

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

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 and communities in applications such as agriculture and surveillance. These drone systems make various real-life applications easier with repair, flexibility, and performance. However, there are multiple key barriers to the modularity of social, economic, environmental, technological, and regulatory factors in the deployment of these systems. Reasons range from the application and other factors that the system is required to meet, including the weight and payload, endurance, frame type, and geometrical structure. Addressing these barriers is essential to expanding the use of modular drones to serve in these applications. This is reviewed through multiple examples of design and geometrical influence in existing modular drone innovations.

Keywords

Modular drone systems, geometry, modular design, aerial robots, UAVs, 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 use of drones, such as in agriculture and surveillance, to meet agricultural demand or various surveillance applications, respectively. 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 in deploying these drones, with societal, economic, environmental, technological, and regulatory perspectives. These are acclaimed to be 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 give rise to barriers in the deployment of these drones, which are addressed in this review.

In this review, the various applications of modular drone systems are explored with a focus on various 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/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). Furthermore, individuals, including drone pilots, manufacturers, farmers, and trainers,

could benefit from modularity in different ways, like economically for farmers, in comparison to using more conventional agriculture drones. This is because of the long-term cost-saving benefits modular designs provide, which is a great deal for farmers, especially in countries like India and China, where they may not have a substantial financial status.

Furthermore, 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.

At first, modular drone systems can be seen as drones that require additional financial investment (Mueller et al., 2022). However, using different geometries in drones and improving their efficiency as well as functionality with modularity can lead to cost-effective maintenance in the long term (Yaacoub et al., 2024). Additionally, the long-term aspect is also true for surveillance drones through modularity, by converting the drone's camera into a multi-component system, for instance (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.

With a focus on design geometries in modular drone systems, the specific design objectives with modularity are addressed in the second section of this review. An overview outlining these objectives is followed by different types of modules. The modules in specific applications like agriculture and surveillance are also reviewed in this section, followed by control methods. The third section focuses on different geometries in drone design with various configurations, like quad or tetra, for example, 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 robots.

2. Modular Drone Design Objectives and Applications

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

2.1. Modularity

Modular drones or UAVs can be described as smart aerial robots that can perform complex tasks more efficiently from 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, as discussed in (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, and allow systems to be reshaped or resized (Yaacoub et al., 2024). These types of modules are useful for agriculture because cleaning parts of the drone heavily used throughout the day can be a more direct and facile task, and saves storage space in smaller farms. Other benefits that would apply to most applications are those of reparability, 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 operation of certain tasks difficult through the new modular design, and hence ensuring that performance is direct for interaction is crucial for overall efficiency. Moreover, how the user interacts with the drone is not a widely touched-upon aspect of different modular solutions for aerial robots.

Several studies have innovated a modular solution for aerial robots using different types of modules. The modules used are often smaller in size than those found in the market for conventional drones and involve the use of specific geometries. Some examples are 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 and attach 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 in this study (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). Overall, these studies showcase how the design of aerial robots, even with testing models, leads to challenges with complexity and is a primary factor in hindering the deployment of modular drones in the market for various applications.

2.1.1. Control Methods

When considering modularity in drone systems, it is critical to consider various control methods for the smooth operation of these robots. Control methods are important because, for operation in complex environments with learning-based control, precise control is required, 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. It 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). Moreover, a few control method architectures include low-level control & stabilization, and higher-level planning (Mueller et al., 2022). Additionally, 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).

2.2. Overview of Real-Life Applications

When discussing the real-life applications of modular drones, a couple of notable applications are agriculture, especially in largely 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 and 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 performance with accuracy when executing tasks (Soori et al., 2023).

2.2.1. 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., gushing fertilizer, seed dispersal, transportation, etc.). Modular agriculture drones are not yet widespread, but their benefits, in terms of functionality and efficiency, can pave the way for the future of agriculture. While there are many leading agriculture 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 agriculture drones in 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 the 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, and 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). Moreover, precision agriculture and remote sensing also fall under these technologies as vital aspects in performing agricultural tasks.

2.2.2. 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/arm holder assembly, similar to agricultural drones, but they are also not very widespread. While surveillance drones may not have an impact similar to 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. Transformation mid-air with 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 using minimal materials, respectively. Moreover, the importance of modular drones in surveillance also stems from IoT and machine learning, along with other technologies. The role of IoT in surveillance is similar to that of agriculture and other UAVs that incorporate it (Gohari et al., 2022).

3. Drone Geometrical Structures

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

3.1. 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 would vary based on the geometry of the drone, but they are essential in the function and design of any aerial robot. (3) Another key part of a drone is the battery. The battery's main function is to allow a drone to operate for a certain endurance. (4) 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 hexacopter design (Ray et al., 2025).

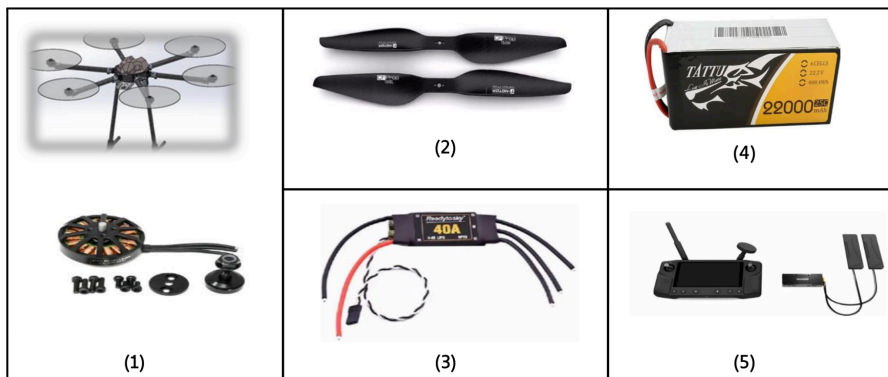


Figure 1: Components of a Hexacopter using Mission Planner Software. Figure adapted and reproduced from Ray et al. 2025. (1) Frame and Brushless Motors; (2) Propellers; (3) Electronic Speed Controller; (4) Battery; (5) Receiver and Transmitter.

Moving on, 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). Then, 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 at an angle like that of airplanes (Dayakar et al., 2024). For drones in sectors like agriculture, these required components are typically accompanied by others or specific modules. Tanks and seed dispersal containers are common parts of agricultural drones, and similarly specialized camera systems for surveillance drones, in general (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.

3.2. 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, with “Quad” and “Hexa” correlating to 4 and 6 rotors, respectively (Camilli et al., 2015). The purpose of a greater number of rotors goes beyond adding more propellers, but is to be suitable for the demands in a particular sector. Agriculture drones require a larger structure that can carry a great load, and those suitable for the weather conditions in different regions, for instance. Hence, agricultural drones typically use a hexa-rotor configuration, which is more suitable. However, the number of rotors does not necessarily linearly correlate to the size or payload of a drone. Similar configurations may be used for different applications.

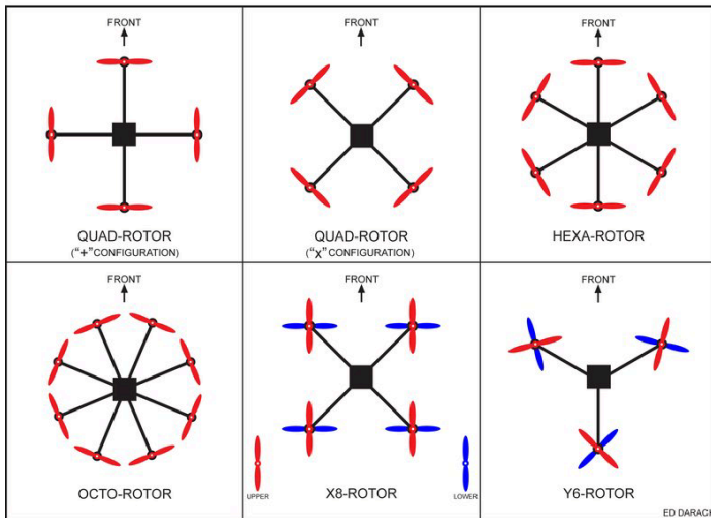


Figure 2: A few common drone structures with single-rotor and double-rotor configurations; Figure reproduced from Camilli et al. (1) Quad-rotor with four arms from the edge of each side of the drone creating a “+” shape; (2) Quad-rotor with four arms from the corner of each side of the drone creating 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.

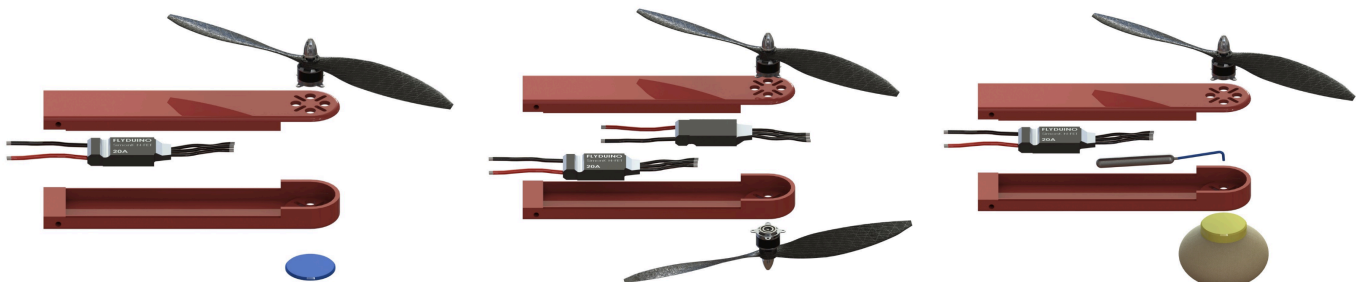


Figure 3: Types of rotor configurations in modular drones with avionic and electronic elements. Figure reproduced from Brischetto et al. (1) Single-rotor configuration; (2) Double-rotor configuration; (3) Amphibious configuration.

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. Additionally, 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).

Moving on, current modular drones utilize different concepts of geometrical structures apart from these, in most cases. 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 by Saldaña et al. 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, modules were assembled differently, and this reflects on 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 in terms of configurations for modular drones, like with conventional UAVs, a threat may be posed in the broader deployment of these systems, which may lead to other barriers.

