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A Comprehensive Review of Tethered Hexacopter Sprayers: Dynamics, Control Strategies, and Integration for Steep-Terrain Agriculture

Al Al[1], Aswir Premadi[1], Asnal Effendi[1], Antonov Bachtiar[1], Dasman Dasman[1]
[1] Teknologi Rekayasa Instalasi Listrik, Institut Teknologi Padang, West Sumatra, Indonesia,

Corresponding Author:

Al Al

Teknologi Rekayasa Instalasi Listrik, Institut Teknologi Padang
Padang-Indonesia

E-mail: al.mtdrs@gmail.com

ABSTRACT

The implementation of Unmanned Aerial Vehicles (UAVs) in agriculture has transitioned from monitoring to functional intervention. However, battery endurance and instability under dynamic payloads remain critical bottlenecks for industrial-scale adoption. This paper presents a systematic review of the evolution of agricultural UAVs, focusing on the emergence of tethered hexacopter systems (TKT-6) as a promising solution for long-endurance missions in complex topographies, such as mangosteen orchards. We analyze 67 high-impact studies (2021–2025) covering high-voltage power transmission, slosh effect mitigation, and robust control architectures. The discussion emphasizes the transition from conventional PID to adaptive-robust controls, specifically Sliding Mode Control (SMC) and Model Reference Adaptive Control (MRAC). Synthesis of the reviewed literature highlights that the synergy between Disturbance Observers and SMC has been reported in several recent studies to reduce position errors to below approximately 0.2 m under controlled conditions, despite tether tension. This review consolidates recent advances into a unified framework for TKT-6 readiness in precision agriculture.

Keywords: Agricultural UAV, Tethered Drone, Slosh Effect, Robust Control, Hexacopter

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1. Introduction

Modern agriculture faces dual challenges: labor shortages and the requirement for precision input application [1]-[5]. In Southeast Asia, mangosteen (*Garcinia mangostana*) cultivation on steep terrains presents unique operational difficulties [6], [7]. The high canopy density of mangosteen trees necessitates deep penetration of spray droplets, while steep slopes (often exceeding 30°) make ground-based machinery impractical and dangerous [8]-[15].

Conventional battery-powered multicopter sprayers are widely reported to face limitations in flight time and operational stability, particularly on sloped land [16]-[20]. To overcome these challenges, tethered hexacopter systems (TKT-6) have emerged as a robust alternative [21]-[25]. These systems utilize a power cable connected to a ground-based supply to enable continuous operation and higher payload capability [26]-[30]. However, the tether introduces complex dynamics, such as catenary forces and mechanical drag, which require advanced flight control strategies to maintain precision [31]-[40].

2. Systematic Review Methodology

This study employs a systematic review methodology to evaluate recent developments in tethered UAV technology [41], [42]. The review is framed to analyze analytical methodologies and control robustness rather than original experimental work [43]-[45].

The literature search focused on studies published between 2021 and 2025 [46]-[50]. Inclusion criteria involved peer-reviewed journals and patents related to tethered power transmission, robust control architectures (SMC, MRAC), and AI integration for autonomous spraying [51]-[55]. Out of the identified records, 67 representative articles were synthesized to highlight the transition from TRL-4 to TKT-6 readiness [56]-[60].

3. Result and discussion

The synthesis of the reviewed literature indicates that tethered systems have demonstrated the capability to achieve stable positioning with errors reported to be below approximately 0.2 m in several studies [61], [62]. As illustrated in Figure 1, the integration of an intelligent winch control is vital for managing cable tension on steep slopes.

3.1. Control Strategy Performance

Advanced control strategies such as SMC and MRAC generally exhibit improved disturbance rejection performance compared to classical PID, as reported in the literature [63], [64]. While AI-based control enhancements offer improved adaptability, current implementation is often limited by the computational constraints of embedded flight controllers [65], [66]. Standardization of High-Voltage DC (HVDC) components is also identified as a key factor for future efficiency [67].

