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Review

Tethered Unmanned Aerial Vehicles—A Systematic Review

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Abstract: In recent years, there has been a remarkable surge in the development and research of tethered aerial systems, thus reflecting a growing interest in their diverse applications. Long-term missions involving aerial vehicles present significant challenges due to the limitations of current battery solutions. Tethered vehicles can circumvent such restrictions by receiving their power from an element on the ground such as a ground station or a mobile terrestrial platform. Tethered Unmanned Aerial Vehicles (UAVs) can also be applied to load transportation achieved by a single or multiple UAVs. This paper presents a comprehensive systematic literature review, with a special focus on solutions published in the last five years (2017–2022). It emphasizes the key characteristics that are capable of grouping publications by application scope, propulsion method, energy transfer solution, perception sensors, and control techniques adopted. The search was performed in six different databases, thereby resulting in 1172 unique publications, from which 182 were considered for inclusion in the data extraction phase of this review. Among the various aircraft types, multirotors emerged as the most widely used category. We also identified significant variations in the application scope of tethered UAVs, thus leading to tailored approaches for each use case, such as the fixed-wing model being predominant in the wind generation application and the lighter-than-air aircraft in the meteorology field. Notably, the classical Proportional–Integral–Derivative (PID) control scheme emerged as the predominant control methodology across the surveyed publications. Regarding energy transfer techniques, most publications did not explicitly describe their approach. However, among those that did, high-voltage DC energy transfer emerged as the preferred solution. In summary, this systematic literature review provides valuable insights into the current state of tethered aerial systems, thereby showcasing their potential as a robust and sustainable alternative to address the challenges associated with long-duration aerial missions and load transportation.

Keywords: UAV; tethered flight; transportation; meteorology; wind energy

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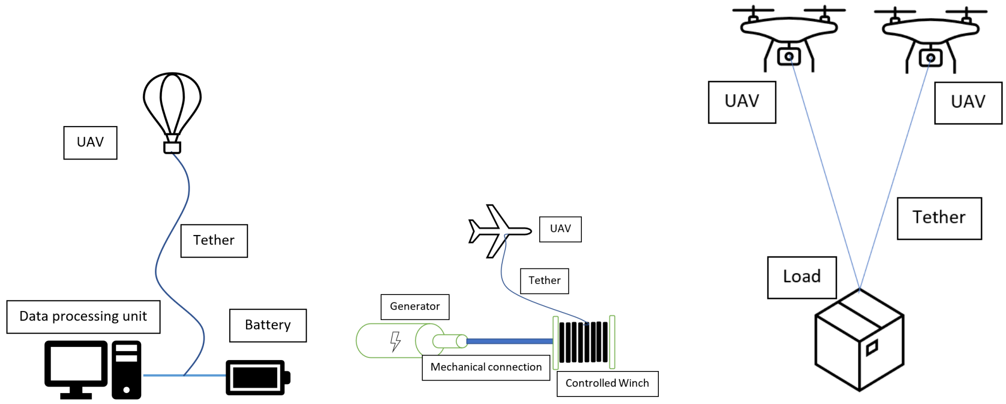
1. Introduction

UAVs have increasingly been used in novel applications in various engineering fields such as inspection [1], harvesting [2], surveillance [3], crop monitoring [4], precision agriculture [5], and remote sensing [6]. UAVs can take many different forms, and, as such, they can be adapted to many different situations. This, coupled with the advantage of being unmanned, affords the advantage of being able to perform many different tasks in an autonomous way.

One characteristic of this type of tool is the use of on-board batteries to power the UAV and its accessory systems [7]. Onboarding powering batteries lead to a total flight time of under 1 hour for most UAVs [8]. Larger batteries with a higher capacity could be used, but that leads to heavier powering systems and smaller UAV payload capacity. In the limit of this battery increase, larger propulsion systems would have to be implemented that lead to higher energy consumption that would lower operational lifetime and may be unfeasible due to project or legal restrictions. This can be avoided if the UAVs are powered from a source on the ground, and the energy is transferred by a tether to the vehicle. This configuration is identified as tethered Unmanned Aerial Vehicles (tUAVs).

The tethered system usually consists of one of two scenarios: (a) a UAV that is kept powered by a ground station or terrestrial platform (that may be an unmanned ground vehicle) by use of a cable that can transmit energy, data, and provide mechanical support between the air and ground operations and (b) one or more free-flying UAVs attached to a load through a tether that serve only as a mechanical connection between the vehicles and the load. In some tUAV applications where there is energy transmission through the tether, the energy flow can even be inverted, where the UAV uses the wind force to generate energy and transmits it to the ground via the tether. Lighter than Air (LtA) and balloon-type UAVs may not use rotary or active propulsion methods. This characteristic, coupled with the tethered configuration, can also be used to prolong mission duration. Typical examples of tethered UAV configurations are shown in Figure 1.



(**a**) (**b**) (**c**)

Figure 1. Typical configurations found in tethered UAVs for various application scopes. (**a**) Lighter-than-air UAV connected to a fixed point on the ground. (**b**) UAV used in wind energy harvesting. (**c**) UAV used to transport a load.

Systematic Review Objectives

During data collection, two recent reviews that concern tUAVs were found: one covering general aspects of tUAVs [9] and another regarding power supply architectures [7]. The following topics are missing in recent reviews about tUAV: the control and perception techniques used in tUAVs, the different types of aircraft that are most often used in each application scope, and the energy transfer technique characteristics for tUAVs. These aspects are important when covering this research topic and thus justify the existence of this systematic review.

The present systematic review assesses the literature regarding the application of tUAVs. This review aims to compile and discuss the following:

- For what applications are tUAVs most used in recent literature?
- What are the aerial vehicle propulsion methods with the best results for each application?
- What are the flight parameters (e.g., altitude and air velocity) used for each class of UAV?
- What are the tether characteristics (mechanical, electrical, and data-wise) for best performance?
- What mechanical interactions are considered during the system modeling and control design phases?

Framing this research in the population, intervention, comparison, and outcomes context (PICOC) framework [10] breaks down to the following:

- Population: tUAVs.
- Intervention: aircraft, propulsion, and flight parameters.
- Comparison: not applicable for the current study.
- Outcomes: the aircraft and flight configurations to optimize the usage of tUAVs.
- Context: publications that utilize tUAVs in simulated and real environments.

There are different strategies to perform literature reviews. The systematic reviews are the most accepted ones because they assure the quality and a full and organised analysis of the main publications on indexed platforms. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) is the most common standard [11] for reporting these literature reviews. The following sections will use this method to state the research parameters and strategies for this review.

2. Materials and Methods

After a full inquiry of the scientific databases, thousands of articles are expected to be reported for review. The usage of specific criteria for the inclusion and exclusion of the articles support this review process and contribute for the fairness of the whole procedure. To assist in the current review process, we used the online tool Parsifal [12] to systematise the whole research process through the following: a protocol definition, duplication removal and screening, quality assessment, and data extraction.

For this systematic review, we only considered the primary indexed publications regarding tUAVs between the period of 2017 and 2022. The initial date of 2017 was chosen to cover a 5-year period, and discuss the latest development on the subject. After the removal of duplicaed entries, the remaining publications were assessed and excluded based on one of the following criteria: publication date before 2017, publication was not a primary manuscript (the authors consider a primary manuscript to be works that present an experiment publication, as a benchmark, that reports how the experiment was performed or a presentation of a novel technique that was applied to tUAVs), the publication was not focused on tethered aerial vehicles, and publication was not written in English.