4. Barriers in Deployment

Common 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. Societal, economic, and environmental factors are among the common barriers for aerial robots, along with technological and regulatory barriers, which are more directly related to UAVs (Sah et al., 2021). Barriers closely related to UAVs would have a great direct geometrical influence. Additionally, current innovations for modular aerial robots are explored further with barriers to deployment.

4.1. Barriers and Geometric Influence

Multiple barriers exist in the deployment of modular aerial robots. In the context of societal barriers, public perception of innovation, different from the drones commonly used, can stir speculation. Automation, awareness, and the use of these drones by 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). 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 security and privacy of individuals, since the purpose of modular drones by businesses in this sector would most probably be enclosed. Moving on, economic and environmental factors also have multiple aspects 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 the affordability of farmers and other concerned individuals. While the cost-saving benefits over a period of 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. 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, respectively.

Additionally, technological and regulatory barriers also include direct and long-term impacts. A couple of technological challenges involve 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. It 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. Also, another technological challenge is simulating the drone with deformation, stress, and strain parameters, which is the most crucial step in testing a design before deployment in any application. The shape, configuration, and overall structure can have a direct impact on the level of adaptation and performance in various applications. 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 go on for a long period due to different measures that have to be considered when training drone pilots and holding them accountable for any faults. 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 the public's eyes to technological challenges.

4.2. 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/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 and modular 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.

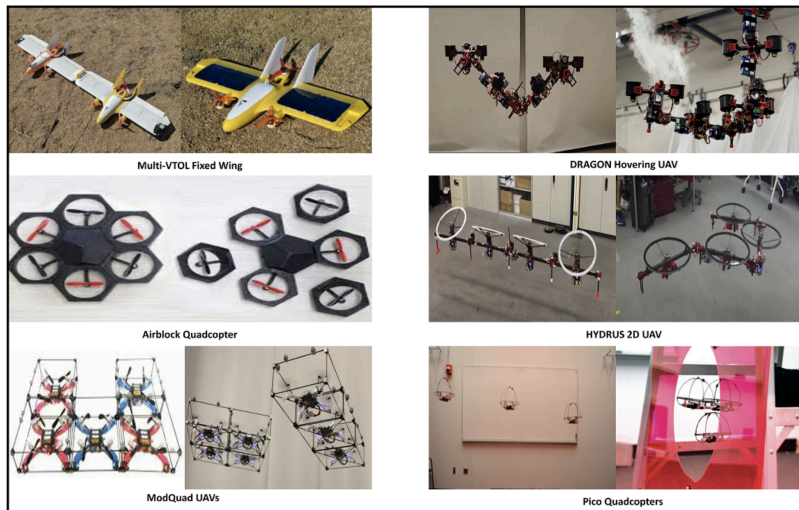


Figure 4: Examples of current innovations of Modular Drones/UAVs; Figure reproduced from Yaacoub et al. (1) Modular fixed-wing innovation relying on modules to effectively adapt to different weather conditions for various applications; (2) DRAGON UAV by Zhao et al., with the ability of multi-degree-of-freedom; (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.

For the non-planar assembly using TetraQuad modules, the approach used 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, and a proportionate structure throughout 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). However, this approach was still considerably effective in demonstrating a mostly accurate trajectory, and allows experimental results to be comparable with similar studies, for example. Moreover, 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.

Additionally, 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 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 within airspace to others via magnets on each edge, which is a passive docking approach (Saldaña et al., 2018). This allows for efficient swarm applications; this aerial robot also features disadvantages. A couple are the 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 this iteration of ModQuad impractical, especially for demanding swarm applications. Iterations of ModQuad addressing these disadvantages, as well as scaling to match the size of conventional drones in these applications, is a way to combat these disadvantages since the conceptual model of ModQuad is strong.

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 4 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 by Saldaña et al. 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.

Moving on, 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 the specific factors of 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, for instance, like with conventional drones shown in Figure 2. Having a range of configurations has made conventional drones successful, as shown in Figure 2, 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. 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.

5. 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 confronted by substantial barriers with 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/aerial robots must focus on addressing these barriers with iteration and 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 for 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 satisfy frameworks and streamline the deployment process. Modularity in 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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The paper "Design and Deployment of Modular Drone Systems with Geometry Optimization: A Review" provides a high-level overview of modular drones, identifying their potential benefits and the significant barriers to their widespread deployment. The use of case studies like the TetraQuad and ModQuad UAVs is a strength. It helps illustrate key concepts. Overall, the paper is well-structured and demonstrates that the author has done a thorough literature review. However, the paper tends to summarize research rather than critically analyze it. Moreover, I am concerned about the inclusion of figures from other papers without obtaining permission, despite citing them.

Comments to the Author

Major Areas for Revision

1. Please include more critical analysis. For example, When discussing the TetraQuad and ModQuad UAVs, you note their advantages and disadvantages. To improve, you can analyze why certain disadvantages exist. For instance, you mention that the ModQuad's reliance on magnets for self-assembly could make it impractical for maintenance. You could expand on this by discussing what alternative docking mechanisms other researchers are exploring or propose what future research is needed to overcome this.

2. Think more about the central argument: Your thesis about the lack of standardized configurations hindering deployment is a great point. However, the connection between this and the various barriers (societal, economic, etc.) could be stronger. For example, state that technological challenges like a short flight range contribute to deployment barriers. You can connect this more explicitly to geometry. How does a non-standardized design geometrically constrain battery size or aerodynamic efficiency, thus limiting flight range? Showing these direct cause-and-effect relationships will make your paper stronger,

3. Try to improve flow. Some transitions seem abrupt. For example, The jump from "Control Methods" to "Real-Life Applications" in Section 2.2 could be smoother.

4. Consider redoing all the figures. As far as I know, journals require you to obtain permission before reusing even if they are cited. I could be wrong, please ask someone in charge, but if it is true please consider making your own figures.

Final Recommendation

Given the above, I suggest a decision of **Accept with major revisions**. The paper has a solid foundation of reviewing literature, especially recent papers. However, the lack of critical analysis and the issue with the figures need to be improved before it can be published.

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

Final Recommendation: Accept with Minor Revisions

The manuscript is an admirable student effort and aligns well with Convergence's mission. Once the authors supply a transparent search strategy, a quantitative comparison table, and tighten the geometry performance argument, the paper will serve as an excellent introductory review for K-12 audiences interested in modular drone systems.

Review Feedback and Recommendations:

In general, the manuscript surveys how modular geometries influence agriculture and surveillance applications and synthesizes deployment barriers (societal, economic, environmental, technological, and regulatory). Two emblematic prototypes are used to illustrate trade-offs between reconfigurability, stability, and market readiness. The paper is clearly structured and offers a useful one-stop introduction for high-school readers entering the field. Some major strengths of this review paper include its pedagogical clarity, balanced viewpoints, and timely topics, which are effectively displayed and presented.

However, to achieve the standard as an accepted Convergence Journal paper, some revisions are required:

- 1) Adding some information about the systematic search strategy

The abstract should mention the review methodology and principal conclusion upfront. In addition, adding a short subsection describing the methods, including databases, time span, and inclusion criteria, is highly recommended.

- 2) Adding some quantitative evidence

In the review paper, the performance claims "greater performance in robots with fewer modules" cite only one simulation study, with no payload, flight time, or energy consumption data tabulated. To improve, insert a comparative table summarizing at least some of the following: configuration, MTOW, endurance, controller type, and demonstrated task.

- 3) Adding some information on geometry–performance

In the review paper, the author rarely explains why tetrahedral frames reduce trajectory error or how arm length affects moment of inertia. To improve, provide one worked example (free-body diagram or simplified dynamics) to show how geometry alters stability margins.

- 4) The barriers section is repetitive

In the barrier section, five paragraphs restate "cost, regulation, complexity" without actionable mitigation steps. To improve, the author could collapse the key aspects into a bullet list, combining with the future research aspect, matching each barrier to

a concrete design or policy remedy.

5) Reference quality and formatting

The reference should be numbered accordingly within the paragraphs, starting with the literature review part. Some sources seem incomplete (“Yaacoub, n.d.”), others are non-peer-reviewed resources, and journal and books page ranges and DOIs are inconsistent. The author could check the required submission format guidelines provided by the Convergence journal, especially on the citation styles and other formatting requirements, spacing, pictures, etc.

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

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 and communities in applications such as agriculture and surveillance. These drone systems make various real-life applications easier with repair, flexibility, and performance. This review explores important design objectives, real-life applications, and various geometrical structures. It follows an analysis of multiple key barriers of social, economic, environmental, technological, and regulatory factors in the deployment of these systems. These barriers are correlated with various innovations in modular drones/aerial robots. A systematic search of the literature and current research was conducted to identify relevant sources. Moreover, reasons for these barriers range from the application and other factors that the system is required to meet, including the weight and payload, endurance, frame type, and geometrical structure. The research indicates that the various geometries used in the design of these systems have an influence on deployment by leading to key barriers. It is reflected through current solutions of modular drones/aerial robots. Moreover, addressing these barriers is crucial to expanding the use of modular drones to serve in real-life applications.

Keywords

Modular drone systems; geometry; modular design; aerial robots; UAVs; 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 use of drones, such as in agriculture and surveillance, to meet agricultural demand or various surveillance applications, respectively. 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 in deploying these drones, with societal, economic, environmental, technological, and regulatory perspectives. These are acclaimed to be 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 give rise to barriers in the deployment of these drones, which are addressed in this review.

In this review, the various applications of modular drone systems are explored with a focus on various 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/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). Furthermore, individuals, including drone pilots, manufacturers, farmers, and trainers, could benefit from modularity in different ways, like economically for farmers, in comparison to using more conventional agriculture drones. This is because of the long-term cost-saving benefits modular designs provide, which is a great deal for farmers, especially in countries like India and China, where they may not have a substantial financial status.

Furthermore, 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.

At first, modular drone systems can be seen as drones that require additional financial investment (Mueller et al., 2022). However, using different geometries in drones and improving their efficiency as well as functionality with modularity can lead to cost-effective maintenance in the long term (Yaacoub et al., 2024). Additionally, the long-term aspect is also true for surveillance drones through modularity, by converting the drone's camera into a multi-component system, for instance (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.

