Reshaping UAV-Enabled Communications with Omnidirectional Multi-Rotor Aerial Vehicles

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Abstract—A new class of Multi-Rotor Aerial Vehicles (MRAVs), known as omnidirectional MRAVs (o-MRAVs), has attracted significant interest in the robotics community. These MRAVs have the unique capability of independently controlling their 3D position and 3D orientation. In the context of aerial communication networks, this translates into the ability to control the position and orientation of the antenna mounted on the MRAV without any additional devices tasked for antenna orientation. This additional Degrees of Freedom (DoF) adds a new dimension to aerial communication systems, creating various research opportunities in communications-aware trajectory planning and positioning. This paper presents this new class of MRAVs and discusses use cases in areas such as physical layer security and optical communications. Furthermore, the benefits of these MRAVs are illustrated with realistic simulation scenarios. Finally, new research problems and opportunities introduced by this advanced robotics technology are discussed.

Index Terms—Multi-Rotor Aerial Vehicles, Communication-Aware Robotics, Pose Optimization, Antenna Orientation.
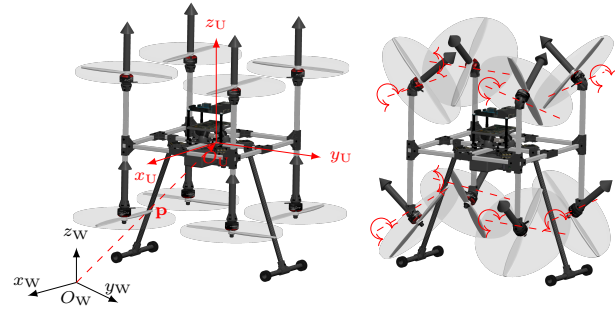
Figure 1: Illustration of u-MRAV and o-MRAV configurations with the global and untilted reference frames [9]. Arcs indicate servo rotation for thrust vector adjustment.

I. INTRODUCTION

Over the past decade, the integration of Unmanned Aerial Vehicles (UAVs) into wireless networks has attracted significant attention from both academic and industrial research communities [1]. UAVs have been extensively studied for two main reasons: their agility allows for swift deployment to address changing demands and optimize network performance [1], and their ability to achieve Line-of-Sight (LoS) improves communication reliability and expands coverage area [2]. Consequently, UAVs have been considered for applications such as replacing damaged base stations in disaster recovery, serving as data relays for remote Internet of Thing (IoT) devices, and acting as aerial base stations to enhance network capacity in urban and underserved areas [1], [2].

Much of the literature focuses on under-actuated MRAVs (u-MRAVs), which have fewer control inputs – such as thrust, pitch, roll, and yaw rate – than Degrees of Freedom (DoF) in 3D space. This means that the 3D orientation of u-MRAVs is dependent on their translational velocity, preventing independent control of position and orientation [3], [4]. Despite their mechanical simplicity and reduced cost, u-MRAVs face challenges such as tilting during motion or under external forces (e.g., wind), complicating communication-aware trajectory planning [5]. This issue is further exacerbated with high-frequency technologies like terahertz and mmWave, which require precise antenna alignment due to high directivity [2]. Many studies incorrectly assume that u-MRAVs can maintain a stable 3D orientation while in motion, which is only true at low velocities and small pitch/roll angles [3].

Recent works work has explored using servo motors or other mechanisms to adjust antenna orientation on u-MRAVs. For example, [6] proposed a control law for dynamically adjusting antenna orientation, while [7] introduced a full-duplex communication system to manage interference through UAV-relative position control. Another study, [8], used reinforcement learning for antenna alignment. However, these solutions focus on highly directional antennas for one-to-one communication.

The robotics community has introduced fully actuated MRAVs (f-MRAVs) and omnidirectional MRAVs (o-MRAVs) [3], [4]. These designs offer more control inputs than DoF, allowing for partial (f-MRAVs) or full (o-MRAVs) independent control over all movement axes. This capability greatly expands their maneuverability and allows precise antenna control throughout the UAV's mission. From a communication standpoint, this feature is crucial for optimizing both the 3D position and orientation of the antenna. For instance, o-MRAVs with dipole antennas can maintain communication with multiple nodes simultaneously, providing more flexibility in dynamic environments. Figure 1 presents an illustrative example of both an u-MRAV and an o-MRAV.