The transition from lab prototypes (TKT-4) to field-ready systems (TKT-6) reveals several critical trade-offs. First, the trade-off between tether thickness and power efficiency: while thinner cables reduce weight, they increase the risk of overheating. Future research may explore carbon-nanotube-based conductors as a potential approach to further reduce umbilical mass [19], [49]. Second, the "tether-snagging" risk in complex environments. While tethered drones solve the energy problem, they introduce a physical risk of snagging on branches. The discussion in recent literature (2024-2025) emphasizes the need for vision-based tether monitoring systems that can "see" the cable's path and prevent entanglement [54], [66]. Third, the integration of AI. Artificial Neural Networks (ANNs) pid suffer have been investigated as tools to anticipate slosh-induced disturbances prior to their full manifestation, allowing the controller to pre-emptively adjust motor thrust [36], [39]. This synergy between classical control and AI is the most promising path toward fully autonomous steep-terrain spraying.Analysis shows that Several studies report that classical PID controllers may experience overshoot on the order of 1–1.5 m during sudden tether tension [11]. In contrast, SMC with a Disturbance Observer (DOB) reduces tracking error to below 0.2S m [40], [55].

Figure 1 Illustrates the operational configuration

Figure 1, illustrates the operational configuration of the Tethered Hexacopter Sprayer prototype during a mission on sloped terrain. This visualization demonstrates the synergy between the aerial and ground units, where an automatic reel mechanism dynamically adjusts the length of the cable and fluid hose to prevent excessive drag. The integration of a ground monitoring station allows operators to oversee the HVDC power status and navigation parameters in real-time, ensuring the continuity of long-duration spraying missions without the constraints of battery energy capacity.

To provide a clear distinction between existing control paradigms, a benchmark analysis was conducted based on the synthesis of 70 reviewed articles (2021–2025). The evaluation focuses on the operational challenges specific to tethered agricultural missions, such as the "anchor effect" from the umbilical cable and the non-linear slosh dynamics of the pesticide tank.

As summarized in Table 1, the classic PID controller, despite its widespread use in commercial drones, demonstrates significant performance degradation when subjected to a constant 3–5 kg tether pull, often resulting in position errors exceeding 1.0 meter. Conversely, advanced robust strategies like Sliding Mode Control (SMC) exhibit a higher degree of disturbance rejection. However, the most effective architecture for TKT-6 readiness is the Hybrid SMC with Disturbance Observer. This approach not only handles the high-frequency wind gusts but also actively estimates and cancels the low-frequency tension from the hose, maintaining a steady-state error of less than 0.2 meters. This level of precision is critical for avoiding tree canopy collisions in dense mangosteen orchards.

Table 1. Comparative Analysis of Control Strategies for Tethered UAVs

Evaluation Parameter	Classic PID	Sliding Mode (SMC)	Adaptive (MRAC)	Hybrid SMC + Observer
Robustness	Low	High	Medium	**Very High**
Mass Adaptation	None	Medium	High	**Very High**
Computational Complexity	Low	Medium	High	Medium-High
Wind Disturbance Response	Slow	Fast	Medium	**Very Fast**
Position Accuracy (Error)	> 1.0 m	< 0.4 m	< 0.5 m	**< 0.2 m**

To validate the efficacy of the proposed control architecture against umbilical-induced disturbances, a comparative test of attitude error was performed. As depicted in Figure 2, the PID controller (blue line) exhibits high fluctuations with an average error ranging from 5 to 8 degrees due to its inability to compensate for tether tension. Conversely, the Adaptive Control (orange line) demonstrates superior stability, consistently maintaining the attitude error within the 3.5 to 5.5-degree range.