After screening the different publications, we fully read the manuscripts. Each publication was quality assessed to validate whether it complied with the aims of the current review. Each question was evaluated with respect to three parameters: Yes (1.0), Partially (0.5), and No (0.0). All the publications that did not sum up a score higher than or equal to 2.0 were rejected and not used for data extraction. For the current work, we considered the following questions for quality assessment:

1. Does the paper refer to the system's configuration?
2. Are the aircraft parameters presented in the publication?
3. Are the flight parameters presented in the publication? (altitude, velocity, flight path, etc.)
4. Is the analysed scenario applied in real-world tests?
5. Are the results of the tests explained in the publication?
6. Is the application presented in the publication feasible with commercial or out-of-the-shelf resources?

The first question's aim was to prioritize publications that explained the system's configuration, such as how the tether and the UAV connect, how the lower end of the tether is used, and what characteristics of the environment are considered in the system's modeling (wind, tether tension, etc). The second question awarded points to publications that describe the type of aircraft used in the published research. This information is important to understand the aerial vehicle's configuration and to segment solutions into aircraft type groups during analysis. The third question prioritized publications that describe how the UAV operates. Different flight parameters may have different mechanical and modeling demands, so it may be interesting to analyse the solutions considering these parameters. The fourth question was meant to award points to solutions that are validated in real-world tests. Simulations are a legitimate way to validate the theory presented, but as it is the case with any complex system modeling, real-world tests confront the theoretical model with various uncertainties that may not be considered during the modeling phase. The fifth question aimed to prioritize solutions that clearly describe and explains the results of the publication. The sixth question's objective was to separate solutions that require conditions that are very difficult to obtain or create with commercial or out-of-the-shelf resources. Examples of such prohibiting conditions include blimps or balloons that require a large volume of gas to inflate or operate, extreme environmental conditions during operations, and other resource-demanding conditions that are not achievable with commercial solutions.

After the quality assessment phase, the publications that summed up scores higher than 2.0 were selected for the data extraction phase. These publications will be referred to as the "selected publications" from this point on in this systematic review.

This review only considered the publications gathered from databases that had the publication date until 31st of December of 2022. The inquiry was made on six databases: ACM Digital Library [13], El Compendex [14], IEEE Digital Library [15], ISI Web of Science [16], Science@Direct [17], and Scopus [18] using the following base search string:

