Robust Planning and Control of Omnidirectional MRAVs for Aerial Communications in Wireless Networks

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***Abstract*— A new class of Multi-Rotor Aerial Vehicles (MRAVs), known as omnidirectional MRAVs (o-MRAVs), has gained attention for their ability to independently control 3D position and orientation. This capability enhances robust planning and control in aerial communication networks, enabling more adaptive trajectory planning and precise antenna alignment without additional mechanical components. These features are particularly valuable in uncertain environments, where disturbances such as wind and interference affect communication stability. This paper examines o-MRAVs in the context of robust aerial network planning, comparing them with the more common under-actuated MRAVs (u-MRAVs). Key applications, including physical layer security, optical communications, and network densification, are highlighted, demonstrating the potential of o-MRAVs to improve reliability and efficiency in dynamic communication scenarios.**

Full-version

The full-version of this paper is available at `https://ieeexplore.ieee.org/document/10829762`. To reference, see [1].

I. Introduction

The integration of Multi-Rotor Aerial Vehicles (MRAVs) into wireless networks has gained significant attention due to their agility, rapid deployment capabilities, and ability to establish line-of-sight communication. However, most Unmanned Aerial Vehicles (UAVs) used in communication systems are under-actuated MRAVs (u-MRAVs), which lack independent control over their 3D position and orientation. This limitation poses challenges in maintaining precise antenna alignment, especially for high-frequency technologies like millimeter-wave and terahertz communications, which require accurate beam alignment.

To overcome these challenges, omnidirectional MRAVs (o-MRAVs) have been introduced. Unlike traditional u-MRAVs, o-MRAVs can control both their position and orientation independently, enabling enhanced communication-aware trajectory planning and more reliable network performance. This capability is particularly advantageous for applications such as physical layer security, Free-Space Optical (FSO) communications, and interference mitigation. Despite their advantages, o-MRAVs introduce additional complexity in terms of design, control strategies, and energy efficiency, which must be addressed for their practical deployment in real-world scenarios.

This paper explores the potential of o-MRAVs in enhancing aerial communication robustness in dynamic environments. It presents their unique capabilities compared to traditional UAVs and discusses the challenges and opportunities associated with their integration into modern communication networks.

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II. System Model and Control Capabilities

o-MRAVs introduce a novel control paradigm in MRAV-enabled communication networks. Unlike u-MRAVs, which couple position and orientation, o-MRAVs possess full actuation, allowing independent 3D position and orientation control. This capability enables robust motion planning and precise antenna alignment, crucial for high-frequency wireless communication technologies such as mmWave and terahertz bands.

The actuation design of o-MRAVs relies on advanced tilting and bidirectional propeller mechanisms, enabling precise adjustments to compensate for disturbances. In contrast to u-MRAVs, which require movement to adjust antenna direction, o-MRAVs can maintain optimal alignment without altering their trajectory, ensuring consistent communication quality. These control advantages are particularly significant in scenarios requiring low-latency, high-reliability links, such as aerial base stations and disaster recovery networks.

III. Aerial Communication Applications

The unique control characteristics of o-MRAVs open new avenues for robust planning and optimization in wireless networks, enabling advancements in areas such as physical layer security, free-space optical communications, and network densification. These capabilities enhance communication reliability, interference mitigation, and adaptive network deployment, making o-MRAVs a valuable asset in dynamic and uncertain environments.

Physical Layer Security and Anti-Jamming. Wireless network security is highly dependent on the radiation patterns of the antennas used by the legitimate nodes. Traditional physical layer security relies on multi-antenna systems to implement beamforming for interference suppression and improve secrecy of the communications. In contrast, o-MRAVs can physically reorient their onboard antennas to direct the nulls of the radiation patterns towards malicious nodes to neutralize them while maximizing the communications quality experienced by the legitimate users. This mechanical

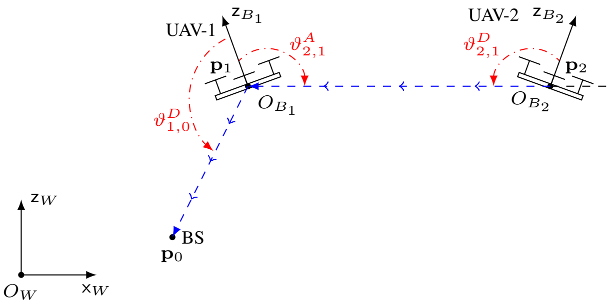

Fig. 1: Schematic of the communication relay scenario.

manipulation of the antenna radiation pattern orientation enhances secrecy rate and mitigates intentional interference, improving communication resilience under adversarial conditions.

Free-Space Optical Communications. FSO communication requires precise laser beam alignment between airborne nodes. Conventional MRAVs struggle with maintaining stable optical links due to orientation drift and aerodynamic disturbances. o-MRAVs improve link stability by allowing real-time orientation control, reducing jitter and ensuring continuous high-throughput optical connectivity. This capability is essential for low-latency, high-bandwidth applications in MRAV-based relay networks.

