Impact of Unmanned Aircraft Regulations on Autonomous Navigation Approaches for Indoor Multi-Rotor Applications — Survey

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***Abstract*—Demand in unmanned aircraft (UA) technologies for real-world applications have increased over the recent years, driving national aviation authorities to implement weight dependent regulations across all UA operations. Introduction of registration for UA weighing 250g and above as well as other regulatory requirements for heavier UA systems have motivated manufacturers to consider weight as a part of design requirement. Although UA weight is not a major concern for most outdoor applications, weight requirements imposed by aviation authorities further emphasizes the importance to develop smaller and lighter UA for safer indoor or urban operations in GPS denied environments. Comparison across various sensors used for autonomous UA navigation methods suggested that benefits of using vision sensors outweighs other methods since most UA are equipped with onboard cameras and thus does not require retrofitting of additional hardware. In addition, vision sensor data can potentially be used for both navigation and non-navigation tasks resulting in a productive and lightweight UA system that is able to avoid or reduce regulatory burdens for GPS denied UA operations.**

***Index Terms*—Unmanned aircraft, Indoor navigation, UA regulations, Monocular vision**

I. INTRODUCTION

The demand for UA technologies in real world commercial applications [1], [2], [3] has been constantly increasing over the recent years due to the technology advancement and economic benefits. This technology has evolved from the first UA in 1783 in the form of a wind dependent air balloon to current times where palm size flying robots with smart features that can be purchased conveniently over the counter. Over the past decade, UA have been extensively used in the outdoor environment for a vast spectrum of commercial applications [2], [3] such as construction, agricultural, surveillance, entertainment and transportation industries. One of the success to the rapid evolution of outdoor UA application is the availability of Global Position System (GPS) [4] that provides the basis for autonomous navigation. GPS technology was approved for civilian use in the 1980s and is now widely used for navigation and positioning applications.

In modern day applications, UA navigation systems cannot solely rely on GPS technology alone. Outdoor applications in obstacle rich urban environment faces intermittent GPS outages caused by signal masking and multi path issues. GPS is usually paired alongside with inertial sensors to provide a dead reckoning system [5] where inertial sensors would provide position information in the event of momentary GPS outage.

Indoor UA applications have also been on the rise in the recent years. Studies have shown that there are growing demands for logistic companies to adopt this technology for inventory management applications in large indoor warehouses [6] where GPS is essentially not available. The adoption of UA technology in the supply chain sector offers competitive economic benefits for supply chain integration, shortening of cycle times to support improved customer service levels and improving supply chain responsiveness.

One of the key challenges to achieve autonomous navigation capabilities in GPS denied, obstacle rich environments is the ability to perform precise and reliable pose estimation with respect to the known obstacles for avoidance collision and path planning functions. Weight and size of such air vehicles is another important consideration for safety when operating in confined spaces that are populated with high human traffic or expensive stock. Safe and practical indoor UA applications cannot be achieved without overcoming such challenges.

The increased demand for commercial UA operations has resulted in a need for national aviation authorities to maintain safety and competency standards in the interest of public safety. UA regulatory frameworks by weight classification will change the way UA are classified especially for commercial UA operations since earlier UA developers had not considered this non-existence requirement in the past as part of their design considerations.

This paper will discuss how UA regulations have impacted the existing autonomous indoor UA navigation solutions and emerging trends for modern day UA systems taking into account UA regulatory requirements.

II. Common Methods of UA Classification

Classifications of UA were generally divided between military or civil applications and further broken down into the type of applications unique to specific operations. For example within each group (military and civil), it can be further differentiated by its take-off weight; flight mechanics e.g. aeroplane, helicopter, multi-rotor, powered-lift; operating range and endurance; or by specific commercial applications. Due to the sharp increase in commercial UA applications, it is now important to consider how national aviation regulators across the world are classifying commercial UA.

A. UA Classifications by Regulations

Since UA operations involves a mixture of stakeholders that could either be aviation trained or some who are not, International Civil Aviation Organization (ICAO) had developed a set of guidance to help respective countries devise a UA regulatory framework according to their own needs without the compromising safety and economical needs. Under ICAO's definition, "*UA is defined as an aircraft intended to be flown without a pilot on board and can be remotely controlled from another place or pre-programmed to carry out a task without intervention*". However, UA regulations for commercial applications still varies across different countries depending if technology or safety was regarded as the higher priority. UA Regulatory framework have been constantly updated to cope with safety requirements, new commercial applications and technology advancements that is unique to the respective countries' UA climate.