While o-MRAVs introduce additional complexity due to their design and control requirements, they offer significant

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advantages in wireless networks by providing highly adaptive aerial platforms [10]. Drawing on the authors' previous work [2], [10], [11], this paper explores how the independent control of both position and orientation in o-MRAVs can enhance communication systems, particularly in areas like physical layer security and beamforming.

II. O-MRAVS: DESIGN, MODELING AND CONTROL

When designing o-MRAVs, several actuation strategies have been proposed in the literature. According to [3], [9], o-MRAVs can be categorized into three classes: (i) *bi-directional* propellers, which reverse rotation to generate thrust in both directions, (ii) *uni-directional* propellers, generating thrust in one direction (clockwise or counterclockwise), and (iii) *actively tilted* propellers, which individually tilt around their axes using servo motors. The third class is the most flexible, allowing for optimized propeller orientation and rotation to improve platform efficiency and payload capacity, though it introduces complexity in mechanical design and control.

In this study, an actively titled o-MRAV with eight bi-directional propellers is considered. These propellers are attached to the vertices of a cube centered at the vehicle's Center of Mass (CoM), as discussed in [9] and depicted in Figure 1. Each propeller tilts around a different axis by the same angle, referred to as the *tilting angle*. This configuration allows the total thrust vector to point in all three orthogonal axis directions.

Modeling the o-MRAV involves defining two reference frames: the untilted frame, centered at the CoM, and the global frame (see Figure 1). The platform's dynamics are modeled as a six-DoF floating rigid body using Newton-Euler formalism, with the state including position, orientation, velocity, and angular velocity. Control inputs consist of the rotor speeds, spinning directions, and tilt angles of the eight bi-directional propellers. Forces and torques generated by the rotors at the CoM depend on rotor positions and orientation. More details are provided in [3], [4], [9].

A. Comparative evaluation of o-MRAVs capabilities

The capabilities of o-MRAVs are compared to their under-actuated (u-MRAVs) and fully actuated (f-MRAVs) counter-parts. As detailed in [3], [9], these capabilities are closely tied to the mechanical design of each platform. While f-MRAVs offer partial independent control of position and orientation, they are limited in many directions. In contrast, o-MRAVs provide full independent control over both 3D position and 3D orientation, enabling more precise and complex maneuvers. This is due to the ability of o-MRAVs to control both the spinning direction and speed of rotors, along with propeller tilting angles (see Figure 1). f-MRAVs, by comparison, have fixed tilting angles and, in most cases, fixed spinning directions, with only motor speed as a variable. For a thorough comparison, three representative features are considered: hovering ability, trajectory tracking, and rotor failure robustness.

Hovering ability. The *ability to hover* refers to the capability of MRAVs to remain stationary at a desired position, crucial for applications like aerial Base Stations (BSs) or as communication relays [2], where multi-rotors offer a clear advantage over fixed-wing UAVs. As outlined in [3], [9], hovering can be classified as static or dynamic. *Static hovering* allows the platform to stabilize both position and orientation with zero linear and angular velocity, enabling heading adjustments. *Dynamic hovering* involves maintaining position with controlled movement and velocity around a point.

u-MRAVs can achieve static hovering and, in some cases, dynamic hovering, with uncontrolled orientation variations (e.g., rotation around a point after a propeller failure). However, this dynamic hovering is typically limited to safety or recovery scenarios and is less energy-efficient [10]. In contrast, f-MRAVs and o-MRAVs can perform both static and dynamic hovering with fully controlled orientation. The main distinction is that o-MRAVs are capable of maintaining a constant position while achieving full control of their orientation in any direction in space. This constitutes the main advantage of o-MRAVs compared to both u-MRAV and f-MRAV designs. This is especially useful for tasks like communication relay, where a rigidly attached antenna can be aimed at a target without moving the vehicle, resulting in more efficient operations.

