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Review

A Decade of UAV Docking Stations: A Brief Overview of Mobile and Fixed Landing Platforms

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Abstract: Unmanned Aerial Vehicles have advanced rapidly in the last two decades with the advances in microelectromechanical systems (MEMS) technology. It is crucial, however, to design better power supply technologies. In the last decade, lithium polymer and lithium-ion batteries have mainly been used to power multirotor UAVs. Even though batteries have been improved and are constantly being improved, they provide fairly low energy density, which limits multirotors' UAV flight endurance. This problem is addressed and is being partially solved by using docking stations which provide an aircraft to land safely, charge (or change) the batteries and to take-off as well as being safely stored. This paper focuses on the work carried out in the last decade. Different docking stations are presented with a focus on their movement abilities. Rapid advances in computer vision systems gave birth to precise landing systems. These algorithms are the main reason that docking stations became a viable solution. The authors concluded that the docking station solution to short ranges is a viable option, and numerous extensive studies have been carried out that offer different solutions, but only some types, mainly fixed stations with storage systems, have been implemented and are being used today. This can be seen from the commercially available list of docking stations at the end of this paper. Nevertheless, it is important to be aware of the technologies being developed and implemented, which can offer solutions to a vast number of different problems.

Keywords: unmanned aircraft systems; docking station; multirotors; landing paltforms

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1. Introduction

Unmanned Aerial Vehicles (UAVs) are being extensively used, and their popularity has been increasing rapidly in the last decade thanks to the rapid growth of microelectronic controllers. Multirotors are the most vastly used platforms in research papers due to their high-precision positioning and the simplicity of control systems using very basic controllers. Other types of UAVs are also used in the reviewed papers, but their number is considerably lower. The main limitation of UAVs is flight endurance, which is limited by the power supply used most often, which is lithium polymer batteries. This problem can be tackled by developing different types of batteries, using internal combustion engines or using hybrid systems. A more promising solution, however, seems to be docking stations that are capable of recharging (or swapping) batteries, storing and even communicating with a UAV. Using docking stations solves the flight endurance issue and it is a step further in automating UAV systems.

Earlier papers frequently used UAV systems such as helicopters or fixed-wing UAVs [1–5]. This is because of the lack of cheap microelectromechanical systems at the time, which can be seen from the more recent work carried out by different authors. Multirotors are being used more often in the latter research efforts.

In this paper, an overview is presented of the work carried out in the last decade. The reviewed papers present different docking station solutions with the accompanying systems. A lot of papers have been written which propose software solutions such as trajectory planning, autonomous landing using different controllers (Fuzzy Logic, MPC, etc.) and even artificial intelligence in the marker tracking used in precise landings. These papers are also taken into account because of their direct impact on docking station design.

In Section 2, a preliminary description of docking station systems is presented. In Sections 3 and 4, two different types of platforms are presented and some are reviewed in detail. In Section 5, commercially available docking stations are listed, and a brief explanation is given for every system.

2. UAV Docking Station—Preliminary Description

A docking station for UAVs is a multipurpose system that enables them to land safely, take off, recharge and/or replace batteries, and transfer data and payload. Some docking stations are even capable of storing UAVs, thus keeping them safe from adverse environmental conditions. The listed processes have to be autonomous to minimize the need for human intervention. Therefore, UAV docking stations allow a longer work time for a drone with no need for an operator to change the battery manually. Docking stations can be classified regarding:

- Mobility (mobile and fixed);
- Charging method (two electrodes, multiple electrodes, wireless, etc.);
- Automatic battery exchange (spare batteries recharging);
- Positioning (active and passive);
- Drone storage (yes or no);
- Package delivery (storage, no storage);
- Type of landing (precision, vision-based, etc.);
- Type of landing platform (self-leveling).

The Figure 1 shows the classification of the docking stations based upon the mobility.

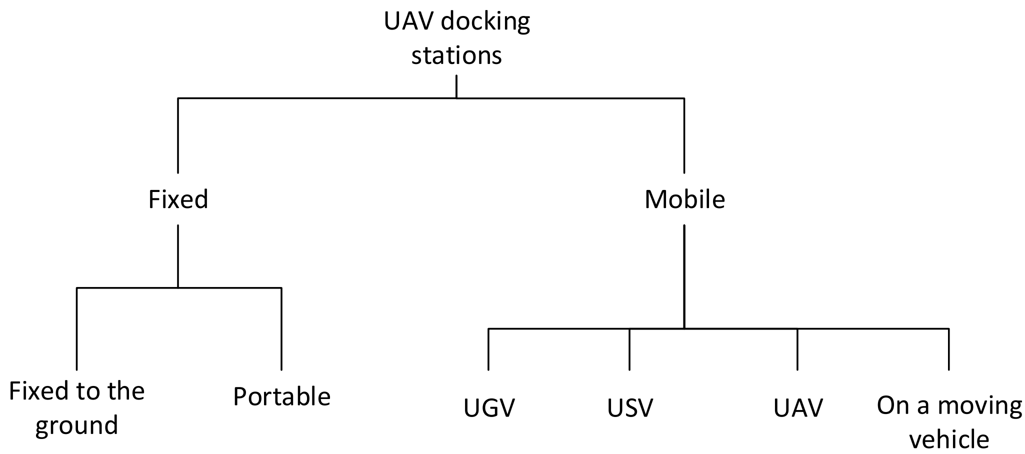

Figure 1. UAV docking stations classification.

