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Design and Deployment of Modular Drone Systems with Geometry Optimization: A Review

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Abstract

The design and deployment of modular drone systems is an area of ongoing exploration and has the potential to support the growth of industries, communities, and fields like agriculture and surveillance. These drone systems make various real-life applications easier with repair, flexibility, and performance. This review explores the influence of different geometries in the design of these drone systems, and follows an analysis of multiple key barriers in the deployment of these systems. It further investigates important design objectives, real-life applications, and various geometrical structures, along with key barriers that correlate with various innovations in modular drones and aerial robots. A systematic search for literature and current research was conducted to identify relevant sources. Reasons for these barriers range from the application and other factors that the system is required to meet, including geometric structure. The research indicates that the various geometries used in the design of these systems have an influence on deployment, as reflected in current solutions of modular drones and aerial robots. Addressing these concerns is crucial to expanding the use of modular drones to serve in real-life applications.

Keywords: Modular drone systems, geometry optimization, modular design, aerial robots, unmanned aerial vehicles (UAVs), deployment barriers

1. Introduction

Innovation through advances in efficiency, cost, and structure has made modularity in drones all the more desirable. Both public and private sectors are increasing their usage of drones, from addressing agricultural demand to supporting various surveillance applications. With continual improvement in drone technology in agriculture, modularity in drones strives to benefit industries and communities associated with agriculture and surveillance activities (Mueller et al., 2022). These applications would typically use specific drone geometries suitable for various scenarios (Sah et al., 2020). However, the geometrical structures used can contribute to barriers from societal, economic, environmental, technological, and regulatory perspectives, becoming common hurdles in the broader deployment of drones (Sah et al., 2020). The concerns associated with these barriers are true for drones as well as aerial robots as a whole (Yaacoub et al., 2024; Wali et al., 2023). Moreover, the design geometries used can influence efficiency both positively, leading to multiple benefits in certain applications, and negatively, as certain geometrical designs can create barriers in drone deployment..

In this review, various applications of modular drone systems are explored with a focus on the design geometries used for different applications. These modules can form a single modular robot as well as detach (Yaacoub et al., 2024). For instance, modularity in agricultural drones can impact involved individuals and communities with ease of use and long-term practicality (Rejeb et al., 2022). Modules may consist of detachable fertilizer tanks or the canopy and arm holder assembly (the top assembly) as multi-component modules for agriculture drones (Yaacoub et al., 2024; Rejeb et al., 2022). These make the process of different tasks (e.g., applying fertilizer on crops) more efficient long-term with the use of independent modules combined with others to create a flexible and efficient system, known as a multi-component system (Brischetto et al., 2016; Yaacoub et al., 2024).

At first, modular drone systems appear to require additional financial investment (Mueller et al., 2022). However, using different geometries in drones and improving their efficiency as well as functionality through modularity can lead to cost-effective long-term maintenance (Yaacoub et al., 2024). The same long-term efficacy is also true for surveillance drones through modularity, such as converting the drone's camera into a multi-component system (Aina et al., 2024). Moreover, this is one implication of how geometries in the design of modular drones can address a barrier, but failures in functionality and adaptability must be considered for deployment.

Furthermore, individuals, including drone pilots, manufacturers, farmers, and trainers, could benefit from modularity in different ways. For example, modular drones are more economical for farmers than conventional agricultural drones. This is because of the long-term cost-saving benefits modular designs provide, which can significantly impact farmers, especially in countries where many farmers struggle financially, like India and China. Moreover, when examining the application of modular drone systems in agriculture, the geometries used in modular structures have a long-term potency to assist with as well as constrain the deployment of these drones. Geometries used for modularity have the potential to improve certain barriers, which could have a long-term economic impact on farmers by using modular agriculture drones. In contrast, the barriers to deployment of modular drones can also be caused by different geometries used because of the complex nature of designing, engineering, and manufacturing these parts (Yaacoub et al., 2024; Sah et al., 2020). For instance, functional failures by using these geometries can arise from compatibility issues due to a lack of continuity across all components of a drone. Adaptability with many different designs of modular aerial robots found in several studies is also a challenge, which can arise from technical challenges with the geometrical structure of the drone (Yaacoub et al., 2024). Increasingly, there are other associated factors in the design of modular drones that can directly hinder the deployment of these modular aerial robots as a whole, which are explored in this review.

With a focus on design geometries in modular drone systems, the second section of this review addresses the specific design objectives of modularity. An overview outlining these objectives is followed by different types of modules. This section also reviews modules in specific applications like agriculture and surveillance, followed by control methods. The third section focuses on different geometries in drone design with various configurations, such as quad or tetra, and a connection with components found within modular drones. Then, the fourth section focuses on deployment barriers with respect to design geometries for modular drones stemming from modular robots as a whole. Lastly, the influence geometries have on the design and deployment of modular drones is summarized, along with takeaways and future objectives for design geometries in the field of modular robotics.

2. Review Methodology and Search Strategy

The review followed a systematic search strategy in identifying multiple studies with current innovations in modular drones and aerial robots, studies on associated barriers to deployment, and a focus on geometry optimization. Literature from 2015–2025 was sourced from large databases, including Google Scholar, IEEE Xplore, and Research Gate. Both current innovations in modular drones and aerial robots, as well as other literature reviews, fall within this time span.

Moreover, for current innovations in the field of modular drones, the inclusion criteria for selecting certain studies were contingent on the demonstration of a geometric configuration for the robot and experimental data on various parameters. Specifically, multiple studies on innovations were first identified, then categorized based on whether or not a design geometry was at least demonstrated with the performance of the drone. From this, the studies most valuable to the analysis of the design and broader deployment of modular drones were selected and reviewed in depth. Additionally, the parameters for choosing these studies included the endurance or flight time tested in the study, and this information was useful for a comparison of quantitative data collected in two or more studies.