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(‘‘unmanned aerial vehicle’’ OR ‘‘autonomous aircraft’’ OR drone OR uav) AND
(cabled OR towed OR wired OR ‘‘energy harvest*’’ OR ‘‘fruit harvest*’’ OR tethered)
AND NOT ‘‘wireless power transfer’’
```

This search string can be divided into three parts:

- The first part contains the main population that the publication should be about, namely, "unmanned aerial vehicle" and its synonyms, such as "UAV" and "drone";
- The second part is the context in which the main population should be applied, namely, "tethered" and its synonyms and two activities in which tUAVs are known to be used: "energy harvesting" and "fruit harvesting". Both involve long term operations in energy-constrained environments that may use tUAVs as a solution to their requirements;
- The third and last part pertains to an application found in initial surveys of the main scope of this review that may fulfill the first two requisites of the search query but is outside of the application scope to be analysed in this review: tUAVs used in wireless power transfer environments.

3. Results

The percentage of articles returned per source, excluding duplications, is presented in Figure 2. The whole review process and the articles included and excluded in each phase are presented in Figure 3, where, of all the articles excluded after screening, 94% were not focused on tUAVs, 3% were not primary manuscripts, and the last 3% were not accessible with the credentials of the authors presented in the header of this document. The language requisite was set in the databases' search parameters. One of the most common subjects of the publications excluded was UAV application in data networks. These articles matched the search string because they use the keywords "cable" and "UAV" but used free-flying drones instead of tethered ones.

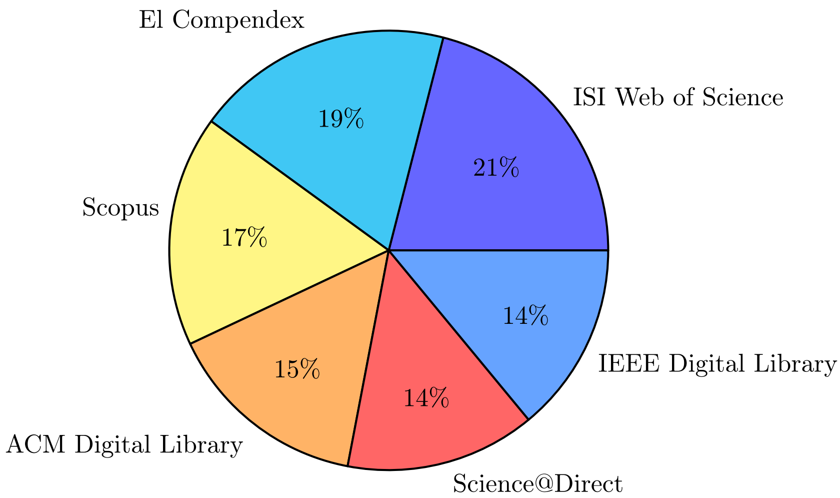


Figure 2. Percentage of articles returned per source.

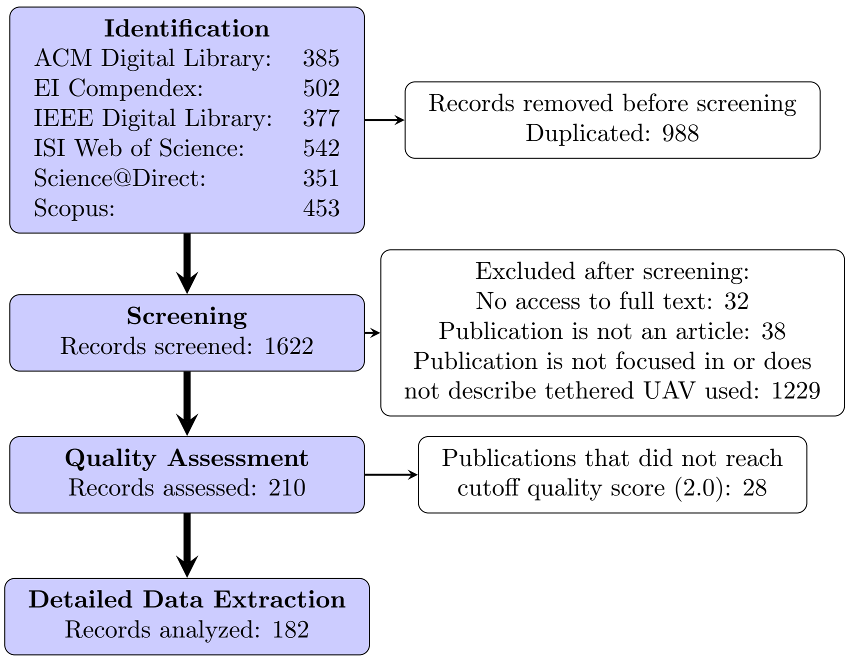


Figure 3. PRISMA flow diagram for the current systematic review.

Considering all publications returned from the search in the databases and excluding duplicate entries, the number of publications per year in the scope of tUAVs shows a steady increase, thus indicating a growing interest in the subject by the academic community. Most publications focus on one application of tUAVs; this justifies a comparative analysis between solutions and the segmentation of the publications using different aspects of the solutions. A plot of publications per year between 2017 and 2022 is shown in Figure 4.

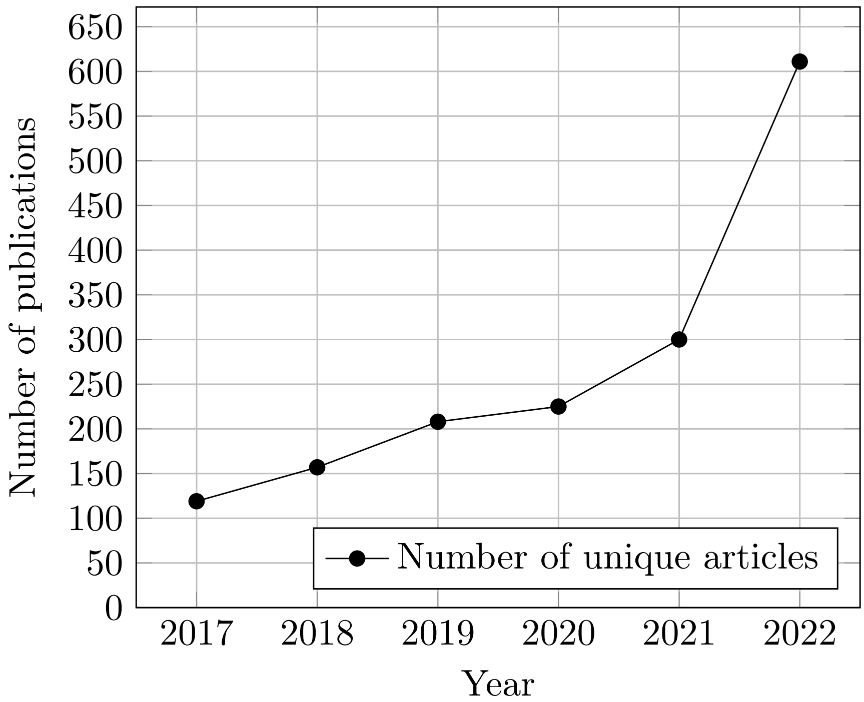


Figure 4. Unique publications per year.

In the next sections, we will report in more detail the results obtained from the screening and quality assessment processes, wherein we analysed the publications in terms of the application scope, the type of aircraft, the method presented for transfer energy from the ground to the UAV, the composition and properties of the tether, the sensors used by the UAV to perceive the environment, the operational altitude of the UAV, and the control technique applied to the solution.

Considering the selected publications' titles and abstracts and using VOSviewer, a bibliometric software [19], to analyse and generate a network map of the correlations between relevant keywords, we obtained the map shown in Figure 5. This network map was generated using binary counting (so only one occurrence of each word was counted in each document), with the minimum occurrences of the keywords set to 10, the number of terms selected set to 25, the clustering resolution set to 1.00, and manually removing common words that do not pertain to the subject (e.g.,: "use"). All other parameters were left in their default value. We can see that there were three clusters identified, which are represented by the different circle's color, with the most relevant words being "cable", "uavs", "platform", and "payload".

One notable occurrence was the word "freedom", which may have come from the expression "degrees of freedom" (a common concept used when designing a control model) or "freedom of movement" (one of the advantages of tUAVs that many articles point out), that is placed in a equidistant position from all of the clusters, meaning that it occurs in all three groups of papers, although it does not belong to the main subject of any publication (this is represented by the small size of the node).

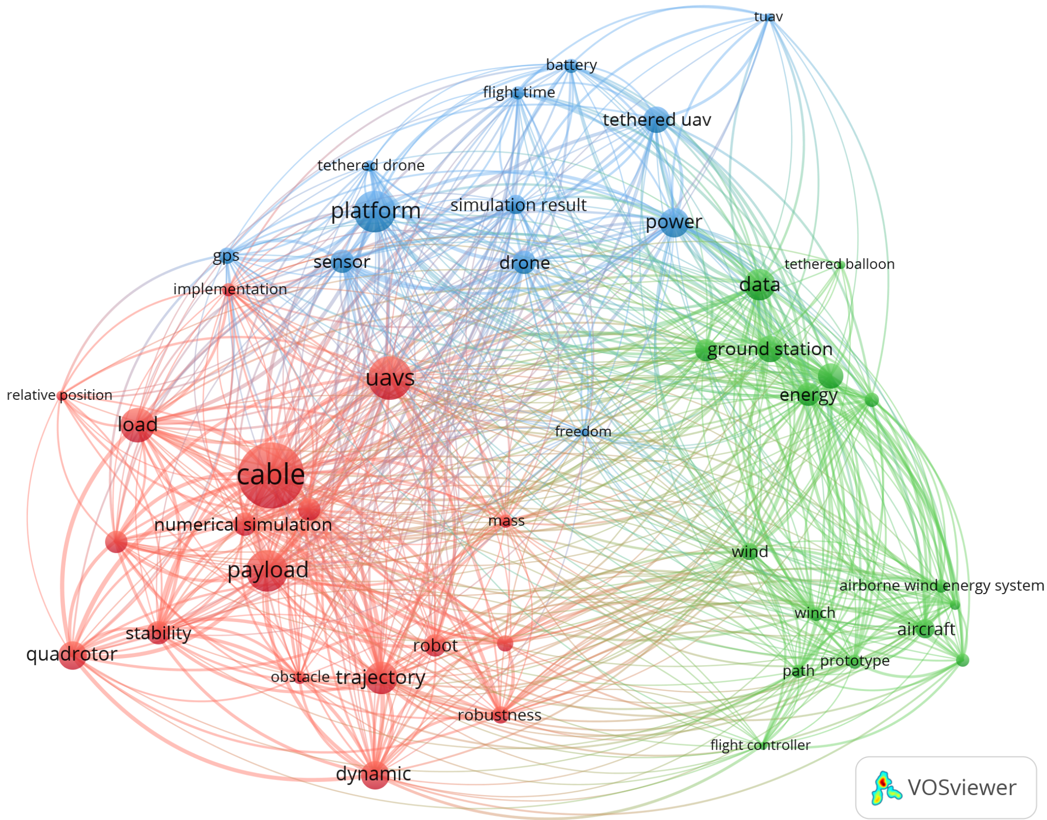


Figure 5. Network map of keywords present in titles and abstracts of selected publications.

3.1. The Scope of the Publications

Although each publication has a unique approach to the subject of tethered UAVs, upon considering only the articles selected for data extraction, we could divide them into broad groups based on the main topic of each one. The main applications detected, ordered by the number of publications, were the following:

- Transportation: The use of one or more tUAVs to move payloads from one location to another using cables. Section 3.1.1 explores this scope in more detail;
- Control and navigation: The design of control blocks and navigation algorithms for tUAVs. Section 3.1.2 describes more details of this scope;
- Meteorology: tUAVs This group was used to measure air quality and meteorological parameters such as wind speed and humidity in long term missions. Section 3.1.3 explores this scope in more detail;
- Wind energy generation: Tethered UAVs used to collect wind force and transfer it through the tether to a generator on the ground;
- Telecommunications: Tethered UAVs used to extend the coverage of telecommunication networks for a temporary situation, either an event that temporarily increased network demand or in disaster situations where normal telecommunications were compromised due to infrastructure damage;
- Power module design: Publications focused on presenting solutions for powering tUAVs. Tackled the issues of transmitting energy from the ground to the aircraft;
- Image processing: Publications focused on converting images captured by tUAVs into useful information.

The graph with the percentages of each division is shown in Figure 6, and Table 1 presents the publications included in each one.