Trajectory tracking ability. The ability to follow a trajectory is crucial for many applications and can be classified based on the type (position and orientation tracking) and the number of DoF the MRAV can independently control. For standard u-MRAVs, only three-dimensional position and one-dimensional orientation tracking are possible, as their pitch and roll angles are coupled with translational movements, limiting control over these axes. Some designs, such as those with radially tilted or tilting propellers [3], extend this capability to achieve more DoF, moving these systems from under-actuated to over-actuated, thus classifying them as f-MRAVs and o-MRAVs. Most f-MRAVs can track three-dimensional position and two-dimensional orientation, and some advanced designs can achieve full three-dimensional attitude tracking [3], [12]. However, these platforms still cannot fully exploit their DoF, limiting their applications despite some advantages over u-MRAVs. Only o-MRAVs can achieve independent tracking of both three-dimensional position and orientation, making them particularly effective in windy or turbulent conditions, reducing the jittering effects commonly seen in u-MRAVs [13].

Rotor failure robustness. While f-MRAVs and o-MRAVs are commonly believed to be more resilient to rotor failures than u-MRAVs due to their higher number of rotors[1], their true robustness lies in their ability to perform controlled hovering, both static and dynamic. In the event of rotor failure, where a propeller becomes unusable and ceases to generate thrust, u-MRAVs struggle to maintain attitude control, making safe landing challenging unless specialized algorithms or additional sensors are employed. Although u-MRAVs may achieve dynamic hovering by rotating uncontrollably around a fixed point in failure scenarios, this is primarily for recovery and safety, and it is not energy-efficient for long-term use.

By contrast, f-MRAVs and o-MRAVs are capable of main-

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[1]Typically, u-MRAVs have four to eight rotors, often with opposed propellers to enhance lift [3].

Table I: Comparison of included system abilities, based on the MRAV design: "included" (✓), "partially included" (✷), and "not included" (✗)

MRAV designs	System Abilities				
	Static Hovering	Dynamic Hovering	Position Tracking	Orientation Tracking	Failure Robustness
u-MRAV	✓	✷	✓	✗	✓
f-MRAV	✓	✷	✓	✷	✷
o-MRAV	✓	✓	✓	✓	✓

taining stable flight even after losing one or more rotors, thanks to their more advanced control mechanisms [4]. Specifically, o-MRAVs, with their ability to independently reorient propellers and dynamically adjust spinning directions, exhibit superior flexibility and robustness. This allows them to adapt more effectively to rotor failures compared to f-MRAVs, ensuring continued operation in more challenging conditions.

Table I compares the capabilities of different MRAV designs, categorizing their abilities as "included" (✓), "partially included" (✷), or "not included" (✗), to highlight the differences between u-MRAV, f-MRAV, and o-MRAV platforms.

B. Challenges and open problems

The development and deployment of o-MRAVs pose several challenges, particularly in control complexity, energy consumption, and design costs. This section highlights these key issues and ongoing research efforts to address them.

Control system complexity. o-MRAVs have inherently more complex control systems due to their ability to independently manage both position and orientation. This adds complexity to 3D positioning and trajectory planning. Specifically, optimizing the orientation of antennas on o-MRAVs involves handling nonlinear, non-convex, and non-smooth optimization problems. These challenges make it difficult to find optimal solutions within a reasonable time frame, as solvers can easily become trapped in local optima. Consequently, sophisticated algorithms are required to optimize both the positioning and orientation of o-MRAVs, ensuring their efficient deployment [1], [2], [5].

Energy consumption. A significant challenge in the development and use of o-MRAVs is balancing performance and efficiency. For o-MRAVs, the propellers must generate sufficient lift so that the total thrust vector can overcome gravity, along with an additional margin to support dynamic maneuvers. However, one of the largest sources of inefficiency in o-MRAVs stems from the fact that some of the forces generated by the propellers are canceled out, as not all of them are aligned with the direction of motion. This occurs because opposing thrusts are required to stabilize and maneuver the vehicle, leading to wasted energy. This performance requirement is at odds with the goal of achieving high efficiency and extended flight times. Efficiency is further compromised when additional weight is introduced for actuation mechanisms. To address this challenge, ongoing research is focused on finding optimal design strategies that efficiently manage the lift produced by the propellers by adjusting the tilting angles and the spinning direction, minimizing the energy lost through opposing thrusts [9].