The inclusion criteria for selecting past literature reviews included how the correlation of the design of a drone was demonstrated with modularity, and other studies on barriers identified for drones. While not all reviews focused particularly on modularity, there were insights in this field, and the overall information provided was useful in the review's analysis of non-standardized designs. From this, a few studies on the design and control of drones were identified, and a subsection on control methods was included. Current research without a direct relation or mention of modularity in drone technology was excluded. Overall, this methodology with a systematic search strategy proved to be effective, especially in identifying and reviewing multiple innovations in modular drones to find commonalities and other aspects towards the field of modular drones as a whole.

3. Modular Drone Design Objectives and Applications

This section explores the modularity and design objectives of drone systems with each type and motion of modules. Control methods and modularity for the applications of agriculture and surveillance are also investigated.

3.1. Modularity

Modular drones or UAVs can be described as smart aerial robots that can perform complex tasks more efficiently than different types of multi-component modules within a drone system. The motion of modules found in a modular drone can include sliding, rolling, and even a hybrid modular movement (Yaacoub et al., 2024). For sliding movements, the modules form a singular structure for the drone, but can be effortlessly detachable at the same time, allowing systems to be reshaped or resized (Yaacoub et al., 2024). These types of modules are useful for agriculture because cleaning parts of the drone that are used throughout the day can be a more direct and simple task, and saves storage space in smaller farms. Other benefits that would apply to most applications are those of repairability, flexibility, performance, and enhanced interaction with the drone and user, making tasks easier as a whole through modular geometries. Interaction is important because even experienced drone pilots may find the operation of certain tasks difficult with new modular designs. Ensuring smooth interaction with the overall performance of a drone is crucial for overall efficiency.

Table 1: Comparison of drone configurations, MTOW, tested endurance, and demonstrated tasks of current modular drone innovations (Wali et al., 2023; Saldaña et al., 2018).

Drone/Aerial Robot	**Single Modular Structure**				
	Modular Configuration	**MTOW / g**	**Endurance (tested) / s**	**Demonstrated Task**	
TetraQuad	Tetrahedral multi-rotor modules	890	50 (mostly stable)	Circular Trajectory	Maximum Altitude of 1.05m (approx.)
ModQuad	Quad-rotor cuboid frame modules	40	20	Aerial self-assembly	Maximum angular velocity of 2.5 rad/s (approx.)
Multi-Module Structure					
TetraQuad (4 Modules)	Tetrahedral multi-rotor modules	3560	50 (partially stable)	Circular Trajectory	Maximum Altitude of 1.1m (approx.)
ModQuad (5 Modules)	Quad-rotor cuboid frame modules	200	20	Aerial self-assembly	Maximum angular velocity of 0.5 rad/s (approx.)

Several studies have innovated a modular solution for aerial robots using different types of modules. The modules employed involve the use of specific geometries and are often smaller in size than those found in the market for conventional drones. Some examples include multi-component and multi-degree-of-freedom systems, as shown in two studies (Wali et al., 2023; Zhao et al., 2018). Scaling is not feasible due to the complexity and unique structures found in modular solutions in most studies (Mueller et al., 2022). For this reason, tests with to-scale modules are not practical because of the complexity in geometry and modular moment. Moreover, a study was conducted to investigate the design of an aerial robot with tetrahedral geometry by attaching individual "TetraQuad" modules in a multi-component approach (Wali et al., 2023). A single module was compared with 4-module and 16-module aerial robots (Wali et al., 2023). The results of this study revealed greater performance in the aerial robots with fewer modules by modelling the accuracy of a circular trajectory path, mainly due to the load and impact on stability (Wali et al., 2023). Another study, which designed an aerial robot "DRAGON," focused on a multi-degree-of-freedom robot for aerial transformation (Zhao et al., 2018). In addition, the creation of ModQuad, a quad-rotor UAV designed for self-assembly in the air through a modular cuboid frame docking system, is yet another example of innovation in modularity for aerial robots (Saldaña et al., 2018). Table 1 compares the configurations of each modular innovation with their respective maximum takeoff weight (MTOW), tested endurance, and demonstrated tasks.

In Table 1, the data collected from experiments with the TetraQuad and ModQuad are presented with one module along with four and five modules, respectively. These two innovations were tabulated because the parameters included are similar, and differences can be discerned, as opposed to other variables and experiments included with the DRAGON UAV. Moreover, Table 1 shows the performance of a single modular structure in comparison to a multi-modular structure. For example, the flight stability of a single TetraQuad module is relatively high during a 50-second flight time, compared to a four-module TetraQuad assembly from a similar flight time (Wali et al., 2023). Moreover, while the four-module assembly has a higher maximum altitude of 1.1m compared to only 1.05m for the single-module assembly, it resulted in greater fluctuation in the experiment (Wali et al., 2023). In addition, the maximum angular velocity in the ModQuad was greater for a single module than for five modules attached (Saldaña et al., 2018). This may be a result of weight distribution with a mid-air assembly of more modules resulting in a smaller velocity (Saldaña et al., 2018). All in all, these studies showcase how the design of aerial robots, even with testing models, leads to complexities and is a primary factor in hindering the deployment of modular drones in the market for various applications.