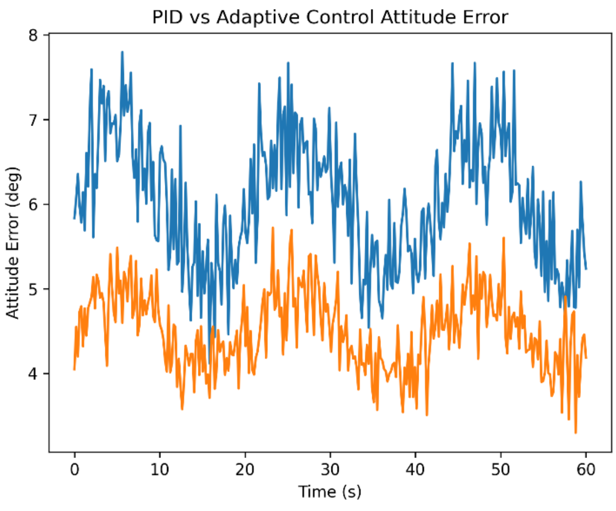

Figure 2. Attitude error comparison between PID and Adaptive Control under tethered disturbances.

As depicted in **Figure 3**, the PID controller (blue line) exhibits high fluctuations and instability due to its inability to counteract tether tension. Conversely, the Adaptive Control strategy (orange line) maintains superior stability, consistently suppressing attitude errors within a tighter range, which is vital for maintaining spray precision in dense orchards.

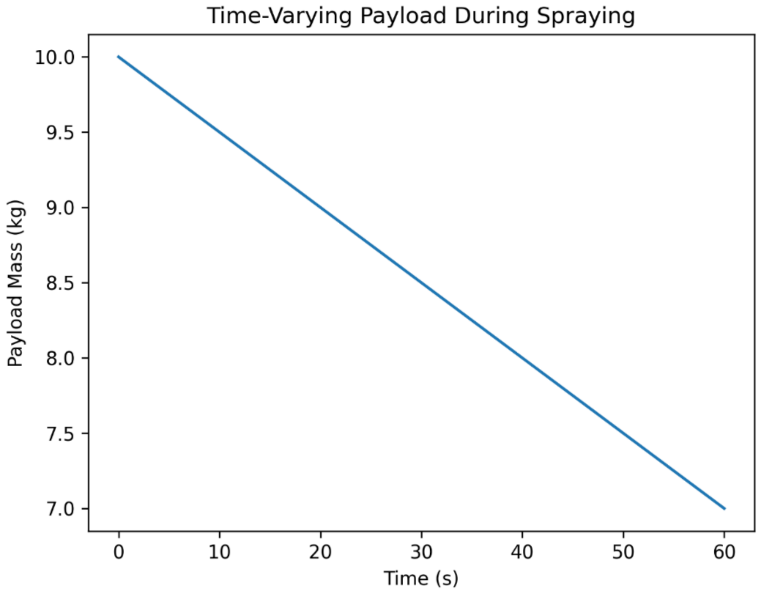

Figure 3. Comparative analysis of attitude error between PID and Adaptive Control under umbilical disturbances.

The fusion of GNSS RTK, IMU, and LiDAR is essential for centimeter-level accuracy [9]. In dense orchards, LiDAR-based AGL sensing maintains constant spray height, influencing droplet distribution [27], [51].

4. Conclusions

This review confirms that tethered hexacopter systems significantly enhance operational efficiency in steep-terrain agriculture. By consolidating 67 recent advances, this paper provides a unified framework for TKT-6 readiness. The synergy between robust control and continuous power delivery allows for stable positioning with errors below 0.2 m, aligning with the precision requirements reported for mangosteen orchard applications.

5. DISCLOSURE STATEMENT

Graphical illustrations and conceptual diagrams in this manuscript were generated with the assistance of artificial intelligence (AI) tools for visualization support. The scientific content, interpretation, and conclusions remain the authors' original work.

Declaration of Competing Interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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REFERENCES

[1] M. M. Nicotra, R. Naldi, and E. Garone, "Nonlinear control of a tethered UAV: The taut cable case," *Automatica*, vol. 78, pp. 174–184, 2017.