Costs and design complexity. Despite their advantages, o-MRAVs also have drawbacks, such as additional actuation mass, increased design complexity, and the presence of singularity cases not encountered in u-MRAVs [3], [4]. Therefore, morphology design is crucial to ensure that the resulting platform meets performance requirements. This necessitates the use of proper optimization tools[2] capable of performing parametric optimization of the tilting angles and the propeller positions relative to the MRAV's CoM. The goal is to maximize the force and torque envelope and their maximum values in each axis direction. As a result, compared to their more commonly used u-MRAV counterparts, many of o-MRAV platforms are designed and developed within laboratory environments, increasing their costs [14].

III. USE CASES

The primary advantage of o-MRAVs is their ability to independently control both orientation and position. From a communication perspective, this capability means that, when the antenna is fixed to the o-MRAVs frame, both its 3D position and 3D orientation can be precisely managed. This unlocks new and interesting opportunities in the field. This section outlines potential use cases in wireless communication networks where the unique characteristics of o-MRAVs offer significant enhancements and introduce innovative solutions to traditional challenges. Figure 2 summarizes the studied use cases.

A. Physical layer security

A traditional challenge in physical layer security is maximizing the secrecy rate during communication between two legitimate nodes in the presence of an eavesdropper. Conventional strategies often employ multi-antenna arrays to direct the radiation pattern's null towards the eavesdropper while enhancing the antenna gain experienced by the legitimate receiver.

However, if the legitimate transmitter is an o-MRAV, similar results can be achieved using a single antenna. This is accomplished by manipulating the 3D orientation of the o-MRAV, allowing the null of the o-MRAV antenna's radiation pattern to be directed towards the eavesdropper while maintaining communication with the legitimate node.

In a related scenario, if a legitimate network faces an attack by a malicious jammer, and the legitimate receivers are o-MRAVs with single antennas, they can reorient themselves to direct their antenna radiation pattern's null towards the jammer. This strategic repositioning can mitigate and neutralize the jamming attack [10].

B. Localization of RF sources

Localization of Radio Frequency (RF) sources is a critical task in various applications, such as search and rescue operations, and identifying the position of malicious jammers. MRAVs equipped with directional antennas and sometimes

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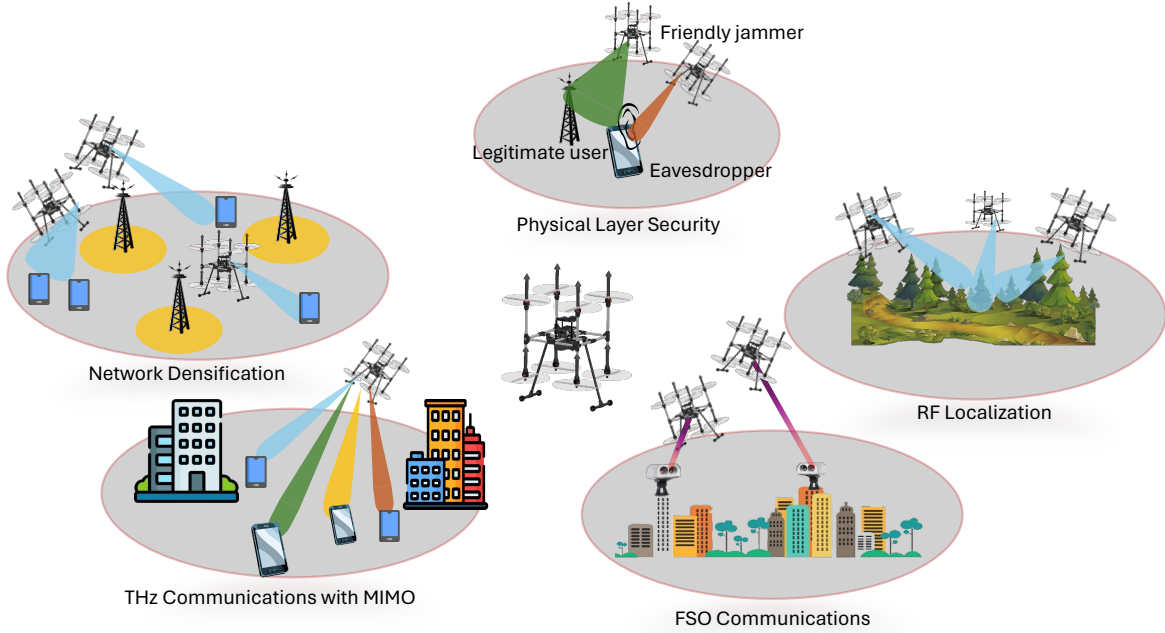[2]https://github.com/ethz-asl/tiltrotor_morphology_optimization