Control Methods

When evaluating modularity in drone systems, it is critical to consider various control methods for the smooth operation of these robots, especially in a range of real-life applications. Control methods are important because precise control is required for operation in complex environments with learning-based control, especially for survivability and robustness (Mueller et al., 2022; Yaacoub et al., 2024). For the two studies addressing multi-component and multi-degree of freedom with specific geometries, control methods are crucial. This is partly due to the stability and complexity arising from the number of modules in the configurations of these aerial robot designs. An example of learning-based control for drones can be adapting to specific weather patterns in a region for long-term use. Types of control associated with herds and swarms of aerial robots as a whole are centralized and decentralized control, respectively (Yaacoub et al., 2024). A few control method architectures include low-level control & stabilization, and higher-level planning (Mueller et al., 2022). Furthermore, with these control method architectures, other physical constraints should be addressed in drones. These were highlighted in FreeBOT, where a free-form architecture resulted in fewer physical constraints, which achieved independent movement of modules (Liang et al., 2020). Additionally, various control methods have to be considered for modular drones to perform in various applications due to differing conditions and requirements for each.

3.2. Overview of Real-Life Applications

When discussing the real-life applications of modular drones, a couple of notable applications are agriculture in highly populated regions with a greater demand for agricultural production, and surveillance for smart cities and other applications. Drone technology in both these applications incorporates the Internet of Things (IoT) and machine learning, with additional technologies relevant to each application (Rejeb et al., 2022; Gohari et al., 2022). The IoT is a large chain of interconnected platforms within the internet that enables monitoring, such as in precision agriculture, optimized efficiency, and automation (Yaacoub et al., 2024; Rejeb et al., 2022). Machine learning is integral for any drone system for adaptability and ensuring accurate performance when executing tasks (Soori et al., 2023).

Agriculture

Agriculture drones are spreading in many countries with a large agricultural demand, particularly in China and India. These drones are used in the public sector for agricultural purposes (e.g., fertilizer application, seed dispersal, transportation, etc.). While modular agricultural drones are not yet widespread, their benefits with functionality and efficiency can pave the way for the future of agriculture. Of the many leading agricultural drones on the market today, few are modular, and drone companies are conducting research into this field to design more efficient and sustainable products (Universiti Tun Hussein Onn Malaysia, et al., 2021). Most agricultural drones on the market use a hexacopter geometry, as it can carry more weight and handle the tasks of covering a larger surface area by dispersing large quantities of substances. Moreover, the importance of modular drones in agriculture stems from long-term benefits, especially from economic, environmental, and social perspectives. The role of IoT in agriculture involves fusing the technologies of machine learning, deep learning, precision agriculture, and remote sensing, along with other forms of data, with drones in this sector (Yaacoub et al., 2024; Rejeb et al., 2022). It has become crucial due to the effectiveness of IoT in merging these technologies and carrying out tasks in the agriculture sector (Rejeb et al., 2022).

Surveillance

Drones for surveillance typically use quadcopter or quad-rotor structures due to their performance in aerial surveys and mapping regions. They are also portable and lightweight, and quadcopters commonly travel in swarms for effective surveillance (Yaacoub et al., 2024). The modularity for these drones would involve modules for the camera and a detachable canopy and arm holder assembly, similar to agricultural drones. While surveillance drones may not have a relatively scalable impact like agriculture drones, they are still crucial and widely adopted globally for a broad range of surveillance tasks. These can vary from general-purpose aerial mapping and data collection to analyzing complex disaster sites with hazard mapping. They are multi-purpose and also play a critical role in smart cities (Gohari et al., 2022). Modularity in surveillance drones can aid in the surveillance applications of hazard mapping from natural disasters or in smart cities through swarm capabilities. Additionally, mid-air aerial transformation from detaching modular units can survey a large surface area at a faster and cost-effective pace. This is possible through the detachment of a single modular unit within airspace and also by using minimal materials, respectively. Moreover, the importance of modular drones in surveillance also stems from the fusion of IoT and other technologies.

4. Drone Geometric Structures

This section focuses on the geometry used in the design of drones with different components required for modular drones and various configurations. The visualization of the geometrical structure with certain configurations is also reviewed, while considering the applications explored.

4.1. Components of a Drone

It is important to have a set of required components for the system when designing a modular drone, with modules acting as a combination or extension. Not all modular drones may share a similar set of components, but there are a few essential components for any drone system:

(1) The frame is the outermost structure of a drone that determines the overall shape. Moreover, the frame provides an aerodynamic structure and acts as a housing for additional payload, with the drone arms connecting all configurations in the frame via arm holders.

(2) Next are the brushless motors and propellers, which work synchronously, to an extent, in providing flight. The propellers generate lift and other forces within a drone, providing thrust and stability. The placement of these parts vary based on the geometry of the drone, but they are essential in the function and design of any aerial robot.

(3) The battery's main function is to allow a drone to operate for a certain endurance.

(4) Additional functional components include the electrical wiring, RC transmitter, electric speed controller (ESC), and landing gear. When designing the landing gear of any UAV system, a virtual simulation is run with parameters of the total deformation, equivalent elastic strain, and equivalent stress to ensure the design can adapt to different circumstances (Universiti Tun Hussein Onn Malaysia, et al., 2021). Additionally, a camera is found on most drones, even if not widely used in sectors like agriculture. Other components of a drone include the flight controller to steer the robot, a mounted camera, and a receiver, which obtains signals from the transmitter to enable control. Figure 1 represents the components used in a conventional quadcopter design.