Most UA regulatory framework concentrates on 4 sub areas of compliance. They are operator's Competency; registration of UA; type of operations and insurance. Examples of national UA framework includes Federal Aviation Authorities (FAA) in the United States implementing Part 107 Unmanned Aircraft guidelines, Civil Aviation Authorities (CAA) in the United Kingdom implementing Dronesafe initiative, European Union Aviation Safety Agency (EASA) in Europe implementing the European drone regulations and last but not least Civil Aviation Authorities of Singapore (CAAS) in Singapore implementing its Air Navigation Act 101 - Unmanned Aircraft Operations. The introduction of new regulatory requirements will eventually change the type and mass of UA systems that commercial applications will adopt due to regulatory compliance. Since the entry to market for any commercial type UA is dependent on the authorities regulatory approvals to operate, it is very therefore important to start bench marking against these regulations in order to accurately determine the potential use cases for new technological developments.

CAAS governs the use of all UA activities with Singapore's Air Navigation Order (ANO) 101 - Unmanned Aircraft Operations. UA regulations in Singapore are generally classified firstly by weight and subsequently by type of UA. UA purpose is categorized by recreational purpose, educational purpose or non-recreational and non-educational purpose. Regardless of its purpose, it is mandatory to register any UA that has a total take off mass above 250g. For commercial purposes, the UA operator is required to hold a valid Unmanned Aircraft Pilot License (UAPL) regardless of total take off mass. UAPL are classified into 2 categories; Class A UAPL is required for below 25kg UA and Class B UAPL is required for above 25kg UA. Each class of UAPL is further divided into 4 UA types; Aeroplane, Airship, Rotorcraft and Powered-Lift. Figure 1 provides an overview of the necessary CAAS regulatory requirements for the respective total UA mass.

<table>
<tr><th>Purpose / UA Mass</th><th>Recreation</th><th>Education</th><th>Commercial <u>or</u> (non-recreation, non-education)</th></tr>
<tr><td>UA ≤ 250g</td><td colspan="2">• Class 2 Activity Permit*</td><td>• Operator Permit
• Class 1 Activity Permit
• UA Pilot Licence</td></tr>
<tr><td>250g < UA ≤ 1.5kg</td><td colspan="2">• Class 2 Activity Permit*
• UA Registration</td><td rowspan="2"></td></tr>
<tr><td>1.5kg < UA ≤ 7kg</td><td colspan="2">• Class 2 Activity Permit*
• UA Registration
• UA Basic Training Certificate or UA Pilot Licence</td></tr>
<tr><td>7kg < UA ≤ 25kg</td><td>• Class 2 Activity Permit*
• UA Registration
• UA Pilot Licence</td><td colspan="2" rowspan="2">• Operator Permit
• Class 1 Activity Permit
• UA Pilot Licence
• UA Registration</td></tr>
<tr><td>UA > 25kg</td><td></td></tr>
</table>

* Only if you are operating in no-fly zones, or above 200 feet AMSL

Fig. 1. Summary Table for CAAS UA Regulations

Similarly, Federal Aviation Authorities (FAA) Part 107 requires all UA weighing between 250g to 25kg flying for work or business to be registered. From a regulatory standpoint, public safety was the key priority and a study was conducted in 2016 by FAA Regulatory Task Force (RTF) to assess the risk levels associated with the mass based categorization. Although it was evaluated that lightweight UA weighing less than 250g pose no lethal threat to inflict serious injuries [7] , this assessment was deemed conservative due to overly simplified assumptions on impact risk evaluation. Instead, a more realistic weight threshold of 2.2kg, based on accounting for the actual kinetic energy transfer of a falling UA, would provide a more conservative weight threshold [8]. Despite recommendations made to adjust the upper weight limit for a "low risk" UA to 2.2kg, most national aviation authorities took the conservative approach with the 250g weight threshold. It is evident from Table I that most national aviation authorities classify UA below 250g as harmless and do not impose regulatory requirements on them.