Moving on, with a focus on design geometries in modular drone systems, the specific design objectives with modularity are addressed in the second section of this review. An overview outlining these objectives is followed by different types of modules. The modules in specific applications like agriculture and surveillance are also reviewed in this section, followed by control methods. The third section focuses on different geometries in drone design with various configurations, like quad or tetra, for example, 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/aerial robots and associated barriers to deployment, with a focus on geometry optimization. Moreover, literature, between 2014 and 2025 (with an ex, was sourced from large databases including Google Scholar, IEEE Xplore, and Research Gate. Both current innovations in modular drones/aerial robots and 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, and then categorized based on whether or not a design geometry was at least demonstrated, even if not directly discussed, with the performance of the drone. From this, the strongest studies valuable to the analysis of the design and broader deployment of modular drones were selected and reviewed in depth. Moreover, the parameters for choosing these studies include the endurance or flight time tested in the study, and this information was useful for a comparison of quantitative data collected in 2 or more studies.

Moving on, the inclusion criteria for selecting past literature reviews were how the correlation of the design of a drone was demonstrated with modularity, and other studies on barriers identified for drones, even if they focused on specific applications. 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, for example. From this, studies pertaining to the design along control of drones were identified, and a subsection on control methods is included (3.1.1). In addition, 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 features 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 the type and motion of modules. Control methods and modularity for the applications of agriculture and surveillance are also explored.

3.1. Modularity

Modular drones or UAVs can be described as smart aerial robots that can perform complex tasks more efficiently from 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, and allow systems to be reshaped or resized (Yaacoub et al., 2024). These types of modules are useful for agriculture because cleaning parts of the drone heavily used throughout the day can be a more direct and facile task, and saves storage space in smaller farms. Other benefits that would apply to most applications are those of reparability, 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 operation of certain tasks difficult through the new modular design, and hence ensuring that performance is direct for interaction is crucial for overall efficiency. Moreover, how the user interacts with the drone is not a widely touched-upon aspect of different modular solutions for aerial robots.

Several studies have innovated a modular solution for aerial robots using different types of modules. The modules used are often smaller in size than those found in the market for conventional drones and involve the use of specific geometries. Some examples are 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 and attach 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 in this study (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 drones and aerial robots (Saldaña et al., 2018). Moreover, Table 1 compares the configurations of each modular drone innovation with the MTOW (Maximum Takeoff Weight), the tested endurance from each study, and a comparison of the demonstrated tasks.

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.)

Table 1: Comparison of Drone Configurations, MTOW (i.e., Maximum Takeoff Weight), Tested Endurance (i.e., Flight Time), and Demonstrated Task of current modular drone innovations (Wali et al., 2023; Saldaña et al., 2018).

From Table 1, the data collected from experiments with the TetraQuad and ModQuad are presented with one module along with 4 modules and 5 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 for the DRAGON UAV. The performance of a single modular structure in comparison to a multi-modular structure is seen. For example, the flight stability of a single TetraQuad module is relatively high during a 50-second flight time from experimental results 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 5 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 challenges with complexity and is a primary factor in hindering the deployment of modular drones in the market for various applications.

3.1.1. Control Methods

When considering 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, for operation in complex environments with learning-based control, precise control is required, 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. It 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). Moreover, 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, especially in largely 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 and 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 performance with accuracy when executing tasks (Soori et al., 2023).

3.2.1. 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., gushing fertilizer, seed dispersal, transportation, etc.). Modular agriculture drones are not yet widespread, but their benefits, in terms of functionality and efficiency, can pave the way for the future of agriculture. While there are many leading agriculture 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 agriculture drones in 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 the 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, and 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). Moreover, precision agriculture and remote sensing also fall under these technologies as vital aspects in performing agricultural tasks.

3.2.2. 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/arm holder assembly, similar to agricultural drones, but they are also not very widespread. While surveillance drones may not have an impact similar to 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. Transformation mid-air with 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 using minimal materials, respectively. Moreover, the importance of modular drones in surveillance also stems from IoT and machine learning, along with other technologies.

4. Drone Geometrical Structures

This section focuses on the geometry used in the design of drones with different components required for a modular drone 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 would vary based on the geometry of the drone, but they are essential in the function and design of any aerial robot. (3) Another key part of a drone is the battery. The battery's main function is to allow a drone to operate for a certain endurance. (4) 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.

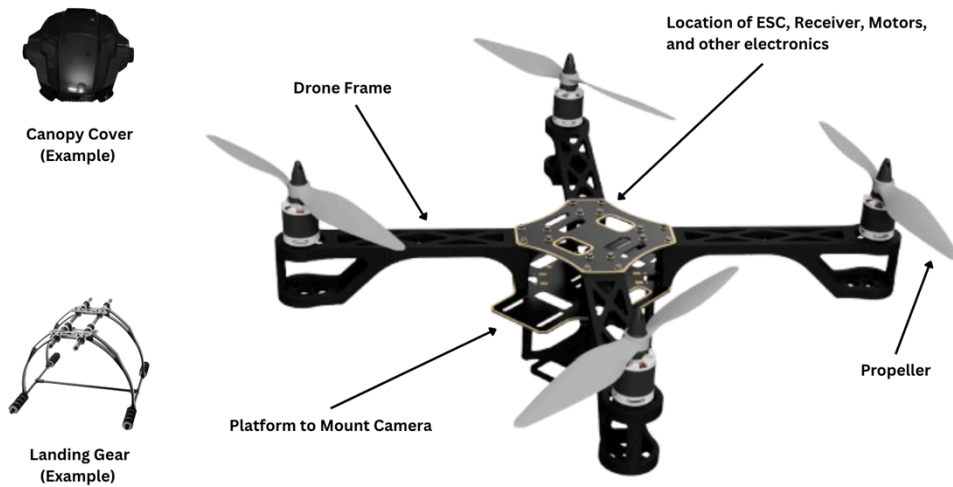


Figure 1: Components of a Quadcopter with examples of a Canopy cover and Landing Gear.

Moving on, 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). Then, 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 at an angle like that of airplanes (Dayakar et al., 2024). For drones in sectors like agriculture, these required components are typically accompanied by others or specific modules. Tanks and seed dispersal containers are common parts of agricultural drones, and similarly specialized camera systems for surveillance drones, in general (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.

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, with “Quad” and “Hexa” correlating to 4 and 6 rotors, respectively (Camilli et al., 2015). The purpose of a greater number of rotors goes beyond adding more propellers, but is to be suitable for the demands in a particular sector. Agriculture drones require a larger structure that can carry a great load, and those suitable for the weather conditions in different regions, for instance. Hence, agricultural drones typically use a hexa-rotor configuration, which is more suitable. However, the number of rotors does not necessarily linearly correlate to the size or payload of a drone.

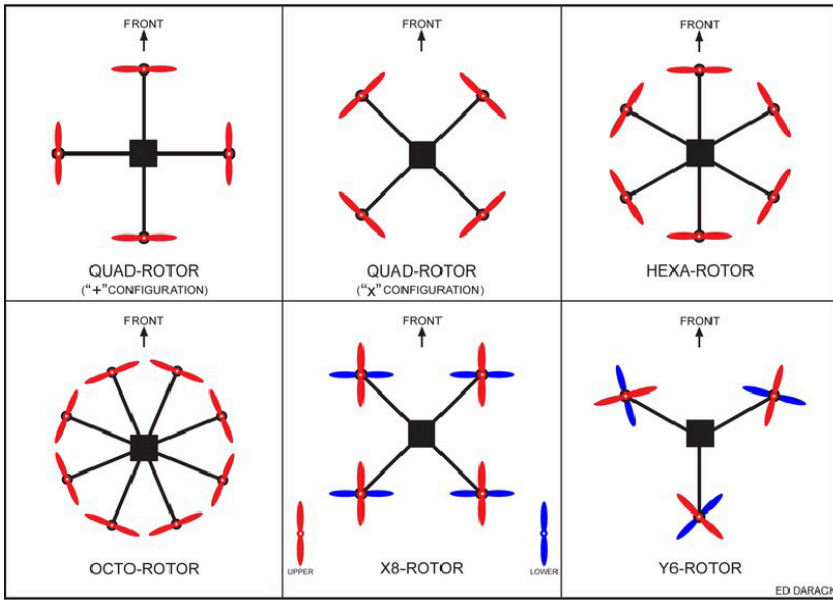


Figure 2: A few common drone structures with single-rotor and double-rotor configurations. Figure reproduced from Camilli et al. (1) Quad-rotor with four arms from the edge of each side of the drone creating a “+” shape; (2) Quad-rotor with four arms from the corner of each side of the drone creating 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.

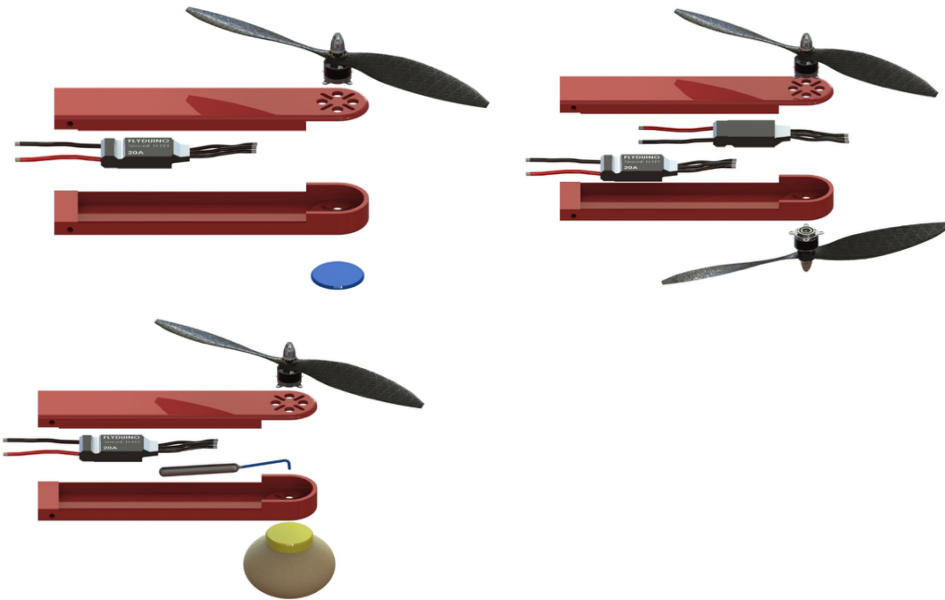


Figure 3: Types of rotor configurations in drones with avionic and electronic elements. Figure reproduced from Brischetto et al. (1) Single-rotor configuration; (2) Double-rotor configuration; (3) Amphibious configuration.