The frame used in a drone is designed with arms attached to a central canopy (or cover) and propellers via arm holders. Electronics are typically placed within the center of the frame under a canopy. This is true for all larger and smaller configurations, such as those found on agricultural and surveillance drones, respectively. The wiring, battery, ESC, and transmitter are all located in the center of the drone and covered with a canopy (Kirankumar et al., 2023). The landing gear of an industrial drone is similar to that of a helicopter (Dayakar et al., 2024). It does not involve wheels because flight is performed vertically instead of horizontally or at an angle similar to the orientation of airplanes (Dayakar et al., 2024). For drones in sectors like agriculture, these required components are typically accompanied by other components or specific modules. For example, tanks and seed dispersal containers are common parts of agricultural drones, and similarly specialized camera systems for surveillance drones (Rejeb et al., 2022; Lee et al., 2021). Without these additional items in drones, they do not have any commercial or practical significance for that application. Moreover, the use, position, and other anatomical features of each component should be thoroughly assessed when designing a modular drone. These features collectively determine the various geometries within the modular structure.

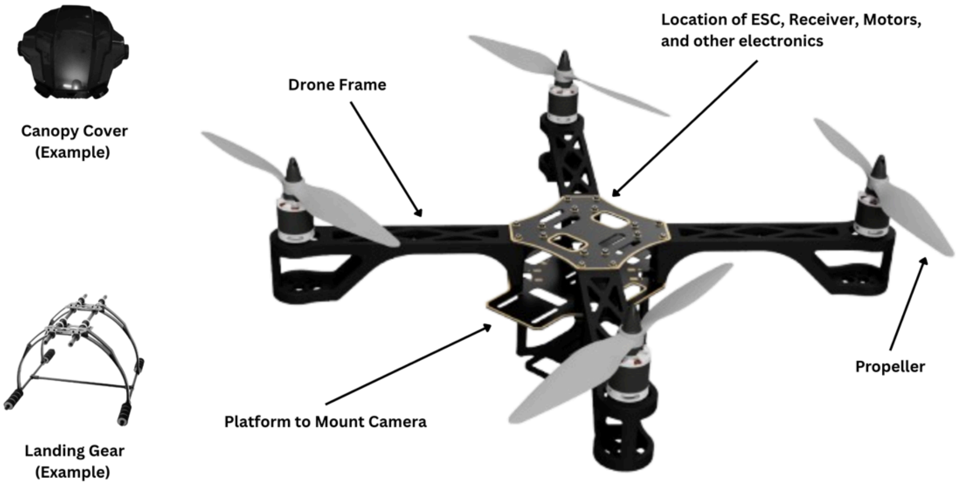

Figure 1: Components of a Quadcopter with examples of a canopy cover and landing gear

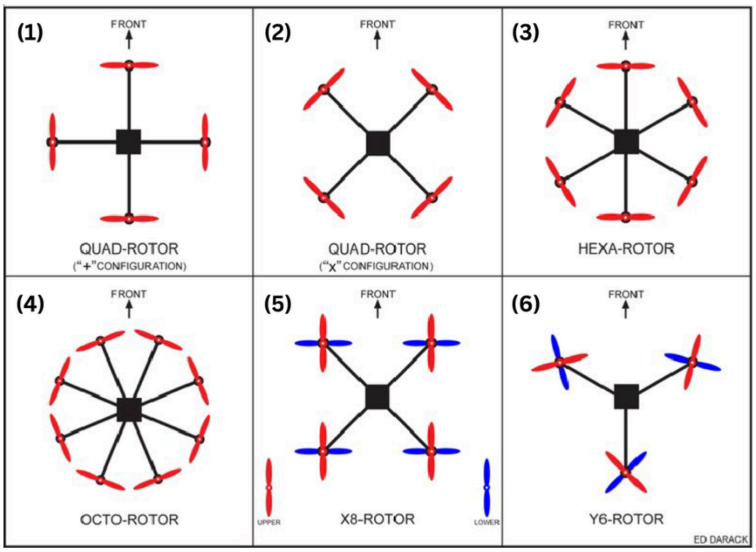

Figure 2: A few common drone structures with single-rotor and double-rotor configurations. Figure reproduced from Camilli et al.

Note: (1) Quad-rotor with four arms from the edge of each side of the drone creating a "+" shape; (2) Quad-rotor with four arms from the corner of each side of the drone creating an "x" shape; (3) Hexa-rotor configuration with six arms forming a symmetrical structure; (4) Octo-rotor configuration with eight arms forming a symmetrical structure; (5) X8-rotor similar to "x" quad-rotor configuration with a double-rotor configuration for a total of 8 rotors; (6) Y6 rotor similar to X8-rotor configuration with three arms and a total of six rotors.

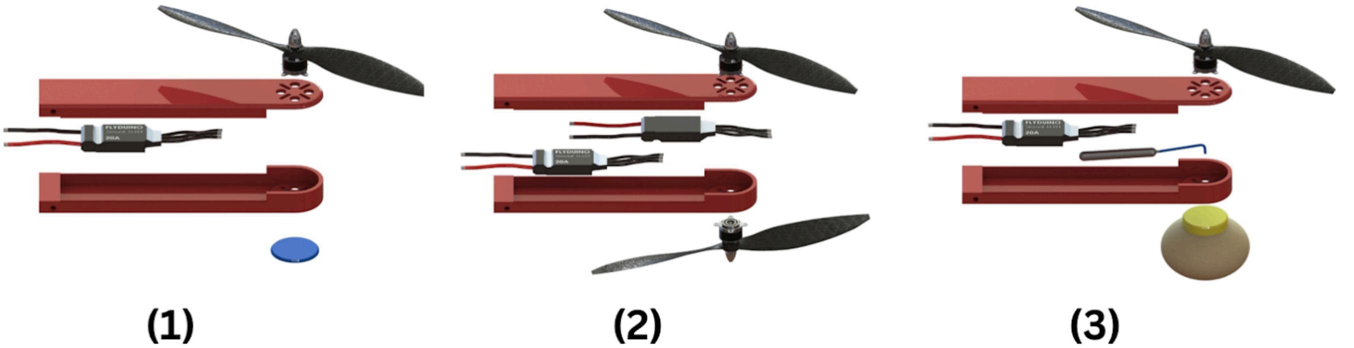

Figure 3: Types of rotor configurations in drones with avionic and electronic elements. Figure reproduced from Brischetto et al.