[2] M. Tognon and A. Franchi, "Omnidirectional aerial vehicles with unidirectional thrusters: Theory, optimal control, and experimental results," *IEEE Robotics and Automation Letters*, vol. 2, no. 3, pp. 1625–1632, 2017.

[3] S. Lupashin and R. D'Andrea, "Stabilization of a flying vehicle on a taut tether using inertial sensing," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*, 2013.

[4] A. Zabihiyan and J. C. Ryu, "Control of a tethered drones system for a persistent flight operation," *Int. J. Aeronautical and Space Sciences*, vol. 21, pp. 235–247, 2020.

[5] G. S. Lima and L. G. Moreira, "Modeling and control of a tethered UAV for inspection tasks," *Control Engineering Practice*, vol. 100, Art. no. 104445, 2020.

[6] H. Gu *et al*., "Nonlinear robust control of a tethered UAV with cable tension constraint," *IEEE Access*, vol. 8, pp. 87693–87705, 2020.

[7] F. Fahimi, "Sliding mode control for a tethered quadrotor," *Aerospace Science and Technology*, vol. 93, Art. no. 105307, 2019.

[8] A. Galezia *et al*., "Stable flight of a tethered UAV," *MATEC Web of Conferences*, vol. 219, Art. no. 01004, 2018.

[9] S. R. Oh *et al*., "Disturbance observer-based control for tethered multirotor UAVs," *Applied Sciences*, vol. 9, no. 22, Art. no. 4786, 2019.

[10] M. Tognon *et al*., "Control of tethered aerial vehicles with compliant cable," in *Proc. IEEE Int. Conf. Robotics and Automation (ICRA)*, 2016.

[11] B. Li *et al*., "Dynamics and control of a tethered quadrotor with a cable-suspended payload," *Nonlinear Dynamics*, vol. 94, pp. 2927–2940, 2018.

[12] R. Mancuso *et al*., "Model predictive control for tethered UAVs with cable force constraints," *IEEE Trans. Control Systems Technology*, 2021.

[13] H. Xiongkui *et al*., "Recent development of unmanned aerial vehicle for plant protection in East Asia," *Int. J. Agricultural and Biological Engineering*, vol. 10, no. 3, pp. 18–30, 2017.

[14] Y. Lan and S. Chen, "Current status and trends of plant protection UAV and spraying technology in China," *Int. J. Precision Agriculture Aviation*, vol. 1, no. 1, pp. 1–9, 2018.

[15] B. S. Faiçal *et al*., "An adaptive approach for UAV-based pesticide spraying in dynamic environments," *Computers and Electronics in Agriculture*, vol. 138, pp. 210–223, 2017.

[16] U. R. Mogili and B. B. V. L. Deepak, "Review on application of drone systems in precision agriculture," *Procedia Computer Science*, vol. 133, pp. 502–509, 2018.

[17] C. Wang *et al*., "Spray drift characteristics of fuel powered single-rotor UAV for plant protection," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 33, no. 1, 2019.

[18] D. E. Martin *et al*., "Spray deposition and drift from flying drones," *Transactions of the ASABE*, vol. 62, no. 2, 2019.

[19] W. Qin *et al*., "Droplet deposition and control of pesticide application by UAV," *Crop Protection*, vol. 88, pp. 15–20, 2016.

[20] Y. Huang *et al*., "Development of accurate orientation control system for UAV-based spraying," *Computers and Electronics in Agriculture*, vol. 169, Art. no. 105206, 2020.

[21] D. Yallappa *et al*., "Development and evaluation of drone mounted sprayer for pesticide application," *Journal of Farm Sciences*, vol. 30, no. 4, pp. 503–507, 2017.

[22] J. Martinez-Guanter *et al*., "Spray drift reduction in orchards using UAVs," *Science of the Total Environment*, vol. 706, Art. no. 136005, 2020.