National aviation authorities do not specifically classify autonomous UA operations. It can be assumed that the intended use for any autonomous UA systems regardless of indoor or outdoor applications is mainly for commercial applications. As such, most commercial UA operations will require relevant permits and licenses from their aviation authorities despite operating fully autonomous system that does not require a pilot in the loop. Table I is a summary table of UA regulatory requirements by some countries.

B. Emerging trend in UA development below 250g

The increase in adoption of the more conservative 250g weight threshold across many national aviation authorities have started to influence UA manufacturers to review their

TABLE I
UA REGULATORY REQUIREMENTS BY COUNTRIES

Countries	UA Registration	Requirements
Australia	All weights	- To operate UA < 2kg for commercial reasons, CASA has to be notified
Canada	For UA between 250g up to 25kg	- UA pilot licence to fly UA that weigh 250 grams (g) up to and including 25 kilograms (kg)
China	For UA >250g	- All drones flown for commercial use requires a commercial UA license
France	For UA ≥ 800g	- Commercial UA operators must pass a theoretical exam and undergo practical training/assessment
Germany	For UA ≥250g	- UA > 5 kg must obtain permit to fly at night - License required for UA > 2kg
Japan	Not required	- UA weighing 200g or more must seek permission to operate
Singapore	For UA ≥250g	- Permits required for commercial UA operations
South Korea	All weights	- License required for all commercial operations with UA ≥ 12kg
UK	For UA ≥250g	- Commercial UA operations Operator ID[1] and/or Flyer ID[2] required for UA > 250g and to obtain Permission to Fly Commercially (PfCO) - Insurance is required for all commerical UA operations
United Arab Emirates	All weights	- Permits required for commercial UA operations
United States	For UA between 250g to 25kg with exceptions for recreational flyers. N paper registration for 25kg above	- License required for all commercial operations - Airspace authorization for UA operations outside of class G airspace

[1]Operator ID - Must be labeled on your drone or model aircraft
[2]Flyer ID - Shows operator have passed the basic flying test
*Accurate at the time of publishing

existing product line of UA systems for the consumer market since most were designed based on applications without regulatory classifications by weight. As a leading UA manufacturer, DJI's commitment for safety led them to launch the Mavic mini in October 2019 that was purposefully designed with a total take-off weight of 249g to avoid the need for UA registration. Other lightweight UA systems were developed prior to the implementation of the weight dependent regulations such as the Ryze Tello that weighs approximately 80g or Parrot Mambo that weighs approximately 73g, such UA are considered basic toy UA with minimal advance features and low resolution cameras.

UA manufacturers typically drive new technological adoption and bring forth new technology innovations into the commercial UA market. This would therefore influence researchers in the areas of UA technologies to consider regulatory weight classifications during the development of UA related technologies.

III. AUTONOMOUS NAVIGATION FOR MULTI-ROTOR

UA navigation is the process where the system determines its position based on a reference and plans an optimal path to navigate to its desired location. Autonomy of the navigation is aided with sensors providing relevant sensor data for localization reference. A basic Multi-Rotor (MR) system architecture is shown in Figure 2 where navigational algorithms in the GNC module determines its state, position estimates and its optimal flight path with respect to its operating environment. The algorithm output commands are subsequently fed to the propulsion system to perform to execute the desired maneuvers.

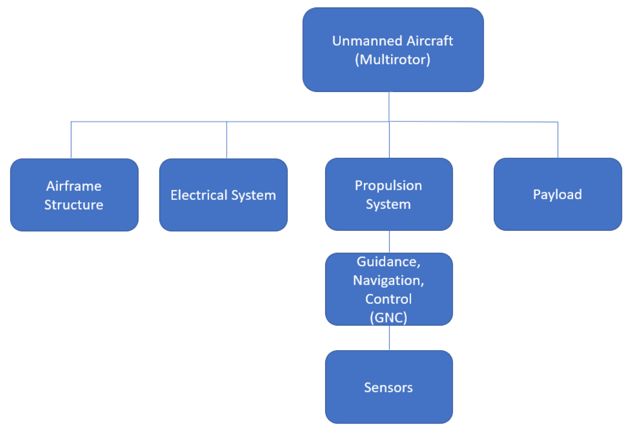

Fig. 2. Basic Multirotor System Architecture

Autonomous navigation can firstly be classified by outdoor or indoor applications and subsequently by global or localized navigational by sensor types as shown in Figure 3. There are also various Indoor localization methods that can be further differentiated between off-board and on-board methods.