Note: (1) Single-rotor configuration; (2) Double-rotor configuration; (3) Amphibious configuration.

4.2. Drone Configurations

Many shapes and structures are used to create a drone configuration. Based on the number of rotors or drone arms in an aerial robot, an appropriate prefix can be applied to name the geometrical configuration: for example, “Quad” and “Hexa” correlating to 4 and 6 rotors, respectively (Camilli et al., 2015). The purpose of a greater number of rotors is not only to add more propellers, but to make the drone suitable for the demands of a particular application. Agricultural drones require a larger structure that can carry a great load, and one suitable for the weather conditions in different regions. Hence, agricultural drones typically use a hexa-rotor configuration. However, the number of rotors does not necessarily linearly correlate to the size or payload of a drone.

Six common configurations found in conventional drones are denoted in Figure 2, with the first four featuring a single-rotor configuration and the last 2 featuring a double-rotor configuration. Alongside these configurations, others with propellers on the underside of the arm and those with amphibious configurations exist as displayed in Figure 3, but are not as widespread. Moreover, modules can be applied to many types of drone configurations in the realm of modular drones. Due to the added complexity in modular designs, the structure is determined by a combination of the motion, material, position, and various shapes used for modules. For instance, surveillance quadcopters and modular quadcopters may have varying visual geometrical structures and typically travel in swarms with multi-purpose applications beyond surveillance (Yaacoub et al., 2025). The tetrahedral structure presented for a non-planar aerial robot assembly is an example of a structure that deviates from the common drone configuration (Wali et al., 2023).

In most cases, current modular drones utilize other concepts of geometrical structures. While these innovations may be much smaller in size due to the practicality of experiments, they have a wider range of capabilities. However, a question arises about how industrial-sized modular drones would perform in different applications due to the unique structures in current innovation. These different structures can be depicted by the ModQuad UAV and TetraQuad Aerial Robot (Saldaña et al., 2018; Wali et al., 2023). The ModQuad uses a cuboid frame to allow a combination of modules and for the UAV to travel in swarms, which is a typical characteristic of quadcopters as a whole (Yaacoub et al., 2024; Saldaña et al., 2018). The cuboid frame varies from the Tetra Quad non-planar assembly by Wali et al., where a tetrahedral structure is a direct example of an unconventional configuration. Due to the elevation of the aerial robot, its modules were assembled differently, and this reflects how different geometries lead to a large categorization of configurations for modular drones (Saldaña et al., 2018). Overall, there are multiple types of drone configurations found in modular drones, and from different studies of modular designs, the impact of geometry on the performance of a UAV or aerial robot varies with the configuration. However, without a standard for modular drone configurations, like with conventional UAVs, more barriers may pose a threat to the broader deployment of these systems.

5. Barriers in Deployment

Common and prominent barriers, along with UAV-focused barriers, are explored in the deployment of modular drones based on the different geometries used in the design of these systems. These include societal, economic, and environmental factors for aerial robots, along with technological and regulatory challenges, which are more directly related to UAVs (Sah et al., 2021). Moreover, constraints for deployment closely related to UAVs would have a greater direct geometrical influence. Additionally, current innovations for modular aerial robots are explored further with barriers to deployment.

5.1. Barriers and Geometric Influence

Multiple barriers exist in the deployment of modular aerial robots. In the context of societal barriers, public perception of innovations that deviate from commonly used drones can stir speculation. Automation, awareness, and the use of these drones in the private sector are a few among the many concerns that can arise with the public with wider adoption of modular UAVs (Sah et al., 2021; Kraus et al., 2020). The automation of technology is impacted by the geometries utilized with modes of multi-component connectivity, and the integration among different technologies used with IoT. Awareness of new ways of designing modular drones with different geometries and knowledge of the IoT is not a consensus among the public, and can lead to concerns with awareness if these systems are deployed in the public sector. The use of these drones in the private sector directly poses a risk to the privacy and security of individuals, since the purpose of modular drones by businesses in this sector would most probably be concealed (Sah et al., 2021). A reason for these societal challenges stems from initial public reaction, wherein the process of deployment should be gradual and allow society to eventually become accustomed to advances in drone technology, as modularity is a relatively new field.

Economic and environmental factors also come with direct and long-term impacts. Greater initial costs and impact on the stock market and economy are examples of both aspects within the economic factors (Yaacoub et al., 2024; Sah et al., 2021). These initial costs would be most impactful in the public sector with agriculture, due to affordability for farmers and other individuals. While the cost-saving benefits over time are prominent in most modular drone systems, a solution to spread awareness would have to be implemented for future deployment. Moreover, the impact on the stock market for the broader deployment of modular drones is unpredictable and can be a great risk for a country's economy, as is common for the release of new technologies. Additionally, environmental factors include pollution and harm to wildlife (Yaacoub et al., 2024; Sah et al., 2021). Pollution from UAVs includes air pollution and noise pollution, with emissions of greenhouse gases and a large presence of UAVs in populated areas.