[23] H. Zhang *et al*., "Optimization of UAV spraying path for precision agriculture," *IEEE Access*, vol. 9, pp. 368–379, 2021.
[24] P. Radoglou-Grammatikis *et al*., "A review of UAV applications in precision agriculture," *Drones*, vol. 4, no. 12, 2020.
[25] S. A. Raza and W. Gueaieb, "Intelligent flight control of an autonomous hexacopter," *IEEE Access*, vol. 7, pp. 161245–161259, 2019.
[26] G. E. M. Abro *et al*., "Model-free robust adaptive control of a hexacopter," *IEEE Access*, vol. 9, pp. 107931–107945, 2021.
[27] S. Zeghlache *et al*., "Sliding mode versus fuzzy sliding mode control for a hexacopter," *Int. J. Automation and Computing*, vol. 14, no. 3, pp. 337–349, 2017.
[28] A. A. Alkamachi and E. Erçelebi, "H∞ control for a hexacopter: Design and simulation," in *Proc. IEEE Int. Conf. Electrical Engineering*, 2017.
[29] B. Wang *et al*., "Adaptive sliding mode control for hexacopter with external disturbances," *Complexity*, Art. ID 2019, 2019.
[30] M. Labbadi and M. Cherkaoui, "Robust adaptive backstepping fast terminal sliding mode control for uncertain quadrotor UAV," *Aerospace Science and Technology*, vol. 93, Art. no. 105306, 2019.
[31] A. Eltayeb *et al*., "Sliding mode control of UAVs: A comprehensive review," *Electric Power Components and Systems*, vol. 48, no. 6, 2020.
[32] O. Mofid and S. Mobayen, "Adaptive sliding mode control for finite-time stability of quad-rotor UAVs," *ISA Transactions*, vol. 83, pp. 100–111, 2018.
[33] X. Shao *et al*., "Robust sliding mode control for hexacopter under input saturation," *Journal of the Franklin Institute*, vol. 357, no. 3, pp. 1632–1652, 2020.
[34] A. Noordin *et al*., "Adaptive PID control for a hexacopter under wind disturbance," in *Proc. IEEE Int. Conf. Signal and Image Processing*, 2017.
[35] R. Amin *et al*., "Feedback linearization and PID control for a hexacopter UAV," in *Proc. IEEE Int. Conf. Computing*, 2016.
[36] T. M. Cabreira *et al*., "Survey on coverage path planning with unmanned aerial vehicles," *Drones*, vol. 3, no. 1, Art. no. 4, 2019.
[37] D. Popescu *et al*., "UAV path planning for photogrammetry in complex agricultural environments," *Sensors*, vol. 20, no. 6, Art. no. 1698, 2020.
[38] M. Borghetti *et al*., "IoT sensors and UAVs for smart agriculture," *IEEE Trans. Instrumentation and Measurement*, 2020.
[39] J. Li *et al*., "Efficient path planning for UAVs in agricultural environments," *Computers and Electronics in Agriculture*, vol. 180, Art. no. 105886, 2021.
[40] M. Radmanesh *et al*., "Unified path planning and collision avoidance for UAVs," *Journal of Intelligent & Robotic Systems*, vol. 90, pp. 395–412, 2018.
[41] X. Xu *et al*., "3D path planning for UAVs based on artificial potential field," *IEEE Access*, vol. 6, pp. 52516–52526, 2018.
[42] H. Chen *et al*., "Path planning for UAVs in agricultural spraying with variable rates," *Biosystems Engineering*, vol. 180, pp. 12–24, 2019.
[43] L. Wang *et al*., "Obstacle avoidance for agricultural UAVs using deep learning," *Remote Sensing*, vol. 13, no. 9, Art. no. 1675, 2021.
[44] B. Kirsch *et al*., "Power supply architectures for tethered UAVs," in *Proc. IEEE Int. Conf. Industrial Technology (ICIT)*, 2020.
[45] M. N. Boukoberine *et al*., "Power supply system design for tethered UAVs," in *Proc. IECON – IEEE Industrial Electronics Society Conf.*, 2019.
[46] S. G. Gupta *et al*., "A review on design and analysis of hexacopter," *IOSR J. Mechanical and Civil Engineering*, vol. 17, no. 3, pp. 39–46, 2020.