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. Additionally, 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).

Moving on, current modular drones utilize different concepts of geometrical structures apart from these, in most cases. 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 by Saldaña et al. 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, modules were assembled differently, and this reflects on 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 in terms of configurations for modular drones, like with conventional UAVs, a threat may be posed in the broader deployment of these systems, which may lead to other barriers.

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

Barrier	Sub-Category
1. Societal	Public perception Use of drones in the private sector Societal awareness Threat to privacy and security
2. Economic	Initial Costs Impact on the Stock Market
3. Environmental	Air Pollution Noise Pollution

4. Technological	Harm to wildlife Adaptation <ul style="list-style-type: none"> - Aerial collision - Weather conditions Performance <ul style="list-style-type: none"> - Short flight range - Uncertainty with non-standardized configurations
5. Regulatory	Accountability Training for drone pilots Legal complexities with stock market

Table 2: Overview of Barriers in Deployment for Modular Drones/Aerial Robots

Multiple barriers exist in the deployment of modular aerial robots. In the context of societal barriers, public perception of innovation, different from the drones commonly used, can stir speculation. Automation, awareness, and the use of these drones by 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, with modularity being a relatively new field.

Moving on, economic and environmental factors also have multiple aspects 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 the affordability of farmers and other concerned individuals. While the cost-saving benefits over a period of 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. This is common for the release of new technologies, and 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, respectively.

Additionally, technological and regulatory barriers also include direct and long-term impacts. A couple of technological challenges involve 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. It 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 the flight range capabilities due to the constrain of battery size and aerodynamic efficiency being limited with 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, and hence creates a conflict for deployment. This conflict directly arises from uncertainty of modular drone performance, and creating a set of standardized configurations through future research is one of the only ways to address deployment. Additionally, another technological challenge is simulating the drone with deformation, stress, and strain parameters, which is the most crucial step in testing a design before deployment in any application. The shape, configuration, and overall structure can have a direct impact on the level of adaptation and performance in various applications. 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 go on for a long period 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 a positive and negative manner, 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 new future, and because of the potential impact on the stock market with legal complexities along with other factors, regulation poses a barrier. 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 the public's eyes, and technological challenges to regulation.

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/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 and modular 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.

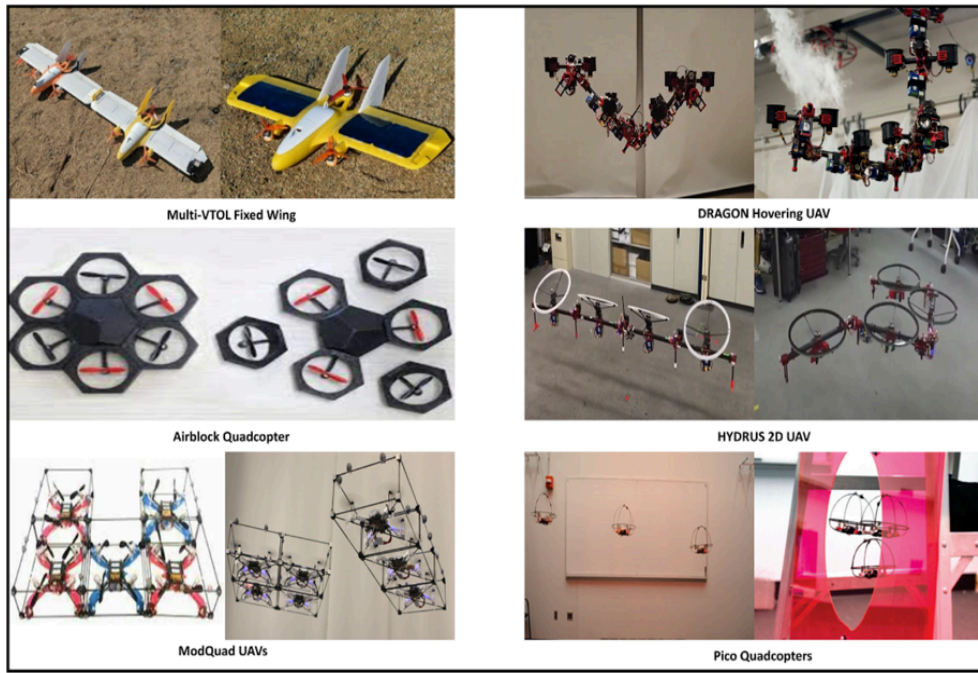


Figure 4: Examples of current innovations of Modular Drones/UAVs. Figure reproduced from Yaacoub et al. (1) Modular fixed-wing innovation relying on modules to effectively adapt to different weather conditions for various applications; (2) DRAGON UAV by Zhao et al., with the ability of multi-degree-of-freedom; (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.

For the non-planar assembly using TetraQuad modules, the approach used 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, and a proportionate structure throughout 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 tetradral frame, to understand the forces and stability margins of this geometry in the design of the TetraQuad assembly.

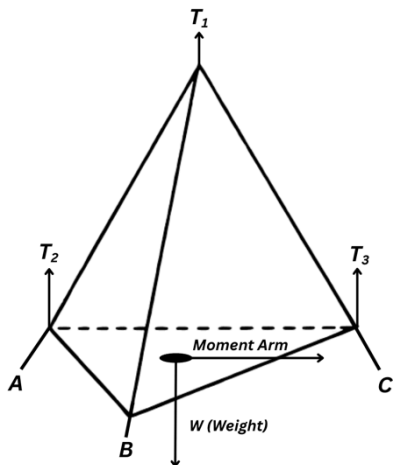


Figure 5: Free body diagram of tetradral frame with forces and stability margins (Not to Scale). T_1 , T_2 , T_3 represent the thrust forces acting on a tetrahedral frame at each node; A, B and C are the vertices for the triangular base nodes of the frame; Moment arm represents the perpendicular distance from the direction of a force (i.e. thrust and weight) to determine the rotational effect of a force.

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 with 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 resistance to deformation (e.g. in different weather conditions with this frame. This is especially in the case of 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). Moreover, with the alternation of the center of mass, forces are spread out more and increases the torque or rotation of the robot overall, and may be the reason as to the less smooth circular locomotion observed. Moreover, 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 on 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.

Moreover, while the experimental results for the TetraQuad drone's altitude oscillation only had a 10% margin of error which is a great accomplishment for a new modular design concept, further refinement and development is necessary (Wali et al., 2023). When considering the non-planar TetraQuad as a prototype, there will be different requirements for a drone to operate commercially, in agriculture and surveillance applications for instance, arising different regulations in countries. For example, there is a process to operating a drone commercially in India which involves registering a drone, and obtaining a pilot certificate, followed by obtaining permission to use certain airspace (Singh et al., 2024). Moreover, iteration in the engineering design process for modular drones is an actionable step to address future regulations for these systems. Regardless, this approach was still considerably effective in demonstrating a mostly accurate trajectory, and allows experimental results to be comparable with similar studies, for example. Moreover, 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.

Additionally, 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 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 within airspace to others via magnets on each edge, which is a passive docking approach (Saldaña et al., 2018). This allows for efficient swarm applications; this aerial robot also features disadvantages. A couple are the 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 this iteration of ModQuad impractical, especially for demanding swarm applications. This challenge with the use of magnets in the ModQuad 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 unlikely clear the design for broader

deployment. Moreover, to mitigate future limitations, a certain standard for modular drones must be introduced, and the concept with 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 4 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 by Saldaña et al. 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.

Moving on, 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 the specific factors of 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, for instance, like with conventional drones shown in Figure 2. Having a range of configurations has made conventional drones successful, as shown in Figure 2, 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. 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 confronted by substantial barriers with 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/aerial robots must focus on addressing these barriers with iteration and 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 for 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 satisfy frameworks and streamline the deployment process. Modularity in 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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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 and communities in applications such as agriculture and surveillance. These drone systems make various real-life applications easier with repair, flexibility, and performance. This review explores important design objectives, real-life applications and various geometrical structures. It follows an analysis multiple key barriers of social, economic, environmental, technological, and regulatory factors in the deployment of these systems. These barriers are correlated with various innovation in modular drones/aerial robots. A systematic search of literature and current research was conducted to identify relevant sources. Moreover, reasons for these barriers range from the application and other factors that the system is required to meet, including the weight and payload, endurance, frame type, and geometrical structure. The research indicates that the various geometries used in the design of these systems has an influence on deployment by leading to key barriers. It is reflected through current solutions of modular drones/aerial robots. Moreover, addressing these barriers is crucial to expanding the use of modular drones to serve in real-life applications.

The design and deployment of modular drone systems is an area of ongoing exploration and has the potential to support the growth of industries and communities in applications such as agriculture and surveillance. These drone systems make various real-life applications easier with repair, flexibility, and performance. However, there are multiple key barriers to the modularity of social, economic, environmental, technological, and regulatory factors in the deployment of these systems. Reasons range from the application and other factors that the system is required to meet, including the weight and payload, endurance, frame type, and geometrical structure. Addressing these barriers is essential to expanding the use of modular drones to serve in these applications. This is reviewed through multiple examples of design and geometrical influence in existing modular drone innovations.

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Keywords

Modular drone systems; geometry; modular design; aerial robots; UAVs; 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 use of drones, such as in agriculture and surveillance, to meet agricultural demand or various surveillance applications, respectively. 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 in deploying these drones, with societal, economic, environmental, technological, and regulatory perspectives. These are acclaimed to be 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 give rise to barriers in the deployment of these drones, which are addressed in this review.