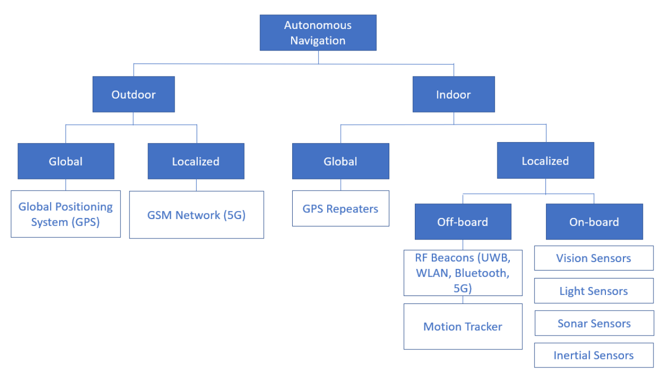

Fig. 3. Classification of Autonomous Navigation by Sensor Type

A. *Outdoor Navigation Methods*

Most outdoor applications can be assumed to be flying over remote or rural areas where the probability of UA striking a person is not more than 0.01% [9] since human population is less dense and the risk of UA falling and causing harm to people below. In addition, the nature of outdoor applications requires a larger UA to have the capacity to carry heavy payloads such as pesticides, parcels or even commercial grade cameras to perform its commercial task. Other considerations such as weather, endurance and range may not be an incentive to operate small UA. UA designed for outdoor autonomous flights relies on the matured GPS method for global navigation [10] [11] and some UA systems are also fitted with other sensors for avoidance collision capabilities [12]. GPS has been around for decades and is popular navigational system used in manned aviation [13]. The increase in demand for commercial applications [14] in the areas of search and rescue, remote sensing, civil infrastructure, agriculture, supply chain and even drone taxi is pushing UA industry into a new era. Most of these UA applications performs autonomous flights using GPS guided waypoints as the point of navigation similar to manned aviation. Advantages of GPS includes 24/7 availability, good location accuracy worldwide and uses standard latitude/longitude reference. Disadvantage is that GPS signals will be attenuated by roofs and walls therefore is not suitable for indoor navigation applications without the use of GPS repeaters.

B. Indoor Navigation Methods

Indoor applications are however more delicate due to confined spaces and obstacles. The potential demand for indoor applications from supply chain industry's perspective mainly evolves around inventory management inside warehouses where UA can be used to perform stock taking and other associated processes. Although GPS reception is poor or non-existence for indoor environments, it is possible to generate GPS signals using Pseudolites (Pseudo-Satellites) [15] installed at corners of room to create a pseudo satellite constellation. This allows GPS signals from each satellite to be received and subsequently relayed through indoor transmitters. No modifications were required on the GPS receiver end and horizontal position accuracy proves to be as accurate. This solution cannot detect obstacles and other infrastructure thus would require additional sensors for collision avoidance.

Other indoor localized navigation method can be achieved with off-board techniques such as RF beacon [16] [17] [18] or motion trackers [19] to track the position of the UA, this method is unable to perform obstacle avoidance on its own as well. Another disadvantage for this method is that it requires RF receivers or visual markers to be installed on the UA and that it must operate within line of sight of its transmitters or trackers. Such technique is also limited to the local area network of the installed RF transmitters and trackers thus can be costly solution if the area of operation is extensive.

Figure 4 summarizes some of the advantages and disadvantages across the various navigational methods. Advantages of vision sensors outweighs the other methods of indoor localized methods. There is no impact to weight since most UA are already equipped with onboard cameras therefore allowing the possibility to use the video feed for vision based navigation tasks.