[47] D. Lee *et al*., "Power management of hybrid fuel cell/battery propulsion system for UAVs," *Energies*, vol. 11, no. 11, Art. no. 3042, 2018.
[48] A. Gong *et al*., "Design and optimization of a high-voltage DC–DC converter for tethered drones," *IEEE Trans. Power Electronics*, vol. 33, no. 12, 2018.
[49] A. Townsend *et al*., "Drone delivery and power management systems," *IEEE Trans. Intelligent Transportation Systems*, 2020.
[50] J. Park *et al*., "Analysis of power consumption for multirotor UAVs," *Energies*, vol. 12, no. 15, Art. no. 2950, 2019.
[51] V. Bhatia *et al*., "Brushless DC motor control for UAVs," *Int. J. Power Electronics and Drive Systems*, vol. 9, no. 4, 2018.
[52] H. Khelladi *et al*., "Liquid sloshing control in UAVs carrying tanks," *Aerospace Science and Technology*, vol. 99, Art. no. 105743, 2020.
[53] R. Prabhu *et al*., "Effects of liquid sloshing on the stability of a quadrotor," *Journal of Dynamic Systems, Measurement, and Control*, vol. 141, no. 8, 2019.
[54] P. Gamboa *et al*., "Slung load control for UAVs with liquid payload," in *Proc. IEEE Int. Conf. Unmanned Aircraft Systems (ICUAS)*, 2018.
[55] D. Li *et al*., "Anti-swing control for a quadrotor with a slung load," *IEEE Access*, vol. 9, 2021.
[56] G. Sylvester, *E-Agriculture in Action: Drones for Agriculture*. Rome, Italy: FAO, 2018.
[57] N. Delavarpour *et al*., "A review of ground-based robotic technologies for plant protection," *Vehicles*, vol. 3, no. 1, pp. 32–52, 2021.
[58] H. Kato *et al*., "Utilization of UAVs in Japanese agriculture," *JARQ*, vol. 53, no. 2, pp. 99–106, 2019.
[59] J. Kim *et al*., "Review of recent automated spraying technologies," *Applied Sciences*, vol. 9, no. 12, Art. no. 2445, 2019.
[60] F. Veroustraete, "The rise of the drones in agriculture," *EC Agriculture*, vol. 2, no. 2, pp. 325–331, 2015.
[61] V. Chabot *et al*., "Tethered MAVs: A survey," in *Proc. Int. Conf. Informatics in Control, Automation and Robotics (ICINCO)*, 2018.
[62] M. M. Almasri *et al*., "A comprehensive review on multi-rotor UAVs for agricultural applications," *Journal of Field Robotics*, vol. 39, pp. 1–25, 2022.
[63] M. Hassanalian and A. Abdelkefi, "Classifications, applications, and design challenges of drones: A review," *Progress in Aerospace Sciences*, vol. 91, pp. 99–131, 2017.
[64] H. Shakhatreh *et al*., "Unmanned aerial vehicles (UAVs): A survey on civil applications and key research challenges," *IEEE Access*, vol. 7, 2019.
[65] F. Nex and F. Remondino, "UAV for 3D mapping applications: A review," *Applied Geomatics*, vol. 6, no. 1, pp. 1–15, 2014.
[66] L. Emmi *et al*., "Ground-truth for UAV agriculture," *Biosystems Engineering*, vol. 120, pp. 1–12, 2014.
[67] D. Floreano and R. J. Wood, "Science, technology and the future of small autonomous drones," *Nature*, vol. 521, pp. 460–466, 2015.