43
44 In this review, the various applications of modular drone systems are explored with a focus on various design
45 geometries used for different applications. These modules can form a single modular robot as well as detach
46 (Yaacoub et al., 2024). For instance, modularity in agricultural drones can impact involved individuals and
47 communities with ease of use and long-term practicality (Rejeb et al., 2022). Modules may consist of detachable
48 fertilizer tanks or the canopy/arm holder assembly (the top assembly) as multi-component modules for
49 agriculture drones (Yaacoub et al., 2024; Rejeb et al., 2022). These make the process of different tasks (e.g., applying
50 fertilizer on crops) more efficient long-term with the use of independent modules combined with others to create
51 a flexible and efficient system, known as a multi-component system (Brischetto et al., 2016; Yaacoub et al., 2024).
52 Furthermore, individuals, including drone pilots, manufacturers, farmers, and trainers, could benefit from
53 modularity in different ways, like economically for farmers, in comparison to using more conventional agriculture
54 drones. This is because of the long-term cost-saving benefits modular designs provide, which is a great deal for
55 farmers, especially in countries like India and China, where they may not have a substantial financial status.

56
57 Furthermore, when examining the application of modular drone systems in agriculture, the geometries used in
58 modular structures have a long-term potency to assist with as well as constrain the deployment of these drones.
59 Geometries used for modularity have the potential to improve certain barriers, which could have a long-term
60 economic impact on farmers by using modular agriculture drones. In contrast, the barriers to deployment of
61 modular drones can also be caused by different geometries used because of the complex nature of designing,
62 engineering, and manufacturing these parts (Yaacoub et al., 2024; Sah et al., 2020). For instance, functional failures
63 by using these geometries can arise from compatibility issues due to a lack of continuity across all components of
64 a drone. Adaptability with many different designs of modular aerial robots found in several studies is also a
65 challenge, which can arise from technical challenges with the geometrical structure of the drone (Yaacoub et al.,
66 2024). Increasingly, there are other associated factors in the design of modular drones that can directly hinder the
67 deployment of these modular aerial robots as a whole, which are explored in this review.

68
69 At first, modular drone systems can be seen as drones that require additional financial investment (Mueller et al.,
70 2022). However, using different geometries in drones and improving their efficiency as well as functionality with
71 modularity can lead to cost-effective maintenance in the long term (Yaacoub et al., 2024). Additionally, the long-
72 term aspect is also true for surveillance drones through modularity, by converting the drone's camera into a multi-
73 component system, for instance (Aina et al., 2024). Moreover, this is one implication of how geometries in the
74 design of modular drones can address a barrier, but failures in functionality and adaptability must be considered
75 for deployment.

76
77 Moving on, with a focus on design geometries in modular drone systems, the specific design objectives with
78 modularity are addressed in the second section of this review. An overview outlining these objectives is followed
79 by different types of modules. The modules in specific applications like agriculture and surveillance are also
80 reviewed in this section, followed by control methods. The third section focuses on different geometries in drone
81 design with various configurations, like quad or tetra, for example, and a connection with components found
82 within modular drones. Then, the fourth section focuses on deployment barriers with respect to design geometries
83 for modular drones stemming from modular robots as a whole. Lastly, the influence geometries have on the design
84 and deployment of modular drones is summarized along with takeaways and future objectives for design
85 geometries in the field of modular robotics.

86 Innovation through advances in efficiency, cost, and structure has made modularity in drones all the more
87 desirable. Both public and private sectors are increasing their use of drones, such as in agriculture and
88 surveillance, to meet agricultural demand or various surveillance applications, respectively. With continual
89 improvement in drone technology in agriculture, modularity in drones strives to benefit industries and

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90 communities associated with agriculture and surveillance activities (Mueller et al., 2022). These applications would
91 typically use specific drone geometries suitable for various scenarios (Sah et al., 2020). However, the geometrical
92 structures used can contribute to barriers in deploying these drones, with societal, economic, environmental,
93 technological, and regulatory perspectives. These are acclaimed to be common hurdles in the broader deployment
94 of drones (Sah et al., 2020). The concerns associated with these barriers are true for drones as well as aerial robots
95 as a whole (Yaacoub et al., 2024; Wali et al., 2023). Moreover, the design geometries used can influence efficiency
96 both positively, leading to multiple benefits in certain applications, and negatively, as certain geometrical designs
97 can give rise to barriers in the deployment of these drones, which are addressed in this review.

98 -
99 In this review, the various applications of modular drone systems are explored with a focus on various design
100 geometries used for different applications. These modules can form a single modular robot as well as detach
101 (Yaacoub et al., 2024). For instance, modularity in agricultural drones can impact involved individuals and
102 communities with ease of use and long-term practicality (Rejeb et al., 2022). Modules may consist of detachable
103 fertilizer tanks or the canopy/arm holder assembly (the top assembly) as multi-component modules for
104 agriculture drones (Yaacoub et al., 2024; Rejeb et al., 2022). These make the process of different tasks (e.g., applying
105 fertilizer on crops) more efficient long-term with the use of independent modules combined with others to create
106 a flexible and efficient system, known as a multi-component system (Brischetto et al., 2016; Yaacoub et al., 2024).
107 Furthermore, individuals, including drone pilots, manufacturers, farmers, and trainers, could benefit from
108 modularity in different ways, like economically for farmers, in comparison to using more conventional agriculture
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137 drones. Then, the fourth section focuses on deployment barriers with respect to design geometries for modular
138 drones stemming from modular robots as a whole. Lastly, the influence geometries have on the design and
139 deployment of modular drones is summarized along with takeaways and future objectives for design geometries
140 in the field of modular robots.

142 **2. Review Methodology and Search Strategy**

144 The review followed a systematic search strategy in identifying multiple studies with current innovations in
145 modular drones/aerial robots and associated barriers to deployment, with a focus on geometry optimization.
146 Moreover, literature, between 2014 and 2025 (with an ex, was sourced from large databases including Google
147 Scholar, IEEE Xplore, and Research Gate. Both current innovations in modular drones/aerial robots and other
148 literature reviews fall within this time span.

149 Moreover, for current innovations in the field of modular drones, the inclusion criteria for selecting certain studies
150 were contingent on the demonstration of a geometric configuration for the robot and experimental data on
151 various parameters. Specifically, multiple studies on innovations were first identified, and then categorized based
152 on whether or not a design geometry was at least demonstrated, even if not directly discussed, with the
153 performance of the drone. From this, the strongest studies valuable to the analysis of the design and broader
154 deployment of modular drones were selected and reviewed in depth. Moreover, the parameters for choosing these
155 studies include the endurance or flight time tested in the study, and this information was useful for a comparison
156 of quantitative data collected in 2 or more studies.

158 Moving on, the inclusion criteria for selecting past literature review was how the correlation of the design of a
159 drone was demonstrated with modularity, and other studies on barriers identified for drones, even if they focused
160 on specific applications. While not all reviews focused particularly on modularity, there were insights in this field,
161 and the overall information provided was useful in the review's analysis of non-standardized designs, for example.
162 From this, studies pertaining to the design along with control of drones were identified, and a subsection on
163 control methods is included (3.1.1). In addition, current research without a direct relation or mention of modularity
164 in drone technology, were excluded. Overall, this methodology with a systematic search strategy proved to be
165 effective, especially identifying and reviewing multiple innovation in modular drones to find commonalities and
166 other features towards the field of modular drones as a whole.

169 **3.2. Modular Drone Design Objectives and Applications**

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

174 **3.2.1. Modularity**

175 Modular drones or UAVs can be described as smart aerial robots that can perform complex tasks more efficiently
176 from different types of multi-component modules within a drone system. The motion of modules found in a
177 modular drone can include sliding, rolling, and even a hybrid modular movement, as discussed in (Yaacoub et al.,
178 2024). For sliding movements, the modules form a singular structure for the drone, but can be effortlessly
179 detachable at the same time, and allow systems to be reshaped or resized (Yaacoub et al., 2024). These types of
180 modules are useful for agriculture because cleaning parts of the drone heavily used throughout the day can be a
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more direct and facile task, and saves storage space in smaller farms. Other benefits that would apply to most applications are those of reparability, 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 operation of certain tasks difficult through the new modular design, and hence ensuring that performance is direct for interaction is crucial for overall efficiency. Moreover, how the user interacts with the drone is not a widely touched-upon aspect of different modular solutions for aerial robots.

Several studies have innovated a modular solution for aerial robots using different types of modules. The modules used are often smaller in size than those found in the market for conventional drones and involve the use of specific geometries. Some examples are 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 and attach 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 in this study (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 drones and aerial robots (Saldaña et al., 2018). Moreover, table 1 compares the configurations of each modular drone innovation with the MTOW (Maximum Takeoff Weight), tested endurance from each study and a comparison of the demonstrated task. Another study, which designed an aerial robot “DRAGON”, focused on a multi-degree-of-freedom robot for aerial transformation (Zhao et al., 2018). Overall, these studies show how the design of aerial robots, even with testing models, leads to challenges with complexity and is a primary factor in hindering the deployment of modular drones in the market for various applications.

Single Modular Structure					
Drone/Aerial Robot	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.)
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Table 1: Comparison of Drone Configurations, MTOW (i.e. Maximum Takeoff Weight), Tested Endurance (i.e. Flight Time), and Demonstrated Task of current modular drone innovations (Wali et al., 2023; Saldaña et al., 2018).

From table 1, the data collected from experiments with the TetraQuad and ModQuad are presented with one module along with 4 modules and 5 modules, respectively. These two innovations were tabulated because the parameters included are similar, and differences can be discerned, as opposed to other variable and experiments for the DRAGON UAV. The performance for a single modular structure in comparison to a multi-modular structure is seen. For example, the flight stability of a single TetraQuad module is relatively high during a 50 second flight time from experimental results compared to 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 5 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 challenges with complexity and is a primary factor in hindering the deployment of modular drones in the market for various applications.

32.1.1. Control Methods

When considering modularity in drone systems, it is critical to consider various control methods for the smooth operation of these robots. Control methods are important because, for operation in complex environments with learning-based control, precise control is required, 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. It 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). Moreover, a few control method architectures include low-level control & stabilization, and higher-level planning (Mueller et al., 2022). Additionally, 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.