A docking station consists of multiple subsystems such as a landing platform, positioning mechanism, electronics, power supply, visual landing aid, battery recharging system, battery swap system, drone storage system, item storage system, and others. UAV docking stations must meet certain criteria to fulfill their goals. Regarding the classification of docking stations, there are requirements for certain types of docking stations.

2.1. Landing System

A landing system consists of a method to guide a UAV, ensure it lands in the correct position, and finally lock it in place. The first requirement is often managed by the UAV itself, but there are occasions where this is not true.

2.1.1. Precise Positioning (in Air)

Precise positioning during the landing phase is crucial to make precise landings. It is important to note that relative positioning between the UAV and the docking station is required. The landing phase consists of a few different phases. The first phase is the approach phase. Usually, systems using GNSS are sufficient to approach the docking station. Before touchdown, the next phase is to precise position the UAV. This phase is crucial to a successful landing with minimal error. Touchdown is the final landing phase. The UAV is usually guided visually using so-called markers that are placed on the docking station, but can be guided using other means. Figure 2 shows the classification of precise positioning systems. Various types of visual markers can be used; the most common are the ArUco markers, but other markers such as Quick Response (QR) codes or custom-made ones can be considered. As listed in Figure 2, there are other methods of precisely guiding a UAV which may include Infrared LEDs or even radio waves. The latter methods are used in cases of low visibility or no visibility at all. A great deal of docking-station-related papers deal with the precise positioning of UAVs.

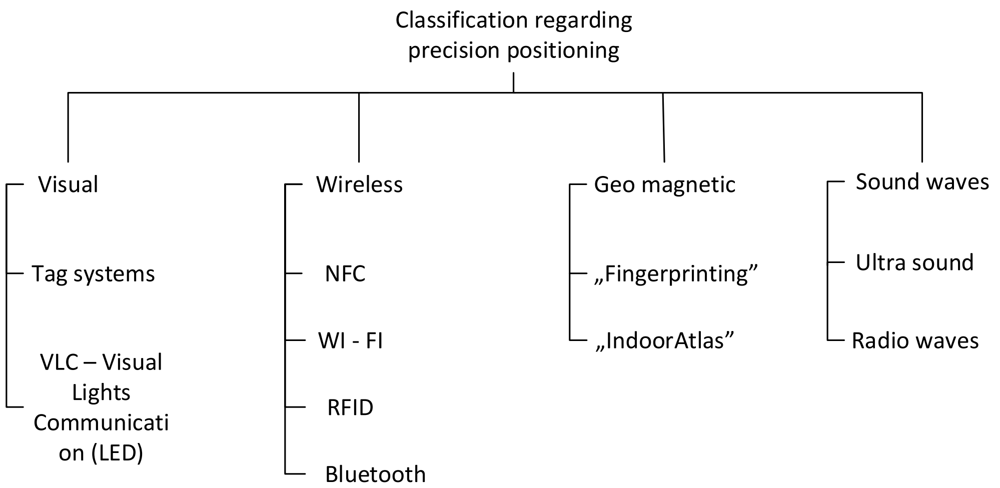

Figure 2. Classification of precise landing positioning systems.

2.1.2. Landing Platform

The second requirement is precise positioning when the UAV makes contact with the docking station. In [6], a detailed overview of related mechanisms is presented. The mechanisms for positioning a UAV are divided into two main groups, which are active ones and passive ones. The active positioning mechanisms consist of an actively actuated mechanism that is used to move the drone into the desired position. The passive ones are not mechanisms by definition; rather, they are only landing pads shaped to make sure the UAV lands perfectly in the desired position. Landing platforms can be classified regarding:

- Positioning: active or passive;
- Orientation: self-leveling, fixed or tilted;
- Power: charging electrodes or wireless charging;
- Vision: visual tags and/or lights.