Table 2: Overview of barriers in deployment for modular drones and aerial robots

Barrier	Sub-Categories	Geometric Influence
1. Societal	Public perception; Use of drones in private sector; Societal awareness; Threat to privacy and security	The identification of new drone structures and shapes used by individuals can alter public trust and acceptance of how new technology is deployed. This is especially true for demanding applications such as agriculture, in which drones may not perform as expected with early deployment.
2. Economic	Initial Costs; Impact on stock market	Complex geometries increase production and maintenance costs due to the requirement of specialized components along with limited scalability, potentially affecting market stability and confidence for investment.
3. Environmental	Air Pollution; Noise Pollution; Harm to wildlife	Aerodynamic inefficiencies in unstandardized drone geometries can lead to an increase in energy consumption and noise pollution (Li Volsi et al., 2024). For instance, changes in rotor placement and structural layout as a whole can disturb populations once deployed in an early stage, as well as affect wildlife and local ecosystems.
4. Technological	Aerial collision; Weather conditions; Short flight range; Uncertainty with non-standardized configurations	Modular drone geometries would majorly complicate stability and scalability. This affects flight range and collision avoidance, for instance, along with other parameters. Unstandardized designs for modular drones can lead to uncertainty in their performance across different weather or operational conditions, even with field testing, since conditions in various applications can greatly differ. (Moral et al., 2024)
5. Regulatory	Accountability; Training for drone pilots; Legal complexities with stock market	A range of new geometries raises challenges with existing classification systems and approval through type-certification processes for many new designs (Xie et al., 2024). Moreover, it would require developing new techniques and frameworks for drone pilot training. Regulatory standards for accountability and operation would have to be modified for smooth and ethical deployment.

Technological barriers also include direct and long-term impacts, with challenges including adaptation and performance (Yaacoub et al., 2024; Sah et al., 2021). Aerial collision with other drones and weather conditions in different regions are some examples of challenges with adaptation that are not directly addressed in current modular drone innovations. The cost of repair can also be high in the case of any form of aerial collision between UAVs, and deployment may not be practical in certain urban areas. This is simply a reflection of how multiple barriers (technological and economic) can build on one another in hindering the deployment of modular aerial robots. A short flight range and execution in different applications fall under performance challenges, which are also not greatly focused on in current innovations. Consequently, a non-standardized design can affect flight range capabilities due to the constraints of battery size and aerodynamic efficiency being limited by a range of varying designs for modular configurations. Moreover, with modular configurations not becoming standardized, it would be a greater challenge to achieve features such as flight range similar to or even improved from existing configurations, creating a conflict for deployment. This conflict directly arises from the uncertainty of modular drone performance, and creating a set of standardized configurations through future research is one of the only ways to address this barrier. Additionally, another technological challenge is simulating the drone with deformation, stress, and strain parameters, which is the most crucial step in testing a drone design before deployment. The shape, configuration, and overall structure can have a direct impact on the level of adaptation and performance in various applications, with the geometric influence for this barrier being more direct. This can lead to scalability or maintenance issues, for example, depending on the extent to which more modules can be attached in a modular design. It also poses a certain extent of unpredictability in real-world applications.

Lastly, regulatory barriers majorly include accountability and training for drone pilots (Yaacoub et al., 2024; Sah et al., 2021). Even with the deployment of modular drones, adoption will most likely take a long time due to different measures that have to be considered when training drone pilots and holding them accountable for any faults. Additionally, challenges with regulation can also lead to the effect of modular drones in the stock market as an economic factor due to the growing complexity of legal structures (Pranchana et al., 2025). It is similar to the concern with the ethical use of artificial intelligence, and is impacting the stock market in positive and negative ways, depending on the sophistication of different AI technologies (Pranchana et al., 2025). Moreover, a similar trend may be seen if modular drones are deployed in the near future. Also, because of the potential impact on the stock market with legal complexities, along with other factors, regulation poses another hurdle. Overall, these five barriers have been the driving factor as to why modular drone systems are not deployed in the public or private sector, due to a combination of multiple perspectives, ranging from public opinion to technological challenges to legal regulations.

5.2. Case Studies

All of the case studies previously discussed have barriers preventing their widespread usage, with a few additional ones in Figure 4. Deploying these modular aerial robots and UAVs in the public or private sector requires addressing each challenge to break down barriers in using these systems. Figure 4 represents a few novel modular drone aerial robot assemblies, all for different purposes. While they were not created for specific applications like agriculture or surveillance, these studies depict a stepping stone in the aerial robot and drone industry. From the innovative solutions showcased by these studies, along with the TetraQuad assembly, for instance, a large canvas can be spread for possible applications they can contribute to (Wali et al., 2023). However, with the original approaches of modularity in these studies, societal, economic, technological, and regulatory barriers arise for the broader deployment of modular drones as a whole. Identification of drones and concerns about their performance and adaptability due to the usage of relatively new technology are almost negligible if modular drones are deployed. Moreover, the costs of producing these technologies would be high (Mueller et al., 2022). This leads to the common technological challenge of adapting all these technologies for a large range of modular aerial robots. This is not a feasible or realistic approach in the context of deploying them for the masses, and regulations by certain agencies or governments may restrict this. In essence, the innovative approaches to modularity in drones and aerial robots by these studies also reflect certain advantages and disadvantages.