32.2. Overview of Real-Life Applications

When discussing the real-life applications of modular drones, a couple of notable applications are agriculture, especially in largely populated regions with a greater demand for agricultural production, and surveillance for

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254 smart cities and other applications. Drone technology in both these applications incorporates the Internet of
255 Things (IoT) and machine learning, with additional technologies relevant to each application (Rejeb et al., 2022;
256 Gohari et al., 2022). The IoT is a large chain of interconnected platforms within the internet and enables
257 monitoring, such as in precision agriculture, optimized efficiency, and automation (Yaacoub et al., 2024; Rejeb et
258 al., 2022). Machine learning is integral for any drone system for adaptability and ensuring performance with
259 accuracy when executing tasks (Soori et al., 2023).

262 **32.2.1. Agriculture**

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

279 **32.2.2. Surveillance**

280 Drones for surveillance typically use quadcopter or quad-rotor structures due to their performance in aerial
281 surveys and mapping regions. They are also portable and lightweight, and quadcopters commonly travel in swarms
282 for effective surveillance (Yaacoub et al., 2024). The modularity for these drones would involve modules for the
283 camera and a detachable canopy/arm holder assembly, similar to agricultural drones, but they are also not very
284 widespread. While surveillance drones may not have an impact similar to agriculture drones, they are still crucial
285 and widely adopted globally for a broad range of surveillance tasks. These can vary from general-purpose aerial
286 mapping and data collection to analyzing complex disaster sites with hazard mapping. They are multi-purpose and
287 also play a critical role in smart cities (Gohari et al., 2022). Modularity in surveillance drones can aid in the
288 surveillance applications of hazard mapping from natural disasters or in smart cities through swarm capabilities.
289 Transformation mid-air with detaching modular units can survey a large surface area at a faster and cost-effective
290 pace. This is possible through the detachment of a single modular unit within airspace and also using minimal
291 materials, respectively. Moreover, the importance of modular drones in surveillance also stems from IoT and
292 machine learning, along with other technologies. **The role of IoT in surveillance is similar to that of agriculture and
293 other UAVs that incorporate it (Gohari et al., 2022).**

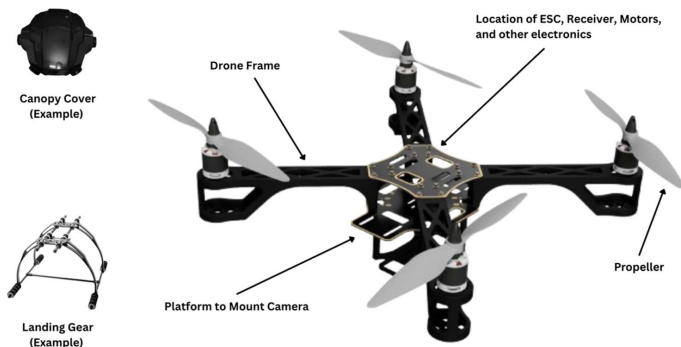
298 **43. Drone Geometrical Structures**

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

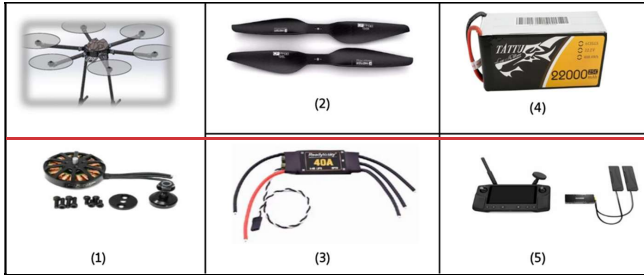
303 4.3.1. Components of a Drone

304 It is important to have a set of required components for the system when designing a modular drone, with modules
305 acting as a combination or extension. Not all modular drones may share a similar set of components, but there are
306 a few essential components for any drone system. (1) The frame is the outermost structure of a drone that
307 determines the overall shape. Moreover, the frame provides an aerodynamic structure and acts as a housing for
308 additional payload, with the drone arms connecting all configurations in the frame via arm holders. (2) Next are
309 the brushless motors and propellers, which work synchronously, to an extent, in providing flight. The propellers
310 generate lift and other forces within a drone, providing thrust and stability. The placement of these parts would
311 vary based on the geometry of the drone, but they are essential in the function and design of any aerial robot. (3)
312 Another key part of a drone is the battery. The battery's main function is to allow a drone to operate for a certain
313 endurance. (4) Functional components include the electrical wiring, RC transmitter, electric speed controller
314 (ESC), and landing gear. When designing the landing gear of any UAV system, a virtual simulation is run with
315 parameters of the total deformation, equivalent elastic strain, and equivalent stress to ensure the design can adapt
316 to different circumstances (Universiti Tun Hussein Onn Malaysia, et al., 2021). Additionally, a camera is found on
317 most drones, even if not widely used in sectors like agriculture. Other components of a drone include the flight
318 controller to steer the robot, a mounted camera, and a receiver, which obtains signals from the transmitter to
319 enable control. Figure 1 represents the components used in a hexacopter design (Ray et al., 2025).

320 -
321 [Figure 1 represents the components used in a conventional quadcopter design.](#)



323
324
325 [Figure 1: Components of a Quadcopter with examples of a Canopy cover and Landing Gear.](#)



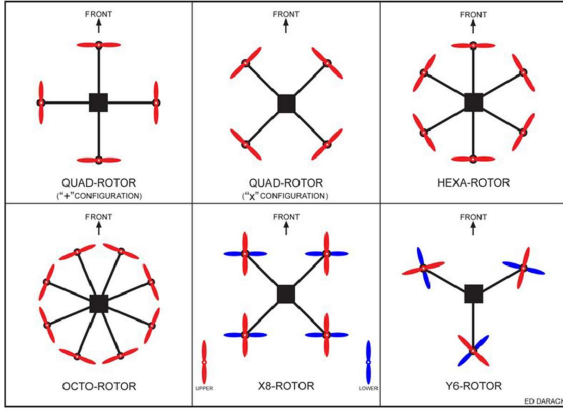
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Figure 1: Components of a Hexacopter using Mission Planner Software. Figure adapted and reproduced from Ray et al. 2025. (1) Frame and Brushless Motors; (2) Propellers; (3) Electronic Speed Controller; (4) Battery; (5) Receiver and Transmitter.

Moving on, 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). Then, 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 at an angle like that of airplanes (Dayakar et al., 2024). For drones in sectors like agriculture, these required components are typically accompanied by others or specific modules. Tanks and seed dispersal containers are common parts of agricultural drones, and similarly specialized camera systems for surveillance drones, in general (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.

4.3.2. 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, with “Quad” and “Hexa” correlating to 4 and 6 rotors, respectively (Camilli et al., 2015). The purpose of a greater number of rotors goes beyond adding more propellers, but is to be suitable for the demands in a particular sector. Agriculture drones require a larger structure that can carry a great load, and those suitable for the weather conditions in different regions, for instance. Hence, agricultural drones typically use a hexa-rotor configuration, which is more suitable. However, the number of rotors does not necessarily linearly correlate to the size or payload of a drone. Similar configurations may be used for different applications.



357
 358
 359 **Figure 2:** A few common drone structures with single-rotor and double-rotor configurations.; Figure reproduced from Camilli
 360 et al. (1) Quad-rotor with four arms from the edge of each side of the drone creating a "+" shape; (2) Quad-rotor with four arms
 361 from the corner of each side of the drone creating an "x" shape; (3) Hexa-rotor configuration with six arms forming a
 362 symmetrical structure; (4) Octo-rotor configuration with eight arms forming a symmetrical structure; (5) X8-rotor similar to
 363 "x" quad-rotor configuration with a double-rotor configuration for a total of 8 rotors; (6) Y6 rotor similar to X8-rotor
 364 configuration with three arms and a total of six rotors.



365
 366
 367
 368 **Figure 3:** Types of rotor configurations in modular drones with avionic and electronic elements. Figure reproduced from
 369 Brischetto et al. (1) Single-rotor configuration; (2) Double-rotor configuration; (3) Amphibious configuration.

370
 371
 372
 373
 374 Six common configurations found in conventional drones are denoted in Figure 2, with the first four featuring a
 375 single-rotor configuration and the last 2 featuring a double-rotor configuration. Alongside these configurations,
 376 others with propellers on the underside of the arm and those with amphibious configurations exist as displayed in
 377 Figure 3, but are not as widespread. Moreover, modules can be applied to many types of drone configurations in
 378 the realm of modular drones. Additionally, due to the added complexity in modular designs, the structure is
 379 determined by a combination of the motion, material, position, and various shapes used for modules. For instance,
 380 surveillance quadcopters and modular quadcopters may have varying visual geometrical structures and typically
 381 travel in swarms with multi-purpose applications beyond surveillance (Yaacoub et al., 2025). The tetrahedral
 382 structure presented for a non-planar aerial robot assembly is an example of a structure that deviates from the
 383 common drone configuration (Wali et al., 2023).

Moving on, current modular drones utilize different concepts of geometrical structures apart from these, in most cases. 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 by Saldaña et al. 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, modules were assembled differently, and this reflects on 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 in terms of configurations for modular drones, like with conventional UAVs, a threat may be posed in the broader deployment of these systems, which may lead to other barriers.

54. 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.

~~Common 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. Societal, economic, and environmental factors are among the common barriers for aerial robots, along with technological and regulatory barriers, which are more directly related to UAVs (Sah et al., 2021). Barriers closely related to UAVs would have a great direct geometrical influence. Additionally, current innovations for modular aerial robots are explored further with barriers to deployment.~~

Barrier	Sub-Category
<u>1. Societal</u>	<u>Public perception</u> <u>Use of drone in private sector</u> <u>Societal awareness</u> <u>Threat to privacy and security</u>
<u>2. Economic</u>	<u>Initial Costs</u> <u>Impact on Stock Market</u>
<u>3. Environmental</u>	<u>Air Pollution</u> <u>Noise Pollution</u> <u>Harm to wildlife</u>
<u>4. Technological</u>	<u>Adaptation</u> - <u>Aerial collision</u> - <u>Weather conditions</u> <u>Performance</u>

	<ul style="list-style-type: none"> - Short flight range - Uncertainty with non-standardized configurations
5. Regulatory	<ul style="list-style-type: none"> Accountability Training for drone pilots Legal complexities with stock market

Table 2: Overview of Barriers in Deployment for Modular Drones/Aerial Robots

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54.1. Barriers and Geometric Influence

Multiple barriers exist in the deployment of modular aerial robots. In the context of societal barriers, public perception of innovation, different from the drones commonly used, can stir speculation. Automation, awareness, and the use of these drones by 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, with modularity being a relatively new field. Multiple barriers exist in the deployment of modular aerial robots. In the context of societal barriers, public perception of innovation, different from the drones commonly used, can stir speculation. Automation, awareness, and the use of these drones by 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). 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 security and privacy of individuals, since the purpose of modular drones by businesses in this sector would most probably be concealed. Moving on, economic and environmental factors also have multiple aspects 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 the affordability of farmers and other concerned individuals. While the cost-saving benefits over a period of 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. 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, respectively.