Network Densification and Capacity Enhancement. In urban environments, aerial base stations deployed via MRAVs must optimize coverage while minimizing interference. o-MRAVs offer fine-grained spatial control, allowing directional antenna steering for beam shaping and interference avoidance. This leads to better spectral efficiency in dense deployments and improves the adaptability of MRAV-based networks in dynamic conditions.

IV. Case Study: Omnidirectional MRAV Relay

To illustrate the impact of o-MRAVs in robust communications, a case study is presented in which an o-MRAV functions as an aerial relay between a mobile MRAV and a ground-based Base Station (BS). This scenario highlights the advantages of independent position and orientation control in mitigating beam misalignment, improving network resilience, and ensuring consistent communication quality under dynamic conditions.

Consider a mobile MRAV (UAV-2) that must transmit data to a ground BS while executing a mission that requires significant maneuvering. Due to its mobility constraints the high directionality of the antennas, maintaining a stable link to the BS is challenging, especially when operating in environments where obstacles or long distances introduce signal degradation. To improve link quality, an omnidirectional MRAV (UAV-1) is introduced as a relay, dynamically adjusting its position and orientation to optimize signal transmission between UAV-2 and the BS. The scenario is schematically represented in Figure 1.

To ensure real-time adaptability, a Nonlinear Model Predictive Control (NMPC) strategy is designed, integrating both robotic dynamics and communication constraints into a predictive control framework. The NMPC problem is formulated as an optimal control problem over a finite horizon N, solving for the control inputs u that minimize communication misalignment and ensure stable transmission:

$$\begin{aligned}
&\underset{\bar{\mathbf{x}},\,\bar{\mathbf{u}}}{\text{minimize}} && \sum_{k=0}^{N} \|\mathbf{y}_{\mathrm{d},k} - \mathbf{y}_k\|^2_{\mathbf{Q}} && \text{(1a)}\\
&\text{s.t.} && \bar{\mathbf{x}}_0 = \bar{\mathbf{x}}(\mathbf{t}_k), k = 0, && \text{(1b)}\\
& && \bar{\mathbf{x}}_{k+1} = \mathbf{f}(\bar{\mathbf{x}}_k, \bar{\mathbf{u}}_k), k \in \{0, N-1\}, && \text{(1c)}\\
& && \mathbf{y}_k = \mathbf{h}(\bar{\mathbf{x}}_k, \bar{\mathbf{u}}_k), k \in \{0, N\}, && \text{(1d)}\\
& && \underline{\gamma} \leq \mathbf{u}_k \leq \bar{\gamma}, k \in \{0, N\}, && \text{(1e)}\\
& && \underline{\dot{\gamma}} \leq \bar{\mathbf{u}}_k \leq \bar{\dot{\gamma}}, k \in \{0, N-1\}, && \text{(1f)}\\
& && \mathbf{g}(\mathbf{u}_k, \mathbf{x}_k, \mathbf{y}_{\mathrm{d},k}, \mathcal{T}) > 0, && \text{(1g)}
\end{aligned}$$

where (1a) is the objective function, (1b) sets the initial state conditions, (1c) and (1d) express the discretized dynamic model for the MRAV and the output signals of the system, respectively, and actuator limits $(\underline{\gamma}, \bar{\gamma}, \underline{\dot{\gamma}}, \bar{\dot{\gamma}})$ are embedded in (1e) and (1f). The constraints (1g) ensure that MRAV-1 will be aligned to MRAV-2 and the BS while moving. The variable $\mathcal{T}$ refers to communication parameters that need to be taken into consideration while solving the problem. Finally, the vectors $\bar{\mathbf{u}}_k$, $\bar{\mathbf{x}}_k$, $\mathbf{y}_{\mathrm{d},k}$, and $\mathbf{y}_k$ denote the k-th element of vectors $\bar{\mathbf{u}}$, $\bar{\mathbf{x}}$, $\mathbf{y}_{\mathrm{d}}$, and $\mathbf{y}$, respectively. The feasibility and effectiveness of the control strategy have been demonstrated via closed-loop simulations in MATLAB, as discussed in [2], but are not reported here due to space constraints.

V. Challenges and Future Research Directions

Despite their advantages, several challenges must be addressed to fully integrate o-MRAVs into robust MRAV-enabled networks. One major concern is *energy efficiency*, as the added control capabilities increase power consumption, requiring optimized flight planning and power-aware actuation strategies. Another critical challenge lies in *computational complexity*, since real-time trajectory and orientation optimization demand efficient algorithms capable of handling nonlinear dynamics and uncertainty propagation. Additionally, *scalability in networked MRAVs* remains an issue, as coordinating multiple o-MRAVs in collaborative aerial communication introduces difficulties in synchronization, interference management, and distributed control. To overcome these challenges, future research should explore hybrid approaches that integrate mechanical and electronic beamforming, machine learning-driven adaptive control, and multi-agent coordination strategies, ensuring the effective deployment of o-MRAVs in aerial wireless networks.

References

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