Figure 2: o-MRAV use cases.

additional mechanical systems for antenna rotation are commonly used for this task. Typically, MRAVs vary their yaw angle to orient the antenna in different directions and collect data to localize the target. While effective, this method has limitations in terms of flexibility and speed.

In contrast, o-MRAVs offer significant advantages in RF source localization. These advanced MRAVs can independently control the roll and pitch angles, in addition to the yaw angle. This enhanced maneuverability allows for the design of more efficient trajectories and enable faster and more accurate localization of RF sources even without a special system for antenna positioning. By leveraging their full range of motion, o-MRAVs achieve superior performance in tasks requiring precise and rapid localization of RF signals.

C. Aerial Free-Space Optical communications

Free-Space Optical (FSO) communications is one of the most promising applications for o-MRAVs. Achieving successful FSO communication requires establishing direct links between the transmitter and receiver, particularly when using flying robots. This leads to the alignment problem [15]. The transmitting MRAVs must precisely direct its laser beam to the center of the optical receiver on the other MRAVs, while the receiving MRAVs must align its lens and photodiode with the incoming laser beam. Maintaining a precise alignment is crucial for effective FSO communication, as even slight deviations can lead to signal loss or degradation.

u-MRAVs often struggle with this alignment due to their limited ability to control orientation independently of their position. In contrast, o-MRAVs offer a substantial advantage in this regard. Their flexible orientation capabilities allow for precise positioning and alignment of the laser beam and optical receiver.

Additionally, u-MRAVs are more prone to jittering, which further complicates the alignment problem. Using o-MRAVs

mitigates the impact of jittering, as these MRAVs are less sensitive to such disturbances.

D. THz and mmWave communications

Some of the key technologies expected to be deployed in 6G networks include terahertz communications and mmWave communications. The extremely high frequencies of these systems will provide very large bandwidths but will also introduce significant absorption losses. To compensate for these losses, 6G systems will utilize high-gain antennas which are highly directional.

When establishing aerial links between MRAVs using these technologies, the same alignment problem described for aerial FSO communications will arise (see Section III-C). High directivity antennas require precise alignment to maintain a strong communication link. Consequently, o-MRAVs will exhibit significant advantages when establishing aerial RF links using these technologies. Their ability to independently control position and orientation will simplify the alignment process, enhance link stability, and improve the overall reliability of 6G communications involving MRAVs.

E. Capacity enhancement in dense areas

The goal of network densification is to enhance network performance and coverage by deploying a large number of small cells within a target area. MRAVs have been considered as rapidly deployable aerial BSs to improve network quality of service. However, network densification can result in high interference and increased coordination costs, leading to additional optimization and planning challenges.

To address this challenge, o-MRAVs can mechanically control the antenna's orientation and direct the signal to reduce interference. By equipping an o-MRAV with a highly directional antenna and combining it with an effective orientation and position controller, communication can be provided

in a highly focused and dynamic manner. This approach allows connectivity to be delivered to specific users, thereby improving the spatial sharing of the electromagnetic spectrum and minimizing interference [1].