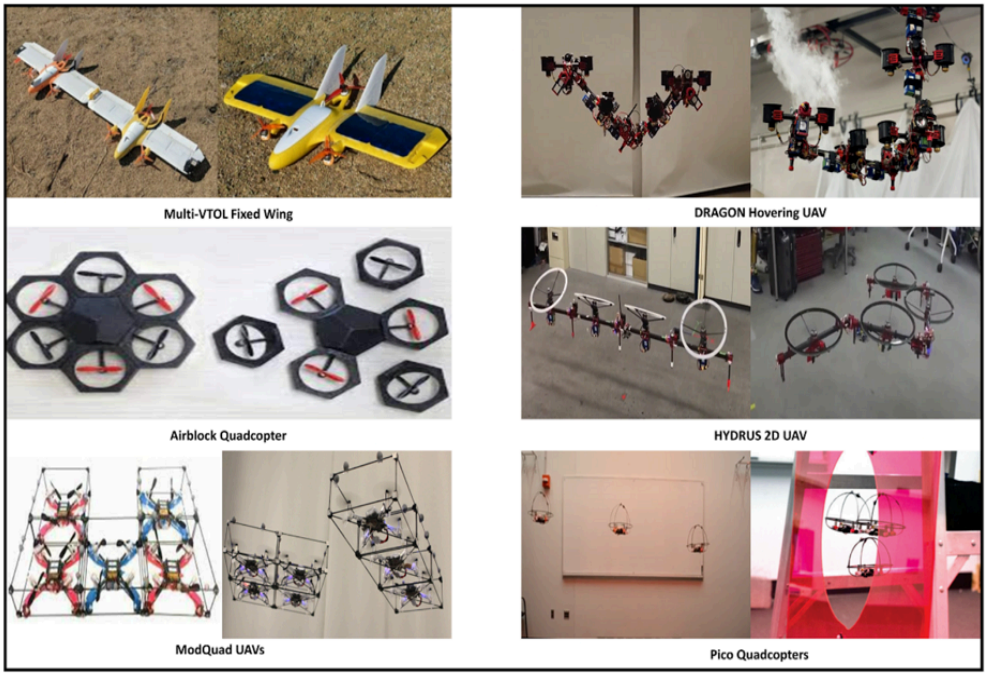

Figure 4: Examples of current innovations of modular drones and UAVs. Figure reproduced from Yaacoub et al.

Note: (1) Modular fixed-wing innovation relying on modules to effectively adapt to different weather conditions for various applications; (2) DRAGON UAV by Zhao et al., with the ability of multi-degree-of-freedom; (3) Airblock Quadcopter, which uses the Makeblock software; (4) HYDRUS, which is a 2D transformable UAV; (5) ModQuad UAV by Saldaña et al., which uses a cuboid frame system to attach multiple modules; (6) Pico quadcopter tested for collision avoidance.

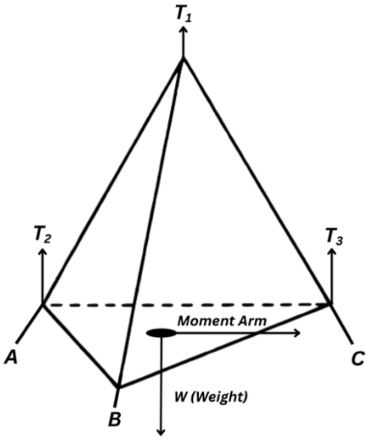

Figure 5: Free body diagram of tetrahedral frame with forces and stability margins (not to scale)

Note: T1, T2, T3 represent the thrust forces acting on a tetrahedral frame at each node; A, B, and C are the vertices for the triangular base nodes of the frame; Moment arm represents the perpendicular distance from the direction of a force (i.e., thrust and weight) to determine the rotational effect of that force.

Non-planar assembly using TetraQuad modules has advantages and disadvantages. A couple of advantages are the ease of attachability to scale replicas of the module to perform practical experiments with different configurations, for a proportionate structure with good stability. While a combination of different modules is a desirable advantage, it directly impacts the performance and efficiency of the robot, leading to a disadvantage. The results revealed a less uniform circular motion for the larger 16 TetraQuad assembly, reflecting the limited effectiveness of this approach, even with minimal issues in stability (Wali et al., 2023). Figure 5 represents a free-body diagram of a tetrahedral frame to depict the forces and stability margins of this geometry in the design of the TetraQuad assembly.

Figure 5 displays the forces acting on a tetrahedral frame, and these principles can be applied to the stability margins in the TetraQuad assembly. With a single tetrahedral frame of a TetraQuad module, the stability with the thrust forces varies from that of the vertically stacked tetrahedral frames of the 16-module TetraQuad. Moreover, the tetrahedral frame used distributes thrust forces evenly through multiple triangular faces. It is generally more stable than flat or more linearized configurations, making it a suitable option for modularity on a larger physical scale (Wang et al., 2017). Here, the center of mass is equidistant from the thrust forces. Additionally, the drone would be highly resistant to deformation (e.g., in different weather conditions with this frame. This is especially true for a single module where stability is dependent on only one compact structure. However, for the 16-module assembly, there is a vertical stacking effect where the center of mass is lowered, and the moment arm is increased to balance the thrust arms (Wali et al., 2023). With the alternation of the center of mass, forces are spread out more and increase the torque or rotation of the robot overall, which may be the reason for the less smooth circular locomotion observed. The diagram may not directly explain the circular trajectory observed, as there is no direct relationship between the center of mass or moment arm and locomotion. However, it provides an understanding of how multiple tetrahedral-shaped modules can alter the performance of a drone, and how the level of stability can vary based on the geometry used in the design of the drone.