In the next subsections of this review, each application scope will be described in its main use cases, the problems tackled and solutions presented, as well as some prominent representative publications. As will be described further, each of the main application scopes had a predominance of a different type of aircraft and, as such, presented unique solutions and issues derived from the different operational parameters of the aircraft type adopted.

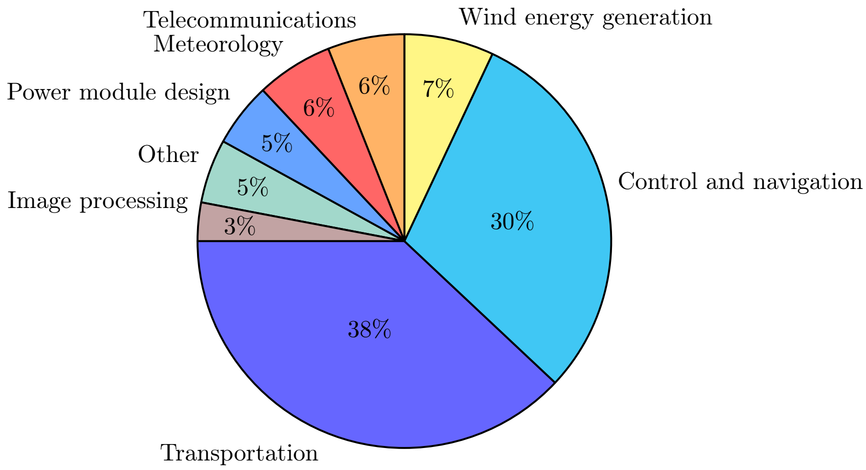


Figure 6. Percentage of main application scopes in analysed publications.

Table 1. Publications divided by their main scope.

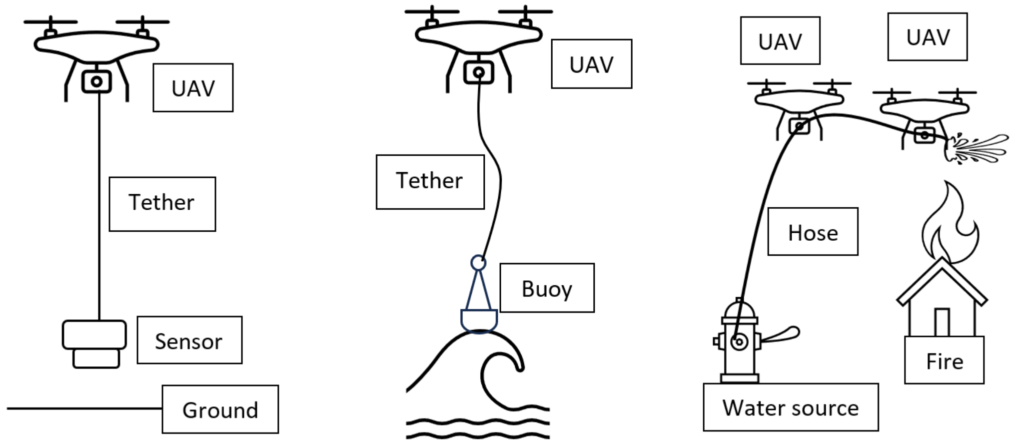
Scope	References
Transportation	[20–88]
Control and Navigation	[89–143]
Meteorology	[144–154]
Wind Energy Generation	[155–167]
Telecommunications	[168–178]
Power Module Design	[8,179–186]
Image Processing	[187–192]
Other	[193–201]

3.1.1. Transportation

The transportation scope encompasses the use of tUAVs with the other end of the tether attached to a load (instead of a fixed point on the ground or a terrestrial vehicle) and where the main objective is to move this load from one position to another. The usage of each propulsion method in the publications categorised in this group follows almost the same percentages as when we consider all the tUAVs publications, with the exception that lighter-than-air vehicles were not found to be used for this application.

As shown in Figure 6, the transportation scope is the most prolific one, which constituted almost one third of the publications. It can be divided into two main types of transportation:

- Load transportation: where a load such as a delivery parcel [29], a weight [21], a planar platform [38], or a military payload [22] is transported by one [39] or more tUAVs [20] using a tether [23] or some other connection such as a rigid rod [42]. Some typical examples of the usage of tUAVs in this application are shown in Figure 7
- Hose transportation: where a hose is transported by one or more UAVs, usually in order to provide some liquid content to a specific location, such as in firefighting [47] and building painting [48]. A typical example of this usage is shown in Figure 7c



(**a**) (**b**) (**c**)

Figure 7. Examples of typical configurations in the load transportation application with different requirements: (**a**) Sensor transportation. (**b**) Buoy dragging. (**c**) Hose transportation.

Although they present a similar general system configuration, with the UAV connected to a massive free-swinging body, these two scenarios present different objectives, and, as such, different problems to be solved: while load transportation focuses on the stabilization of the end mass [24,27,39,41] and avoiding collisions [29,44], the hose transportation scenario aims to keep the ejected fluid contact point stable [48], thereby compensating for the forces arising from the ejection itself, without caring much for the UAV's or hose's swinging movement; furthermore, in hose transportation, the path of the UAV has to consider the avoidance of sharp bends in order to keep the liquid's flow from decreasing.

One subcategory inside the load transportation application that is worth mentioning is the use of tUAVs to either recover a military payload in a dangerous area [22,35] or to transport a load by dragging it (instead of lifting it in the air) using a multicopter UAV [60] or a high speed vehicle performing circular motion [34,45]. These applications differ from the bulk of the load transportation publications, as their system configuration is slightly different: in the military payload recovery, the load needs to be quickly attached while the UAV is moving (so precise slow maneuvering of the UAV is not an option), and in the load dragging scenario, the payload weight may surpass the maximum lifting capacity of the UAV.

Although this application does not present one of the main advantages of using tUAVs (that of being able to transfer energy from the ground to the UAV), the research concerning this scope addresses technical issues that are similar to the ones found in typical tUAV applications such as tether control, tether pose estimation, and the environmental influence on the tether. Table 2 presents some examples of publications from various application scopes that investigate similar challenges or propose similar solutions.

Table 2. Publications from different scopes focusing on similar issues or solutions.

Technical Issue Addressed	Publication Scope	Example Publication
Tether pose estimation	Transportation UAV–USV Cooperation	[91] [103]
Wind disturbance mitigation	Transportation tUAV control	[24] [121]
Control considering tether influence	Transportation Inspection	[25,56] [190]

3.1.2. Control and Navigation Scope

The second scope in regard to the number of selected publications presented in Figure 6 groups papers that focus on control and navigation problems.

As the control and navigation techniques can be employed in a multitude of scenarios and problems, these publications can be divided in some groups regarding the issue addressed in each of them. Table 3 presents a list of these divisions and the publications grouped in each one.

Table 3. Problems tackled in publications labeled as control and navigation.

Control and Navigation Issue Addressed	Publications
Control model	[92,101,102,105,107,111,112,114,116,117,126,132,137,138,142,143,201]
Localisation	[89,97–99,104,108,120,123–125,128]
Navigation	[91,93–95,106,129,130,133–135,139–141]
PID Tuning	[110]
Tether pose estimation and control	[90,103,115,118,121,197]
Tethered landing	[119,127]
Tethered UAV stabilization	[96,113,122]
UAV and UGV cooperation (moving)	[100,136]
UAV takeoff and flight control	[109,131]