IV. SIMULATION EXPERIMENTS: O-MRAVS FOR JAMMING AND EAVESDROPPING MITIGATION

This section examines two scenarios in the area of physical layer security where o-MRAVs demonstrate significant advantages over u-MRAVs. The first scenario involves an o-MRAV communicating with a legitimate node while countering a jammer, showing how the o-MRAV can optimize antenna direction to enhance communication efficiency [10]. The second scenario addresses eavesdroppers attempting to intercept communication, where a friendly jammer is used to disrupt eavesdropping and safeguard the transmission [11].

While this study focuses on comparing o-MRAVs and u-MRAVs due to the pronounced mechanical and operational differences between these platforms, it is worth noting that comparing o-MRAVs with f-MRAVs could provide additional insights, particularly for applications that require a higher degree of orientation control. However, f-MRAVs still lack the full 3D orientation control offered by o-MRAVs, as discussed in Section II-A, which is a critical factor in the communication scenarios considered here. As such, the comparison has been prioritized between o-MRAVs and u-MRAVs, where the differences in capabilities are more pronounced. Future work could explore a detailed comparison with f-MRAVs, especially for use cases where partial orientation control may be sufficient.
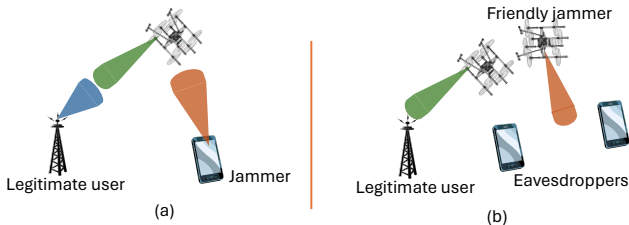

Figure 3: (a) An o-MRAV communicating with a legitimate user in the presence of a jammer, (b) a friendly jammer disrupting eavesdroppers.

A. Enhancing security against jamming with o-MRAVs

A legitimate network consisting of two ground nodes and one o-MRAV is considered, as shown in Figure 3(a) and detailed in [10]. The o-MRAV receives data streams from the ground nodes while a malicious ground node transmits a jamming signal aimed at disrupting communications. The goal is to optimize the 3D position and orientation of the o-MRAV to maximize the minimum Signal-to-Interference-plus-Noise Ratio (SINR) for both ground users.

Four different strategies are tested to achieve this: (i) *Optimum Pose*, numerically optimizing the position and orientation of the o-MRAV; (ii) *Maximum Gain*, orienting the o-MRAV so that the main lobe of its antenna radiation pattern points
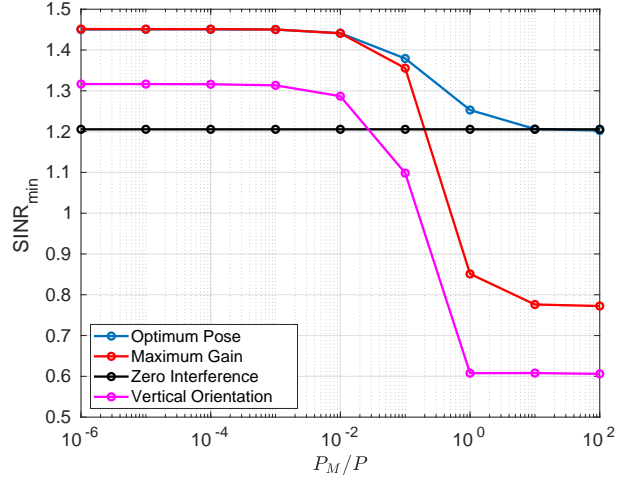

Figure 4: Minimum SINR for different jamming powers.

towards the ground users, then optimizing its position numerically; (iii) *Zero Interference*, orienting the o-MRAV so that the null of its antenna radiation pattern points towards the jammer, followed by numerical optimization of its position; (iv) *Vertical Orientation*, optimizing the position of an u-MRAV with a fixed, vertically oriented antenna.