The experimental results for the TetraQuad drone's altitude oscillation only had a 10% margin of error, which is a promising initial result for a novel design, even though further refinement is necessary for commercial viability. When considering the non-planar TetraQuad as a prototype, there will be different requirements for a drone to operate commercially with regulations varying between countries. For example, there is a legal process to operate a drone commercially in India, which involves registering a drone (including type certification), obtaining a pilot certificate, and gaining permission to use certain airspace (Singh et al., 2024; Xie et al., 2025). Regardless, the approach used in the TetraQuad assembly was still considerably effective in demonstrating a mostly accurate trajectory, and allows experimental results to be comparable with similar studies, for example. An improvement that can be made is testing the subject in different environments and performing sets of different trajectories beyond circular motion. This can enhance the results presented with an understanding of how similar aerial robots can perform in real-world circumstances. Moreover, iteration in the engineering design process for modular drones is an actionable step to address future regulations for these systems.

The ModQuad UAV by Saldaña et al., which is a quad-rotor aerial robot, is yet another great example of a current modular aerial robot innovation. Its primary function is to self-assemble in mid-air, and its structure includes a quad-rotor drone within the center of a modular cuboid frame, as a single unit (Saldaña et al., 2018). Each of these units can attach in the airspace via magnets on each edge, which is a passive docking approach (Saldaña et al., 2018). This allows for efficient swarm applications. However, it also faces disadvantages, such as trajectories and maintenance. The trajectories revealed from the study can vary greatly in the real world, especially with swarm applications in various environments. Moreover, maintenance is also a challenge because relying on magnets for mid-air self-assembly would require regular replacement and can make the use of ModQuad impractical, especially for demanding swarm applications. This challenge with the use of magnets exists because it is a relatively new concept introduced for swarm applications through modularity. Also, the reliance on magnets has not been tested in larger-scale applications with maintenance, where it may be beneficial long-term, which would likely not clear the design for broader deployment. Moreover, to mitigate future limitations, a certain standard for modular drones must be introduced, and the use of magnets can undergo multiple iterations in the engineering design process to achieve efficient maintenance in different applications for deployment (Patel V., 2024).

When analyzing the TetraQuad and ModQuad UAVs, the names may appear similar, but the approach to modularity is distinct. Firstly, the suffix “Quad” for the nonplanar assembly by Wali et al. represents four identical modules attached. However, the suffix represents a quad-rotor drone as the powerhouse of the system, encapsulated by a modular cuboid frame, which then attaches to identical units mid-air for the ModQuad. This highlights the contrasting nature of the modular aerial robots presented in these studies on the surface level, which further reflects the true feasibility of deployment, especially with perspectives beyond the technologies incorporated. Moreover, when considering ModQuad, it involves geometric choices that favor one capability, like reconfigurability with easy attachment of different modules, but come at the expense of maintenance. Conversely, maintenance is not a significant challenge for the TetraQuad, but reconfigurability and scalability remain a challenge because another row of tetrahedral modules cannot be simply attached.

Other studies also follow different approaches, contrasting with those found in the TetraQuad and ModQuad assemblies. The technological hurdles in modularity may be similar to basic features of flight time, range, and payload, but specific economic, environmental, and social factors vary (Sah et al., 2021). All these barriers are evident from the modular solutions presented in these studies, from small to large degrees. When considering these studies, the geometrical structures, shape, and other anatomical features do not follow a general or standardized range of configuration, such as with the conventional drones shown in Figure 2. Having a range of configurations has made conventional drones successful through decades of design and innovation for the masses. Moreover, a threat is posed to modular drone deployment by factoring in the way drones would be perceived by a society situated with conventional drones. For deployment, all studies would have to undergo multiple iterations as part of the design process until a system that meets the regulations for modular drones is achieved. From these modular innovations, it can be seen that certain geometric choices favor one or more capabilities, but often come at the expense of others, which have to be addressed for future deployment. Overall, while there are disadvantages to multi-component aerial robots and barriers that arise, they introduce a new scope of designing modular drones for various applications. These barriers stimulate a transition to a more structured approach towards deployment, similar to a universal set of configurations found in conventional drones, foreseeing a long journey for the deployment of modular drones.

6. Conclusion and Future Work

The design and deployment of modular drones and aerial robots are influenced by geometries and have the potential to reshape the applications of agriculture and surveillance by offering many benefits through various perspectives. From modular design to the implementation of drone configurations through modularity, the nature of these drones and aerial robots was explored. However, the deployment of modular drones is met with barriers, including societal, economic, environmental, technological, and regulatory challenges. While innovations like the TetraQuad and ModQuad showcase unique approaches through multi-component modularity, these solutions give rise to geometric complexities, leading to barriers in deployment.

Looking forward, future work in the field of modular drones and aerial robots must focus on addressing these barriers through further research. Societal, economic, and environmental challenges can be addressed through rigorous iteration of current innovation, considering these perspectives in the design of modular drones. For technological challenges, further research should be conducted to improve performance and adaptability through geometry optimization as a whole. Regulatory frameworks also need to be developed and/or evolve to address the complexity of modularity in these systems. Moreover, research should advance standardized geometric configurations for modular drone designs to fulfill frameworks and streamline the deployment process. The use of modular drones in applications such as agriculture and surveillance would require addressing barriers and conducting research to pave the way for drones in these applications. Overall, this multidisciplinary approach will be critical for the broader deployment of these systems, with barriers stimulating a transition to a more structured approach, foreseeing a long journey for the deployment of modular drones through design.

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Mentor Contribution Statement

Dr. Devin Carroll and **Mr. Kieran N. Tait** provided guidance, constructive feedback, and subject-matter expertise throughout the research process. Their support primarily consisted of guiding the student through the process of gathering secondary research and overseeing the flow of academic writing. Their advice also included detailed feedback on clarity and terminology to align the manuscript with scientific conventions. Overall, the mentors' contributions were intellectual and advisory in nature, and this statement acknowledges their role as mentors while affirming that all research and writing were conducted independently by the student author.