Moving on, economic and environmental factors also have multiple aspects 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 the affordability of farmers and other concerned individuals. While the cost-saving benefits over a period of time are prominent in most modular drone systems, a solution to spread awareness would

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455 have to be implemented for future deployment. Moreover, the impact on the stock market for the broader
456 deployment of modular drones is unpredictable and can be a great risk for a country's economy. This is common
457 for the release of new technologies, and environmental factors include pollution and harm to wildlife (Yaacoub et
458 al., 2024; Sah et al., 2021). Pollution from UAVs includes air pollution and noise pollution, with emissions of
459 greenhouse gases and a large presence of UAVs in populated areas, respectively.

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460 Additionally, technological and regulatory barriers also include direct and long-term impacts. A couple of
461 technological challenges involve adaptation and performance (Yaacoub et al., 2024; Sah et al., 2021). Aerial collision
462 with other drones and weather conditions in different regions are some examples of challenges with adaptation
463 that are not directly addressed in current modular drone innovations. The cost of repair can also be high in the
464 case of any form of aerial collision between UAVs, and deployment may not be practical in certain urban areas. It
465 is simply a reflection of how multiple barriers (technological and economic) can build on one another in hindering
466 the deployment of modular aerial robots. A short flight range and execution in different applications fall under
467 performance challenges, which are also not greatly focused on in current innovations. Consequently, a non-
468 standardized design can affect the flight range capabilities due to the constrain of battery size and aerodynamic
469 efficiency being limited with a range of varying designs for modular configurations. Moreover, with modular
470 configurations not becoming standardized, it would be a greater challenge to achieve features such as flight range
471 similar to or even improved from existing configurations, and hence creates a conflict for deployment. This conflict
472 directly arises from uncertainty of modular drone performance, and creating a set of standardized configurations
473 through future research is one of the only ways to address deployment. Additionally, another technological
474 challenge is simulating the drone with deformation, stress, and strain parameters, which is the most crucial step
475 in testing a design before deployment in any application. The shape, configuration, and overall structure can have
476 a direct impact on the level of adaptation and performance in various applications. It also poses a certain extent
477 of unpredictability in real-world applications.

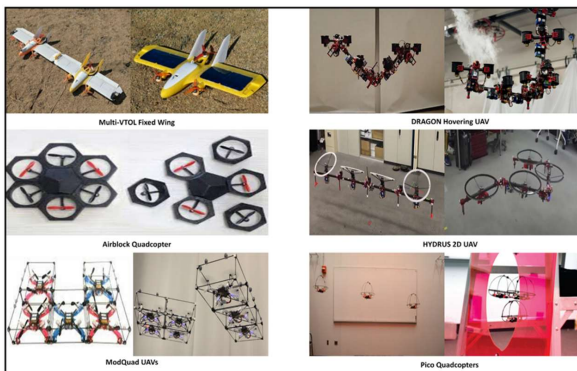
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478 Additionally, technological and regulatory barriers also include direct and long-term impacts. A couple of
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487 in testing a design before deployment in any application. The shape, configuration, and overall structure can have
488 a direct impact on the level of adaptation and performance in various applications. It also poses a certain extent
489 of unpredictability in real-world applications. Lastly, regulatory barriers majorly include accountability and
490 training for drone pilots (Yaacoub et al., 2024; Sah et al., 2021). Even with the deployment of modular drones,
491 adoption will most likely go on for a long period due to different measures that have to be considered when training
492 drone pilots and holding them accountable for any faults. Additionally, challenges with regulation can also lead to
493 the effect of modular drones in the stock market as an economic factor due to the growing complexity of legal
494 structures (Pranchana et al., 2025). It is similar to the concern with the ethical use of Artificial Intelligence, and is
495 impacting the stock market in a positive and negative manner, depending on the sophistication of different AI
496 technologies (Pranchana et al., 2025). Moreover, a similar trend may be seen if modular drones are deployed in the
497 new future, and because of the potential impact on the stock market with legal complexities along with other
498 factors, regulation poses a barrier. Overall, these five barriers have been the driving factor as to why modular
499 drone systems are not deployed in the public or private sector, due to a combination of multiple perspectives
500 ranging from the public's eyes, and technological challenges to regulation. Lastly, regulatory barriers majorly

501 include accountability and training for drone pilots (Yaacoub et al., 2024; Sah et al., 2021). Even with the
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504 barriers have been the driving factor as to why modular drone systems are not deployed in the public or private
505 sector, due to a combination of multiple perspectives ranging from the public's eyes to technological challenges.

507 54.2. Case Studies

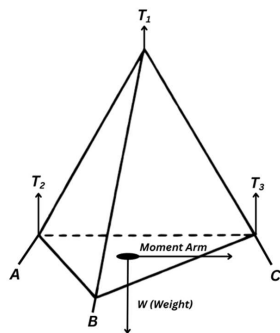
508 All of the case studies previously discussed have barriers preventing their widespread usage, with a few additional
509 ones in Figure 4. Deploying these modular aerial robots/UAVs in the public or private sector requires addressing
510 each challenge to break down barriers in using these systems.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



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525 **Figure 4:** Examples of current innovations of Modular Drones/UAVs; Figure reproduced from Yaacoub et al. (1) Modular fixed-
526 wing innovation relying on modules to effectively adapt to different weather conditions for various applications; (2) DRAGON
527 UAV by Zhao et al., with the ability of multi-degree-of-freedom; (3) Airblock Quadcopter, which uses the Makeblock software;
528 (4) HYDRUS, which is a 2D transformable UAV; (5) ModQuad UAV by Saldaña et al., which uses a cuboid frame system to attach
529 multiple modules; (6) Pico quadcopter tested for collision avoidance.

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531 For the non-planar assembly using TetraQuad modules, the approach used has advantages and disadvantages. A
532 couple of advantages are the ease of attachability to scale replicas of the module to perform practical experiments
533 with different configurations, and a proportionate structure throughout with good stability. While a combination
534 of different modules is a desirable advantage, it directly impacts the performance and efficiency of the robot,
535 leading to a disadvantage. The results revealed a less uniform circular motion for the larger 16 TetraQuad assembly,
536 reflecting the limited effectiveness of this approach, even with minimal issues in stability (Wali et al., 2023). [Figure](#)
537 [5](#) represents a free-body diagram of a tetradral frame, to understand the forces and stability margins of this
538 geometry in the design of the TetraQuad assembly.



539
540
541 [Figure 5](#): Free body diagram of tetradral frame with forces and stability margins (Not to Scale). T_1 , T_2 , T_3 represent the thrust
542 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
543 arm represents the perpendicular distance from the direction of a force (i.e. thrust and weight) to determine the rotational
544 effect of a force.

545
546 [Figure 5](#) displays the forces acting on a tetrahedral frame and these principles can be applied to the stability
547 margins in the TetraQuad assembly. With a single tetrahedral frame of a TetraQuad module, the stability with the
548 thrust forces varies with that of the vertically stacked tetrahedral frames of the 16-module TetraQuad. Moreover,
549 the tetrahedral frame used distributes thrust forces evenly through multiple triangular faces. It is generally more
550 stable than flat or more linearized configurations, making it a suitable option for modularity on a larger physical
551 scale (Wang et al., 2017). Here, the center of mass is equidistant from the thrust forces. Additionally, the drone
552 would be highly resistance to deformation (e.g. in different weather conditions with this frame. This is especially
553 in the case of a single module where stability is dependent on only one compact structure. However, for the 16-
554 module assembly, there is a vertical stacking effect where the center of mass is lowered, and the moment arm is
555 increased to balance the thrust arms (Wali et al., 2023). Moreover, with the alternation of the center of mass, forces
556 are spread out more and increases the torque or rotation of the robot overall, and may be the reason as to the less
557 smooth circular locomotion observed. Moreover, the diagram may not directly explain the circular trajectory
558 observed as there is no direct relationship between the center of mass or moment arm and locomotion. However,
559 it provides an understanding on how multiple tetrahedral-shaped modules can alter the performance of a drone,
560 and how the level of stability can vary based on the geometry used in the design of the drone.

561 Moreover, while the experimental results for the TetraQuad drone's altitude oscillation only had a 10% margin of
562 error which is a great accomplishment for a new modular design concept, further refinement and development
563 is necessary (Wali et al., 2023). When considering the non-planar TetraQuad as a prototype, there will be different
564 requirements for a drone to operate commercially, in agriculture and surveillance applications for instance, arising
565 different regulations in countries. For example, there is a process to operating a drone commercially in India which

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566 involves registering a drone, and obtaining a pilot certificate, followed by obtaining permission to use certain
567 airspace (Singh et al., 2024). Moreover, iteration in the engineering design process for modular drones is an
568 actionable step to address future regulations for these systems. -HoweverRegardless, this approach was still
569 considerably effective in demonstrating a mostly accurate trajectory, and allows experimental results to be
570 comparable with similar studies, for example. Moreover, an improvement that can be made is testing the subject
571 in different environments and performing sets of different trajectories beyond circular motion. This can enhance
572 the results presented with an understanding of how similar aerial robots can perform in real-world circumstances.