IV. Vision-based Methods for Indoor Navigation

With the advancement in camera and graphics processing units (GPU) technology, computer vision approach has been a popular alternative for mobile robotics and even autonomous vehicles to achieve precise localization and pose estimation by detecting objects or obstacles through feature extraction and background noise omission. Recent surveys [20], [21], [22] indicated a growing popularity with such approach which is also known as Visual Simultaneous Localization and Mapping (VSLAM) for autonomous navigation of indoor drones in the absence of GPS. Advancement in computer vision technologies provided several advantages and benefits leading to low cost and lightweight navigation system. Other benefits for vision based approach is the ability to capture rich details of an environment with image data that is not only useful for navigational purposes but the same image data can also be used in parallel for non-navigation applications such as surveillance, architectural, photogrammetry or infrastructure inspection purposes.

V. Conclusion and Future Work

The adoption of weight dependent regulations across national aviation authorities have influenced leading UA manufacturer to consider weight requirement during the development of UA related technologies. A comparison across various navigation sensors suggested that vision sensors have several advantages over other navigational sensors without compromising significantly on the UA weight; especially for indoor applications since most off-the-shelf UA are equipped with onboard cameras. Vision sensor data is also useful in two folds; (1) to perform onboard localized navigation that is crucial for autonomous navigation in obstacle rich indoor environments and (2) the same vision data can be used for other non navigational tasks that is equally important in commercial real world applications. These requirements should be considered when developing a safe and lightweight indoor autonomous UA that can also allow commercial UA operators to avoid weight dependent UA regulations if necessary.

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Environment	Coverage	System	Advantages	Disadvantages	Impact to weight
Outdoor	Global	Global Positioning System (GPS)	- Readily available globally - Relatively low cost - Works in all weather	- Requires Line of Sight - Multipath issues in urban environment - Not able to detect obstacles	Minimal since most UA are euipped with GPS
	Localized	GSM Network (5G)	- High speed and capacity - Low latency and power consumption	- High cost to operate (Still in development) - Coverage is dependent on cell tower locations - High power consumption - Not able to detect obstacles	Minimal as 5G chipsets are integrated with advance companion boards
Indoor	Global	GPS Repeaters	- Provides real GPS signals to indoor environment	- Requires Line of Sight - Multipath issues in enclosed environment - Require to set up pseudolites or GPS repeaters - Limited to operate within pseudolite range - Not able to detect obstacles	Minimal since most UA are equipped with GPS and pseudolites are not mounted onto UA
	Localized (Off-board)	RF Beacons	- Good accuracy	- Requires Line of Sight - Accuracy is dependent of RF access points - Requires RF transcievers on UA - Multipath issues in enclosed environment - Not able to detect obstacles - Limited to operate within RF transmitter range	Minimal. Only RF reciever required on UA
		Motion Trackers	- Good accuracy - No multipath issues compared to RF beacons	- Requires Line of Sight - Not able to detect obstacles - Limited to operate within RF transmitter range	Minimal. Only visual markers required on UA
	Localized (On-board)	Vision Sensors	- No external infrastructure required - Most UA are equipped with onboard cameras - Image data provides rich information about its environment and can be useful beyond its purpose of navigation - Versatile by applying various image processing methods to localization and mapping techniques - Possible to adopt Machine Learning to improve navigation - Able to provide depth information through image processing	- Can be affected by poor lighting conditions - May require higher processing capabilities depending on image size	Nil since most UA are equipped with onboard cameras
		LIDAR Sensors	- No external infrastucture required - High accuracy - No affected by lighting conditions - Able to provide depth information	- Requires LIDAR sensor to be integrated on UA - LIDAR sensors are costly - Weight and size is not suitable for small UA - 3D point cloud does not provide rich information as compared to vision sensors - 3D point cloud requires extensive amount of computing resources - High power consumption	Yes (E.g RPLIDAR weighs 200g, Velodyne Puck Lite weighs 590g)
		Sonar Sensors	- No external infrastucture required - Low cost - Not affected by lighting conditions	- Not able to produce map of surrounding - Slower sensing rate since its base on speed of sound - low accuracy	Minimal as a typical sonar weights only 8.5g
		Inertial Sensors	- Low cost - Low power consumption	- Errors accumulates over time - Requires other sensors to improve accuracy - Subjected to magnetic disturbance	Minimal since most UA are euipped with GPS

Fig. 4. Impact of Autonomous Navigation Methods in Different Environments

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