manipulator," in *2014 IEEE international conference on robotics and automation (ICRA)*. IEEE, 2014, pp. 5544–5549.

[11] A. Ollero, M. Tognon, A. Suarez, D. Lee, and A. Franchi, "Past, present, and future of aerial robotic manipulators," *IEEE Transactions on Robotics*, vol. 38, no. 1, pp. 626–645, 2022.

[12] M. Hamandi, Q. Sable, M. Tognon, and A. Franchi, "Understanding the omnidirectional capability of a generic multi-rotor aerial vehicle," in *2021 Aerial Robotic Systems Physically Interacting with the Environment (AIRPHARO)*, 2021, pp. 1–6.

[13] Y. Aboudorra, C. Gabellieri, R. Brantjes, Q. Sablé, and A. Franchi, "Modelling, analysis, and control of omnimorph: an omnidirectional morphing multi-rotor uav," *Journal of Intelligent & Robotic Systems*, vol. 110, no. 1, p. 21, 2024.

[14] T. D. Howard, C. Molter, C. D. Seely, and J. Yee, "The lynchpin—a novel geometry for modular, tangential, omnidirectional flight," *SAE International Journal of Aerospace*, vol. 16, no. 3, pp. 291–303, mar 2023. [Online]. Available: https://doi.org/10.4271/01-16-03-0018

[15] R. Rashad, J. Goerres, R. Aarts, J. B. C. Engelen, and S. Stramigioli, "Fully actuated multirotor uavs: A literature review," *IEEE Robotics Automation Magazine*, vol. 27, no. 3, pp. 97–107, 2020.

[16] K. Bodie, M. Brunner, M. Pantic, S. Walser, P. Pfändler, U. Angst, R. Siegwart, and J. Nieto, "Active interaction force control for contact-based inspection with a fully actuated aerial vehicle," *IEEE Transactions on Robotics*, vol. 37, no. 3, pp. 709–722, 2021.

[17] M. Kamel, S. Verling, O. Elkhatib, C. Sprecher, P. Wulkop, Z. Taylor, R. Siegwart, and I. Gilitschenski, "The voliro omniorientational hexacopter: An agile and maneuverable tiltable-rotor aerial vehicle," *IEEE Robotics Automation Magazine*, vol. 25, no. 4, pp. 34–44, 2018.

[18] D. Brescianini and R. D'Andrea, "Design, modeling and control of an omni-directional aerial vehicle," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, 2016, pp. 3261–3266.

[19] A. Ali, C. Gabellieri, and A. Franchi, "The pendumav: A six-input omnidirectional mav without internal forces – design, dynamics, and se(3) control," 2026. [Online]. Available: https://arxiv.org/abs/2510.15071

[20] M. Zhao, T. Anzai, F. Shi, X. Chen, K. Okada, and M. Inaba, "Design, modeling, and control of an aerial robot dragon: A dual-rotor-embedded multilink robot with the ability of multi-degree-of-freedom aerial transformation," *IEEE Robotics and Automation Letters*, vol. 3, no. 2, pp. 1176–1183, 2018.