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573 Additionally, the ModQuad UAV by Saldaña et al., which is a quad-rotor aerial robot, is yet another great example
574 of a current modular aerial robot innovation. Its primary function is to self-assemble mid-air, and its structure
575 includes a quad-rotor drone within the center of a modular cuboid frame, as a single unit (Saldaña et al., 2018).
576 Each of these units can attach within airspace to others via magnets on each edge, which is a passive docking
577 approach (Saldaña et al., 2018). This allows for efficient swarm applications; this aerial robot also features
578 disadvantages. A couple are the trajectories and maintenance. The trajectories revealed from the study can vary
579 greatly in the real world, especially with swarm applications in various environments. Moreover, maintenance is
580 also a challenge because relying on magnets for mid-air self-assembly would require regular replacement and can
581 make this iteration of ModQuad impractical, especially for demanding swarm applications. This challenge with the
582 use of magnets in the ModQuad exists because it is a relatively new concept introduced for swarm applications
583 through modularity. Also, the reliance on magnets has not been tested in larger scale applications with
584 maintenance, where it may be beneficial long-term, which would unlikely clear the design for broader deployment.
585 Moreover, to mitigate future limitations, a certain standard for modular drones must be introduced, and the
586 concept with magnets can undergo multiple iterations (in the engineering design process) to achieve efficient
587 maintenance in different applications for deployment (Patel V., 2024).This allows for efficient-swarm-applications;
588 this aerial robot also features disadvantages. A couple are the trajectories and maintenance. The trajectories
589 revealed from the study can vary greatly in the real world, especially with swarm applications in various
590 environments. Moreover, maintenance is also a challenge because relying on magnets for mid-air self-assembly
591 would require regular replacement and can make this iteration of ModQuad impractical, especially for demanding
592 swarm applications. Iterations of ModQuad addressing these disadvantages, as well as scaling to match the size of
593 conventional drones in these applications, is a way to combat these disadvantages since the conceptual model of
594 ModQuad is strong.

595 When analyzing the TetraQuad and ModQuad UAVs, the names may appear similar, but the approach to modularity
596 is distinct. Firstly, the suffix "Quad" for the nonplanar assembly by Wali et al. represents 4 identical modules
597 attached. However, the suffix represents a quad-rotor drone as the powerhouse of the system, encapsulated by a
598 modular cuboid frame, which then attaches to identical unitsunits' mid-air for the ModQuad by Saldaña et al. This
599 highlights the contrasting nature of the modular aerial robots presented in these studies on the surface level,
600 which further reflects the true feasibility of deployment, especially with perspectives beyond the technologies
601 incorporated.

602 Moving on, other studies also follow different approaches, contrasting with those found in the TetraQuad and
603 ModQuad assemblies. The technological hurdles in modularity may be similar to basic features of flight time, range,
604 and payload, but the specific factors of economic, environmental, and social factors vary (Sah et al., 2021). All these
605 barriers are evident from the modular solutions presented in these studies, from small to large degrees. When
606 considering these studies, the geometrical structures, shape, and other anatomical features do not follow a general
607 or standardized range of configuration, for instance, like with conventional drones shown in Figure 2. Having a
608 range of configurations has made conventional drones successful, as shown in Figure 2, through decades of design
609 and innovation for the masses. Moreover, a threat is posed to modular drone deployment by factoring in the way
610 drones would be perceived by a society situated with conventional drones. For deployment, all studies would have

611 to undergo multiple iterations as part of the design process until a system that meets the regulations for modular
612 drones is achieved. Overall, while there are disadvantages to multi-component aerial robots and barriers that arise,
613 they introduce a new scope of designing modular drones for various applications. These barriers stimulate a
614 transition to a more structured approach towards deployment, similar to a universal set of configurations found
615 in conventional drones, foreseeing a long journey for the deployment of modular drones.

617 65. Conclusion and Future Work

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

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

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Tracked Changes for “Design and Deployment of Modular Drone Systems With Geometry Optimization: A Review”

(Note: The numerical order of the Revisions does not correspond to the chronological order of their creation.)

1. **Five new citations** were included in the manuscript to support critical analysis and the central argument.
(Refer to lines 587-599)
2. **More critical analysis** included for cited studies “TetraQuad” and “ModQuad”.
(Refer to lines 340-342; 360-366; and 374-379)
3. Additional details on the **connection to the central argument** in section 5.1.
(Refer to lines 437-444 and 457-463, respectively)
4. Information about the **systematic search strategy**, with the methodology and conclusion in the abstract.
(Refer to lines 6 to 15)
5. An **additional section/subsection** “2. Review Methodology and Search Strategy,” was included to outline the systematic search strategy, resulting in a total of 7 sections instead of the initial 6.
(Refer to lines 79-103)
6. **Figure 1** has been changed to a diagram created by the author.
(Refer to line 245)
7. Inclusion of a free-body diagram (created by the author) as **Figure 5** with a supporting caption and description.
(Refer to lines 415-436)
8. The **repetition of the Barriers section was improved** with a table listing each barrier and its sub-categories, along with reduced repetition in the brief of section 5 written before the table.
(Refer to line 325)
9. A **comparative table** has been included based on the 2 emblematic studies mainly discussed in the review. The table contains the following: Configuration, MTOW, Endurance, and demonstrated task, based on data available from studies cited.
(Refer to lines 135-159 for the table and description)
10. **Transition** from control methods to real-life applications improved.
(Refer to lines 163-177)
11. Original Word Count of manuscript: **6310**; Current Word Count of manuscript: **8072**

Reviewer 1

October 5th, 2025

I would like to sincerely thank the editor for facilitating the review of my manuscript and the reviewer for the insightful comments. I have read the reviews carefully and revised the manuscript in response to the reviewer comments. I believe my manuscript has significantly benefited from these revisions. Below, I am including a pointwise response to the reviewer.

Response to Reviewer 1:

1. "The author does not include much critical analysis."

Response: I agree with the reviewer that the review may not include sufficient critical analysis to explain why disadvantages in current modular designs exist. I have revised section 5.2 with more critical analysis on the two studies (Kindly refer to change no. 2 in the tracked changes document).

2. "The author should think more about the central argument."

Response: I thank the reviewer for providing this valuable comment on the connection to barriers in deployment. I have revised section 5.1 with additional details on direct cause and effect relationships (Kindly refer to change no. 3 in the tracked changes document)

3. "Try to improve flow."

Response: I thank the reviewer for this insightful comment, and the transition from section 3.1.1 to 3.2 was improved (Kindly refer to change no. 10 in the tracked changes document).

4. "Consider redoing all the figures."

Response: I appreciate the reviewer's view of the inclusion of figures in the manuscript. I viewed the inclusion of Figures 2-4, cited from open-access articles, valuable to the particular section in the discussion of drone geometries and configurations in comparison to any figures that would be created by the author. Moreover, I have reached out to the Convergence Journal, and the citations' satisfies the guidelines. I thank the reviewer for this comment and Figure 1 was redone accordingly with a diagram created by the author (Kindly refer to change no. 6 in the tracked changes document)

With best regards,

██████████

Reviewer 2

████████████████████
████████████████████
October 5th, 2025

I would like to sincerely thank the editor for facilitating the review of my manuscript and the reviewer for the insightful comments. I have read the reviews carefully and revised the manuscript in response to the reviewer comments. I believe my manuscript has significantly benefited from these revisions. Below, I am including a pointwise response to the reviewer.

Response to Reviewer 2:

1. "Adding some information about the systematic search strategy"

Response: I thank the reviewer for this insightful comment, I have revised by abstract and included a subsection on the systematic search strategy in the manuscript (refer to change no. 4 in the tracked changes document).

2. "Adding some quantitative evidence"

Response: A comparative table on 3 measures has been included in section 3.1 (refer to change no. 9 in the tracked changes document).

3. "Adding some information on geometry–performance"

Response: I appreciate the comment by the reviewer, a free–body diagram (created by author) in section 5.2 with a supporting description has been included (refer to change no. 7 in the tracked changes document).

4. "The barriers section is repetitive"

Response: I thank the reviewer for this comment and the barriers section was revised with a table listing examples associated with each barrier and reduced repetition in section 5 (refer to change no. 8 in the tracked changes document).

5. "Reference quality and formatting"

Response: I appreciate the reviewer's alternative view on a numerical format for in–text citations. The manuscript was created with citations according to Convergence's submission guidelines stating "Authors should use in–text citations with the author–date format", instead of numbered accordingly within paragraphs. In addition, non–peer reviewed sources were used to strengthen arguments, and they include emerging themes not reflected in peered reviewed literature. Lastly, DOIs and page ranges for a few citations could not be found and were hence excluded from the References section.

With best regards,
████████████████████

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

Decision: Accepted with minor revisions

The revised manuscript demonstrates significant improvement and is now much stronger. The addition of a formal methodology section, deeper critical analysis of case studies, new comparative tables and original figures, and a more structured discussion of barriers greatly enhances the paper's rigor, clarity, and contribution. The authors have been highly responsive to feedback, and the core of a valuable review article is now clearly present.

Review Details:

While the paper is nearly ready for publication, the following points will help refine its impact and clarity for the final version:

1. Sharpen the Abstract and Introduction:

The current abstract and introduction contain some repetition and could be more forcefully framed. The abstract should be a powerful, concise summary. Consider restructuring it to: a) The promise of modular drones, b) The central thesis, c) The paper's methodological approach, and d) The main conclusion/future direction. The introduction should then set this up without repeating the abstract verbatim.

2. Clarify the "Central Argument":

The paper's strongest claim is that geometric choices directly influence deployment barriers. While this is discussed, it could be more explicit and systematic. For each barrier category in Section 5, consider adding a dedicated paragraph or a summary table that explicitly states: "How does geometry influence this barrier?"

3. Strengthen the Synthesis in Case Studies:

The analysis of case studies is good, but it could be synthesized more effectively. After discussing each, add a comparative paragraph that directly contrasts them. This illustrates a fundamental trade-off in modular drone design: geometric choices that favor one capability (e.g., scalability, reconfigurability) often come at the expense of another (e.g., performance, maintainability)."

4. Refine Language for Academic Precision:

The writing is clear but can be elevated. Scrutinize the manuscript for slightly vague or conversational phrasing. Ensure a critical tone is maintained; for instance, rather than stating a 10% error margin is a "great accomplishment," frame it as "a promising initial result for a novel design, though further refinement is necessary for commercial viability."