As can be expected from publications that focused on the control and navigation issues, most of them, 82%, described at least part of the sensors used for the control loop. The same percentage of publications described the sensors used for perception of the UAV. Some solutions applied their technique only to a simulated environment and used the data available in the simulation as their main perception source [92,95,96,105,111,112,114–116,124,126,127]; other publications used data purely from the Inertial Measurement Unit (IMU) module of the UAV [94,98,106] or fused IMU data with some other sensor's data such as a camera mounted on the UAV [100,110,113], GNSS [107,109,197], ultrasound sensors [97], and sensors that measured the force [99,103,125], angle [103,120,123], and length [123] of the tether. Other perception sensors used in the publications includes GNSS (without IMU data) [119], Kinect [89], and Light Detection and Ranging (LiDAR) [93]. One control problem particular to tUAV application is the consideration of the forces applied by the tether to the vehicle in the control loop. In Table 3, these articles are listed under "Tether pose estimation and control", which used the estimated tether pose in order to enhance the aerial vehicle control.

In terms of the propulsion method of the tUAVs presented in these papers, 4% used fixed wing [101,107,109,117], one publication used a helicopter aircraft [119], and all the others used multirotorcrafts.

3.1.3. Meteorology

The usage of flying vehicles such as balloons and airplanes to measure and establish aerial and meteorological conditions spans as far back as from the 19th century [202]. The precise and continuous measurement of the atmospheric conditions can increase weather forecast's precision, which is crucial to a number of activities. Some typical tUAV usage in the meteorology application scope is shown in Figure 8.

(**a**) (**b**)

Figure 8. Examples of typical configurations in the meteorology application. (**a**) Sensor system on board the UAV. (**b**) Sensors distributed over the tether length.

Considering the selected publications in this scope, 73% of them did not describe the tether composition, and it is inferred that they only used it to keep the UAV's altitude and position stable, while some presented a superficial description of the tether, such as "3 wire cable" [153] or composite cable [148,149]. It is expected that, due to the altitude used in this scope's experiments , energy transmission becomes impracticable. Energy loss on kilometer-long cables demand either high voltages in the thousands or wider energy cables. Either solution leads to a heavier payload.

As this application requires the outdoor usage of the UAV, it is expected that the use of the GNSS as the main perception sensor would be adopted [145–147,149,152], together with LiDAR [148].

Out of all of the solutions presented in publications grouped inside this scope, 73% of them operated in altitudes higher than 800 m [144,145,147–151,154], while the other publications operated in altitudes lower than 200 m [146,152,153].

3.2. Propulsion Method

The propulsion method of the aircraft used in the tethered mode is important to define other components of the system. Considering all the selected publications, the most common aircraft type used was the multirotor, followed by the fixed-wing aircraft and lighter-than-air aircraft. The distribution of each propulsion method in the selected publications is presented in Figure 9.

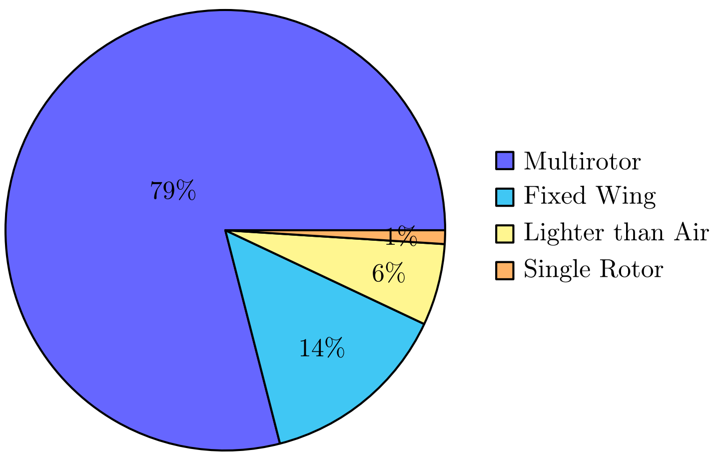


Figure 9. Propulsion method percentages considering all selected articles.

By grouping the publications by application scope, the results showed that each scope had a different type of UAV that was most predominant in the selected publications. The percentages for each scope are presented in Figure 10.

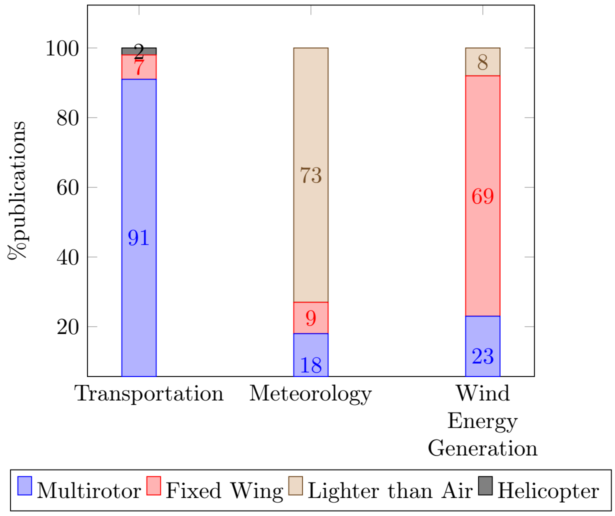


Figure 10. Percentage of each propulsion method per application scope.

The transportation application had a predominance of multirotor aircraft. As explored in previous sections, this scope focuses on stabilization, either of the load or the contact point of the jet of water being expelled by the hose attached to the UAV. In this manner, the multirotor's capacity to hover in place and correct oscillations by using precise maneuvering gives it an advantage when compared to other propulsion methods.

The meteorology scope's publications mostly used lighter-than-air aircraft, especially due to the long-term characteristics of the experiments, with some even lasting for one month [147]. This is explained mainly by the fact that lighter-than-air tethered aircraft have the advantage of consuming little energy once they reach the desired position and altitude. Furthermore, this configuration allows the UAV to reach altitudes that are higher than 1 km [144,147–151,154].

3.3. Energy Transfer Method

The method of powering the UAV in tethered scenarios is an important characteristic of the solution due to energy losses in the cable being proportional to its length. Considering that some solutions operate in altitudes that are higher than 100 m [153,171,179,182] and even as high as 1 km [154] and 11 km [160], their energy transfer solution has a great impact on the project.

Unfortunately, the majority of the publications (89%) either did not use ground-to-air energy transfer(34%) or did not describe the method used in the presented solution (55%). Table 4 presents the main reasons for not using the tether for energy transfer in each publication. The most-adopted solution between those that actually described it was to use DC energy transmission, either with voltages below 100 V [8,124,152,180,183], between 166 V and 380 V [179,181,182,187] or over 2000 V [171]. Some publications only described their energy transfer as being DC [89,160], while another only published the voltage value as 400 V, without discriminating if the energy was alternate or continuous [197]. Regarding AC energy, there are publications that used 220 V [154] and 600 V [153]. Figure 11 presents a summary of the publications according to the description of their energy transfer system.

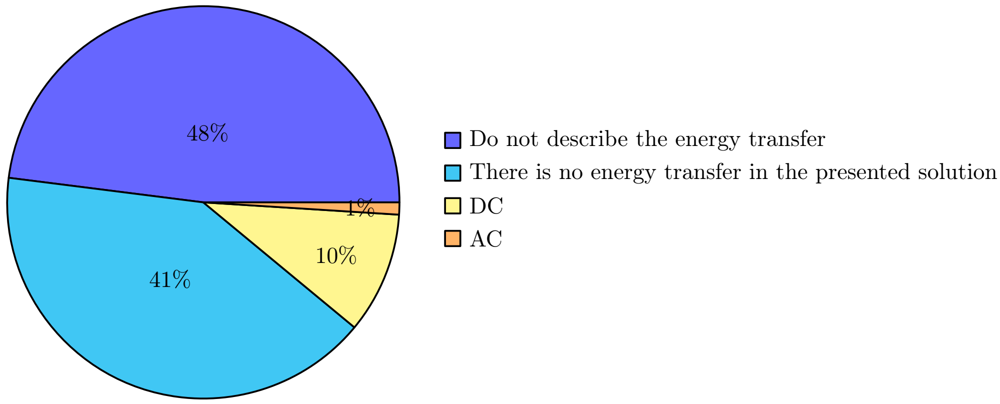


Figure 11. Percentage of the publications that described their energy transfer technique.

Table 4. Publications that did not transfer energy over tether.

Reason for Not Transferring Power over the Tether	Publications
No connection between UAV and ground	[20–44,47,48,50,51,53–56,58–69,71,74–83,86–88,90,91,129,134,137,140,143]