From the results presented in Figure 4, several observations can be made. When the jamming signal is weak, the *Maximum Gain* strategy aligns with the optimal solution. As the jamming signal becomes stronger, the *Zero Interference* strategy becomes optimal indicating that suboptimal solutions can achieve optimal poses under extreme jamming conditions.

Another observation is that all solutions saturate as the jamming signal strength increases. The performance of the *Zero Interference* strategy remains stable because it consistently nullifies the jamming signal. The optimal solution also converges towards the *Zero Interference* strategy, effectively neutralizing the jammer. In contrast, the *Maximum Gain* strategy, while maximizing antenna gain towards the legitimate users, it gradually adjusts its position so that the null of its antenna points towards the jammer. The *Vertical Orientation* strategy positions the u-MRAV directly above the jammer, ensuring that the null of the antenna points towards it, thereby neutralizing the jamming effect. These results demonstrate the clear advantages of optimizing both the position and orientation of the o-MRAV in mitigating jamming attacks and establishing robust communication links. The flexibility of the o-MRAV allows for effective management of the interference generated by the jammer, especially under strong jamming conditions. Further details can be found in [10].

A comparison between the optimal performance of the o-MRAV (blue plot in Figure 4) and the u-MRAV (magenta plot in Figure 4) reveals significant differences, especially under strong jamming conditions. The o-MRAV's independent orientation control leads to a notable improvement in SINR, particularly as jamming power intensifies. It is important to note that the frame of the MRAV has the potential to modify the radiation pattern of the antenna, and this factor should be considered when optimizing the o-MRAV's pose.
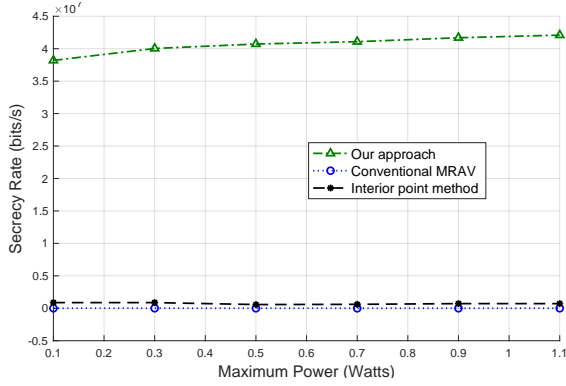
Figure 5: Secrecy rate versus maximum power for 2 eavesdroppers.

B. Friendly jammer o-MRAV against eavesdroppers

In this second scenario, a downlink communication is considered where an o-MRAV communicates with a legitimate ground node while two eavesdroppers attempt to intercept the transmission, as depicted in Figure 3(b) and described in [11]. To secure the communication, a second o-MRAV is deployed to jam the eavesdroppers. The objective is to optimize the position, orientation, and transmission power of both o-MRAVs to maximize the secrecy rate for the legitimate user.

The optimization strategy is as follows: for the jamming o-MRAV, its orientation is adjusted so that the null of its radiation pattern consistently points towards the legitimate user. This setup enables the jamming o-MRAV to emit high interference power without affecting the legitimate communication. The orientation of the jamming o-MRAV at each position is determined by this constraint. For the communicating o-MRAV, its antenna is oriented such that the main lobe of its radiation pattern is directed towards the legitimate user, while maximizing the horizontal separation between the projected maximum antenna gain and the eavesdroppers. The orientation strategy is thus unique for each position. Finally, the 3D positions and transmission powers of both o-MRAVs are optimized.

The proposed approach is compared with two benchmark strategies: (i) *Interior-point method*, where the optimization problem is solved with respect to (w.r.t.) all variables, including orientations, positions, and powers of the MRAVs, using the interior-point method; (ii) *Conventional MRAV*, assuming u-MRAVs with fixed orientations and applies the interior-point method to optimize the positions and transmission powers of the MRAVs.