Connection for mechanical purposes during part of the operation	[193] (only during recovery of payload) [119,131]
Very high operating altitude (>1 km)	[147,148,175]
Short-term missions (inspection)	[133,163]

3.4. Tether Composition

The tether composition, considering its mechanical, electrical, and data transfer characteristics, is an important feature to differentiate the applications in the cabled tUAVs context.

The majority of the publications (78%) that discussed tUAVs did not actually describe the tether's mechanical, electrical, or data transmission properties. A small percentage of publications(14%) described only the mechanical or electrical aspects of the tether, such as materials or elasticity; these included publications with superficial descriptions such as "thin line" [26], electrical characteristics such as "3 wire cable" [153] or "0.83 mm cable" [156], as well as cable material such as "silicone rubber hose" [48]. A more detailed description was present in 8% of the publications. To be considered complete, a description must provide the definition of the cable used for energy transmission, data transmission, and mechanical support of the UAV. Figure 12 presents the percentage of publications according to the description of the tether used, while Figure 13 groups the publications that did not present a description, according to their application scope.

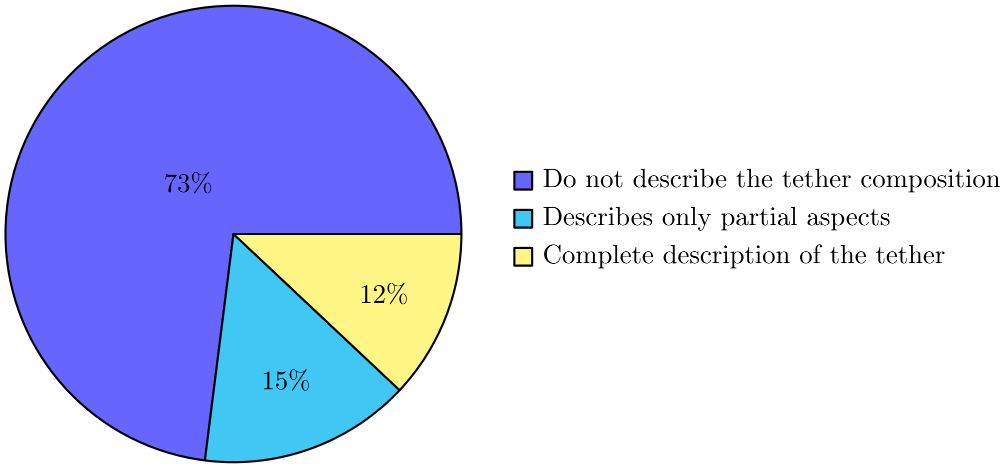


Figure 12. Percentage of the publications that described the tether mechanically, electrically, and information-wise.

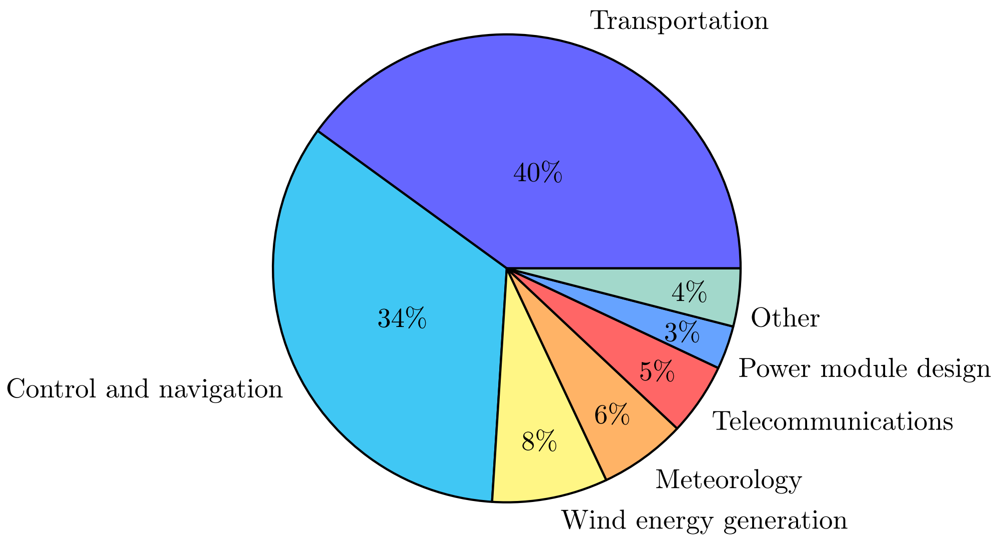


Figure 13. Scope of the publications that did not describe the tether composition.

Although the presence of the tether limits the movement range of the UAV, the publications that applied he transportation of a hose to the tUAV [47,48,57,86] demonstrated that it is possible to have some movement while connected to a ground point.

3.5. Perception Sensors

Considering that the four main applications described in Figure 6 depend, at least in part, on the accurate localisation of the UAV, the main perception sensors used by each publication is an important analysis due to the distinct characteristics of the system:

- The presence of a fixed point on the ground that may be better localised than the UAV (e.g., a meteorology station that has a known precise position) may provide a good starting guess, as well as the possibility to compute only the relative position between the UAV and the ground contact point;
- The tether mechanical information (e.g., the tension and angle) may provide a good estimation of the position of the UAV relative to a fixed point on the ground.

The main perception sensors used in the analysed publications is presented in Figure 14.

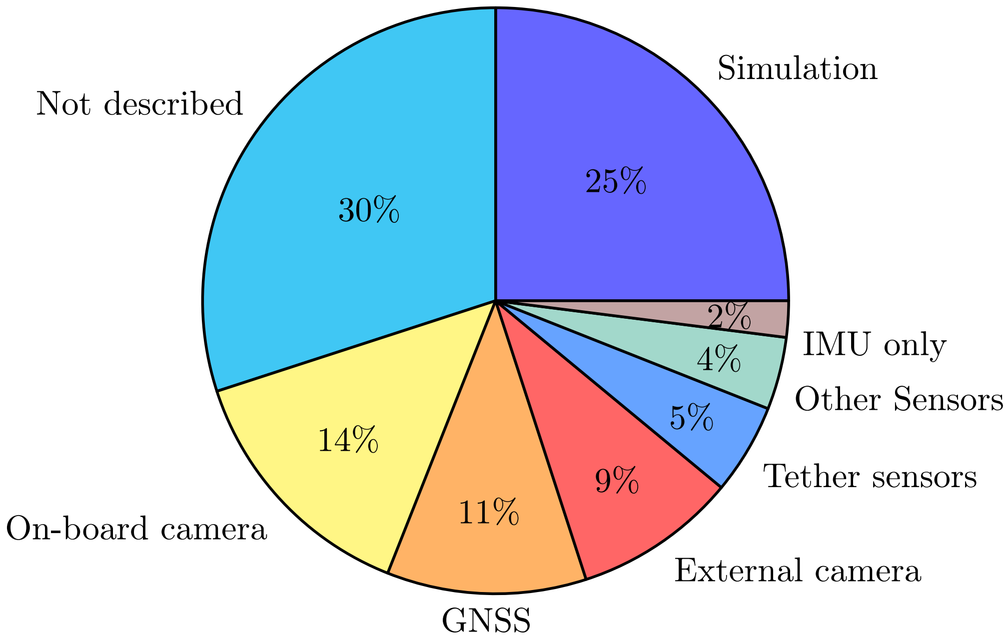


Figure 14. Percentage of publications grouped by main perception sensors.

Almost one third of the publications did not clearly state the sensors that they used for the tUAVs perception. Another third of the publications applied a simulated environment to test their methodology and used the data available in those simulations as their main perception source.

Between the publications that used some kind of onboard camera as the main perception sensor, there were some that only described their sensor as a camera [8,56,100,110,113,117], monocular camera[39] or electro-optical pod [189]. Other papers described the model of the camera used, such as the Foxeer Predator V4 [21], the Kinect [89], Realsense D435 [49] or the RecognitSys support module [181]. Installing motion capture camera systems in the environment externally to the UAV is another option for perceiving the UAV and the tether [20,23,24,30,33,44,50,53,60,91]. For outdoor applications, GNSS is an option that is adopted for localisation in some solutions, either using only GNSS data [55,119,146,147,149] or coupling it with IMU data [107,109,145,152,197]. Estimating the location of the UAV by measuring the tether parameters is also a solution in some cases, which is achieved by either measuring the tether tension [99], angle [120], tension and angle, [103] or by fusing it with IMU readings [120,123,125,190]. Pure IMU data were used in a few cases [48,94,98,106,195].

3.6. Operational Altitude

The operational altitude of the UAV is crucial to determine the tether length and the mechanical demands of the operation. The distribution of the selected publications grouped by operational altitude range is presented in Figure 15.

Table 5 presents the distribution of publications that correlated the propulsion method and the operational altitude of each one (note that an operational altitude of zero means that the solution presented in the publication was tested or simulated without the UAV taking off). One observation that can be made is that, while publications that used lighter-than-air aircraft tUAVs predominantly focused on altitudes that were higher than 100 m [144,146,148–151,154,155] and which reached up to 20 km [147], those that prefered multirotor propulsion were almost evenly distributed in all altitude classes. Fixed-wing solutions in terms of operational altitude were a little less concentrated, with some publications using altitudes in the 11 m to 20 m range [107,109,195] or in the 21 m to 100 m range [22,159]; however, just like with lighter-than-air vehicles, most publications focused on altitudes that were higher than 100 m.

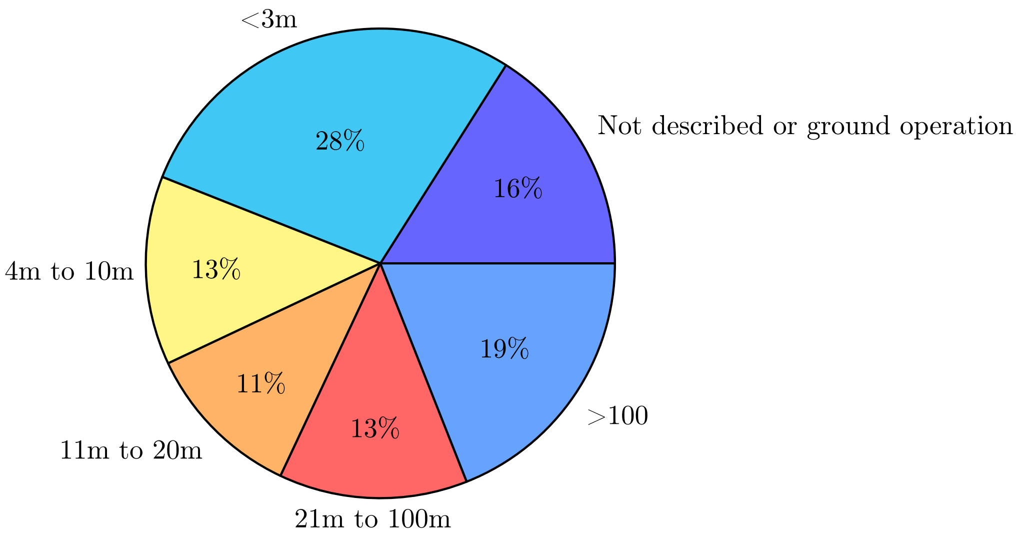


Figure 15. Percentage of publications grouped by operational altitude of the UAV.

3.7. Control Technique

As shown in Figure 6, the technique used to stabilize and control the tethered UAV was one of the most discussed scopes in the selected publications. The control of the tethered UAV differed from the untethered mode due to the different forces applied to the aircraft by the tether. The effect of wind on the tether and the subsequent forces applied to the UAV were also a source of analysis and discussion in some of the papers.

The most-used control techniques and their representation in the analysed publications can be separated in four groups: those that presented some form of PID, those that used commercial control modules, and those that did not present technical details about the control solution adopted. Most publications (68%) used a classic PID control loop with some variation that differentiated them from a textbook implementation of PID. A few (2%) implemented artificial neural networks, evolutionary algorithms [22,25,110], or reinforcement learning [43] over the PID control loop. Almost one third (29%) did not describe their control technique.

Table 5. Paper distribution correlating UAV's propulsion method and operational altitude.

	Operational Altitude					
Propulsion Method	**0 m**	**≤3 m**	**4 m to 10 m**	**11 m to 20 m**	**21 m to 100 m**	**>100 m**
Multirotor	[42,46,63,69,73, 81,87,100,108,122, 124,128,132,141–143,172,177,180, 187,189,190,194]	[20,21,23,24, 27,29,30,33,37–41,43,48–50,53, 56,57,60,61,64,66, 68,72,75,77,78,88, 89,91,92,94,96–98,104,110,111, 113,116,123,125, 126,134,137,139, 140,167,176,200]	[25,28,32,45,47, 52,54,58,65,67,70, 71,82,84,85,95,99, 105,106,115,130, 201]	[44,51,59,62,74,80, 83,86,93,103,112, 135,136,152,183, 192]	[8,31,55,102,114, 120,127,133,138, 156,169–171,181, 182,184,186,188, 191,197,199]	[79,90,118,121, 131,153,163,168, 174,178,179]
Fixed wing	[101,157,164,185, 196,198]	∅	[166]	[107,109,195]	[22,159]	[34–36,76,117, 129,145,158,160–162,165,193]
Lighter than air	∅	∅	[173]	∅	∅	[144,146–151,154,155,175]
Helicopter	∅	∅	∅	[26,119]	∅	∅

4. Discussion

This systematic review assesses the publications since 2017 for tUAVs. Each application scope where this technical solution is applied has their own properties and problems to be tackled. For instance, the load transportation scope has the tether's end not connected to a fixed point on the ground, which is something that does not happen in the other applications. This changes the forces considered in the control loop and the localisation techniques, which makes any energy transfer from the ground to the UAV through the tetherunfeasible. On another scope, the wind energy harvesting application has to consider the energy needed to keep the UAV in the air, as a higher energy demand goes against the main purpose of the scope. Although each scope is responsible for a different percentage of the publications, as shown in Figure 6, we can conclude that all the main application scopes contribute to the growing interest in tUAVs.

One of the main advantages of th tUAVs over a free-flying solution is the possibility of long term operation of the aircraft due to the power being transferred from the ground to the UAV. Another advantage is the added payload capacity due to the absence of the onboard battery. A final point in favor of the tUAVs is the addition of a well-localised point on the ground that facilitates the localisation of the UAV to estimate its location and pose relative to the known ground point. The main disadvantages are the lack of sensing in the body of the tether, which forces the algorithm to estimate the pose of the tether based on the sensors present in the UAV. Another disadvantage is the restriction to the UAV's mobility caused by the finite length of the tether.

The main problems tackled in the publications are the estimation of the forces involved in the tether connection, the compensation of the wind effect, the estimation of the tether's pose, the stabilization of the load, and the path planning of the UAV.

As shown in Figure 9, most of the research with tUAVs used the multirotor aircraft model. However, as can be seen in Figure 10 for each one of the main application scopes, a different propulsion method was most often used. There are, however, exceptions to this statement; for instance, the load transportation scope was dominated by the usage of multirotor tUAVs, but some publications explored the application of fixed-wing aircraft [22,34–36] and even helicopters [26] as a viable solution.

The energy transfer method, together with the composition of the tether, were largely not described in the publications. This represents a difficulty in reproducing the presented solution or transposing it to a different scenario. The few publications that actually described their energy transfer techniques mostly used DC voltages over 100 V to minimize the losses due to the Joule effect in the tether. Thus, high DC voltage presents a better solution for transferring power over long tethers. A standardization of the power transfer in the tethered UAV scenario is still absent in recent publications on the subject.

The control block of the publications mostly iterated starting from some form of PID architecture. Even the works focused on control solutions started from the PID base and applied a novel approach over it. Evolving or machine learning algorithms applied to the control block were present only in a few articles [22,25,110], and reinforcement learning [43] over the PID control loop were even fewer. This dominance of the PID is mostly due to the robustness of the classic method that presents good results even in uncertain scenarios, such as when we do not know the wind behavior [35], the end mass attached to the tether (in a load transportation application) [42,60], or the configuration of the environment where the navigation occurs [93]. The results in the analysed publications point to the usage of classic PID control or a variation built over it, with little room for innovation on this block of the system's design.

Considering the PICOC framework that was used to build the search string and comparing it to the selected publications, it is possible to make the following analysis: (P)—the expected population of tethered UAVs was confirmed in the selected publications. Some articles used variations of the "tether" element, such as rigid rods and grippers, but still adopted the same system model; (I)—the analyzed parameters were able to group the articles according to the technological solutions. This pointed to possible future developments and challenges for the scope; (C)—as each publication adopted a different collection of solutions, it was not possible to directly compare the adopted solutions; (O)—the flight configuration that optimized the usage of tUAVs varied according to the context and flight parameters (e.g.,: the system configuration suited for meteorological measurements may not be the best solution for a wind energy harvesting scenario); (C)—both the simulated and real-world tests were able to fulfill the research requirements in the selected publications. Simulated experiments were able to provide the very accurate measurements and results needed for the validation of mathematical models and control architectures. Real-world experiments were able to test the tethered system against a multitude of factors that are not normally modeled in simulated environments.