Figure 5 illustrates the dependency of the secrecy rate on the maximum power in case of our proposed approach, compared to the two benchmarks. The results show a significant performance advantage of the proposed approach, which provides a higher secrecy rate compared to the interior-point method. This improvement is due to the non-convex nature of the secrecy rate function, where the interior-point method can become stuck in a local optimum, leading to suboptimal performance. Furthermore, Figure 5 shows that the conventional u-MRAV performs the worst, as it cannot optimize its antenna orientation, leading to considerably lower performance in terms of secrecy rate. Additional information is available in [11].

V. DISCUSSION AND FUTURE RESEARCH DIRECTIONS

The introduction of o-MRAVs into communication networks offers the potential to optimize both the 3D position and 3D orientation of onboard antennas. This innovation raises several key questions for future research, as described next.

Optimal 3D Orientation and Positioning. A significant area of investigation involves determining the best position and antenna orientation for o-MRAVs to optimize communication performance across various use cases. This includes analyzing different scenarios to understand how precise positioning and orientation can maximize Signal-to-Noise Ratio (SNR), minimize interference, and ensure reliable connectivity. While a servo-based mechanism for redirecting the antenna alone is indeed more energy-efficient, the advantage of o-MRAVs lies in their ability to seamlessly integrate position and orientation control of the entire platform. This is particularly useful in dynamic environments where both the MRAV and surrounding communication partners are in constant motion, allowing for more stable and adaptable communication links. Although the energy efficiency of directing the entire vehicle for antenna adjustment may seem less optimal, the flexibility and robustness offered by o-MRAVs in complex and rapidly changing conditions outweigh this limitation in many use cases.

Energy Consumption. o-MRAVs are designed with thrust forces that sometimes counteract each other, and additional weight from actuation mechanisms (see Section II-B) further increases energy consumption and reduces mission endurance. The inefficiency of using full thrust to orient an antenna, along with optimizing energy usage, presents a major challenge for widespread adoption of these platforms. To enhance their viability in communication applications, significant research is needed to reduce energy consumption while maintaining high communication performance. Future work should consider integrating servo-based mechanisms for antenna redirection, which could complement o-MRAVs by offering hybrid solutions that enhance energy efficiency. The primary strength of o-MRAVs is their ability to control both position and orientation simultaneously, making them particularly useful in dynamic environments where both the MRAV and its communication partners are constantly in motion. Another promising solution to address energy consumption is the use of tethered o-MRAVs, which can provide continuous power supply. This would be especially beneficial for applications requiring prolonged operation, such as long-term surveillance or persistent communication relay tasks.

Trajectory Planning. Another crucial aspect involves planning the trajectory of o-MRAVs to optimize their movements for efficient communication and navigation. This task requires careful consideration of the dynamical model of o-MRAVs, taking into account the forces and torques applied to the CoM by the rotors, and the orientation of the antenna to enhance the transmission rate. The goal is to ensure that these vehicles can navigate complex environments while maintaining optimal positions for communication.

2D and 3D beamforming. It is essential to investigate the performance of o-MRAV-assisted networks when equipped with antenna arrays. These arrays facilitate beamforming techniques, enabling precise control over beam direction. Integrating o-MRAVs with 2D and 3D beamforming has the potential to substantially enhance network performance and support higher data rates.

These areas of research are critical for unlocking the full potential of o-MRAVs to enhance the performance of communication systems.

VI. CONCLUSIONS

This paper introduced omnidirectional MRAVs and outlined their capability to independently control 3D position and orientation. A comparison with u-MRAV and f-MRAV systems was provided, demonstrating the superior hovering ability, trajectory tracking, and rotor failure robustness of o-MRAVs. The study showcased how o-MRAVs can improve network performance in areas such as physical layer security, localization, and network capacity. Simulation results showed their effectiveness in mitigating jamming and eavesdropping attacks, emphasizing their potential in secure communications. Future research should focus on optimizing 3D orientation and positioning, minimizing energy consumption, planning efficient trajectories, and integrating advanced beamforming techniques. Our findings indicate that o-MRAVs can offer significant improvements over traditional MRAV designs, making them a promising technology for future communication networks.

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