Therefore, given the present literature review, the next steps for the implementation of tUAVs should be as follows:

1. Compare different energy transfer techniques and parameters in selected scenarios while considering tUAVs and long-term operations;
2. Employ effective use of vision algorithms related to the tether identification and pose estimation. This review showed that, once the tether pose is correctly estimated, the various control techniques are able to use that input to achieve various objectives (e.g.,: UAV stabilization and tether collision avoidance). The analysis also showed that vision techniques are able to perceive different aspects of the UAV's environment. The unification of these two solutions can prove to be an advancement of the tUAV scope;
3. Compare different processing architectures in tUAV scenarios. Given that there is the possibility to easily transfer data over the tether, what type of data is more suited to be processed by the UAV or by the ground station?

Considering the publications analyzed in this review, the future of tUAVs points to some applications: long-term UAV operation in various fields; the cooperative transportation of loads; wind power generation; and emergency telecommunication backup. Moreover, some gaps need to be researched to assure a robust implementation of tUAVs:

- The implementation of tUAVs in agricultural scenarios;
- Safety measures for the tUAV considering the presence of the tether;
- the localisation of the tUAV in consideration of the tether pose estimation and all parameters associated with it;
- Tether mechanical integrity estimation, especially considering long-term operation.

5. Conclusions

This paper performed a systematic review of the indexed literature on tUAVs. The review collected publications from different sources and covered a wide range of topics inside the tethered UAV topic, namely, the main application scopes and the focus of each of them, the propulsion method of the UAVs, the energy transfer method, the tether composition, the perception sensors, the operational altitude, and the control technique.

Between the manuscripts accepted for consideration in this review, most of the works used multirotor aircraft, which were distributed in almost all scopes and altitudes. The works that used lighter-than-air vehicles focused mainly in the meteorology scope and, therefore, applied their solutions to higher altitudes. Fixed-wing aircraft dominated the wind generation scope and also operated mainly in higher altitudes. Helicopter aircraft appeared only in a very few publications and mostly applied their tUAVs to altitudes between 11 and 20 m.

High-voltage DC energy usage in the tether, classic PID technique in the control block, and IMU data fused with visual or some other sort of environmental data (e.g., LiDAR) for perception were present in most solutions and appeared to have good enough results for these project's aspects, so future investigation should use these configurations as a starting step and then iterate further.

The most significant advancement from the control point of view detected in the publications is the development of tether pose estimation algorithms that allow the UAV to control the tether pose to achieve various objectives, such as avoiding collision of the tether, keeping the tether taunt during flight, and evenly distributing the load tension between multiple UAVs. In the energy transfer area, the development of custom energy converters can be pointed to as the main development. These converters are capable of transmitting hundreds of watts while keeping the circuit and the wire weights low due to the payload restrictions of the UAVs. Regarding the sensor side, the development of custom sensors that are capable of measuring the angle and tension of the tether can be considered the main achievement.

Future investigation should focus on implementing the solutions presented in the publications in real-world scenarios, as part of the publications used simulations to validate their proposals, and others tested their implementations in controlled laboratory environments. On this matter, subjecting the solutions to harsh real-world scenarios such as climate, wind, and other natural elements may highlight issues that are not considered in the simulated or lab-controlled tests. Some elements that are hard to model in a simulated scenario but that are easy to implement in a real-world test include the following: weather wear in the tUAV and tether material; the presence of flying and land animals and their influences on the system; day and night cycles and the changes they provide in environmental conditions such as temperature, light, and wind; the presence of particle deposits in the electronic and mechanical systems; and the sea salt effect for maritime applications.

Another open investigation field is the application of tUAVs in agricultural solutions. The long-term characteristics of this solution may prove to be useful in precision agriculture, especially when coupled with ground robots to provide capabilities that are not viable from a terrestrial point of view. Localisation, mapping, and path planning tasks can be greatly enhanced in agricultural scenarios if the tUAVs cooperate with the elements on the ground. The lack of infrastructure to support the UAV in agricultural areas such as the requirement of charging its batteries and the need of landing due to adverse weather conditions can all be managed by connecting the UAV to a mobile ground vehicle from which the UAV can draw its power and land in the case of necessity.

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