2.2. Battery Management System

The main purpose of docking stations is often the replenishment of the UAV's power supply. In the case of an electric power supply, this task can be fulfilled using a charging method or by completely swapping out the battery as a whole. Docking stations are most often fitted with a method to charge the battery using electrical contacts on the UAV. They are usually positioned on the landing gear of the UAV. There are, however, methods that use wireless charging (WPT) systems. The second method for replenishing the power supply consists of swapping the whole battery out. It is vital to secure safe operation with the battery. This means a storage system has to be designed in a safe way to handle the battery during swapping operation.

2.3. Storage System

The storage system's main function is storing and protecting the UAV or payload. Different docking station solutions have different storage systems. The UAV itself can be stored within the docking station, and in some cases, there is a need to store a certain type of payload that can be transported with the UAV. Storage systems may also include mechanisms for loading and unloading the payload.

2.4. Data Transfer

Sometimes, a UAV needs to be able to communicate with the ground station between multiple flights. Some solutions offer the ability for the UAV to dock at the station and to connect to the ground station used to command the flights of the UAV. The system can be used to assign new flight plans to the aircraft or to download logs of the previous flight and upload them to a different location. It can be used for package retrieval as in [7], where a docking station was used for sensor package retrieval.

3. Fixed Docking Station

Docking stations can be of different types. One possible classification is based upon the ability of the docking station to move. This section brings a brief overview of the docking stations which are fixed in place. It should be noted that this does not mean that the docking stations cannot be moved, but simply put, they are fixed during their operation. They can be portable, usually meaning smaller in size, but during the operation, they must be fixed in one position.

A big portion of the papers written is the software solutions for guidance during landing. Dealing with precise landings is the main concern in designing docking stations. One of the main methods, as mentioned before, is the visual approach using onboard cameras and tags on the docking stations, also called markers. Papers such as [8–15] deal with such solutions. The visual approach is a good option for small UAVs and micro-UAVs which have a camera since there is no need for any extra sensors to be mounted on. These methods can be improved further using different kinds of controllers such as Fuzzy Logic controllers, MPC, and Deep neural networks. These algorithms are explained in [16–20]. Some of the mentioned methods for improving visual approach can have a small footprint on the flight controller, but some can be computationally intense, so they have to be selected carefully if one is willing to use them. Other methods for precise landings on fixed docking stations include other types of sensors. There are solutions that extend the setup of the docking station using Visual Lights Communication (VLC) such as [21,22]. Other systems use different sensors mounted on the UAV such as Optical Flow, IRLock/Mark one Beacon systems, fisheye cameras, and Inertial Measurement Units (IMUs). These systems were researched in the following papers: [23–26]. While needing some extra payload, these systems are the most precise. If the docking station lacks a positioning system, these systems can be a necessary improvement of the station.

Authors showed a method for precise positioning using ultrasound waves that propagate through the air in [27]. It can be a viable solution for low-visibility conditions or no visibility at all.

Fixed docking stations consist of setups with different systems onboard. They can simply be a platform with an active positioning system on which the drone can land such as the one described in [28] or a platform with a passive positioning system—[29]. Another solution can be a robotic arm manipulator which can be used for docking purposes. In [30], a robotic arm was fixed in place while the UAV had a gripper attached to it. This can be an excellent solution for multiple different circumstances since a robotic arm can be attached to various types of objects. It can be used in conditions such as a very uneven terrain or where steep angles must be used in the approach phase.

There are solutions that consist of a landing pad with no positioning systems and only wireless charging for the battery, such as [31–35]. It is a great way to keep a UAV charged if long routes should be crossed, but it can also be used to keep a UAV charged with no additional equipment needed on the docking station. Wireless charging of batteries is the most robust solution, but it can often be slow, and the UAV has to be positioned correctly in order to achieve wireless charging full potential. To assess this problem with wireless charging, charging with electrodes is being used. In [36], the author presented two different solutions for charging UAV batteries using electrodes.

A docking station with landing guidance and a wireless charging pad is presented in [37]. No additional computer vision systems have to be added to the UAV; thus, it could be a viable option to be used with low-cost or micro-UAVs.

More complex solutions include the ability to exchange batteries such as the ones in [38–43]. These are excellent solutions, where the time needed to recharge should be minimal.

Among the searched papers, docking stations with storage for the UAV can be found in [44–46].

A docking station for a small UAV with a guidance method using optical sensors and an active positioning system is presented in [47].

Another study carried out in [48] proposes a different charging station solution. It consists of an overhead docking station with a latching system with the ability to charge a UAV's battery. It can be used in indoor flights where charging from below might pose an obstruction.

Detailed Overview

Different types of fixed docking stations are briefly presented with their respective working principles.

In [44], a fixed docking station is presented. It accomplishes multiple tasks such as UAV storage, protecting it from adverse environmental conditions, a battery replacement mechanism, data transfer during the flight, and finally, a method for precise landing using an ArUco-marker with integrated backlight. Figure 3 shows the docking station with its subsystems.

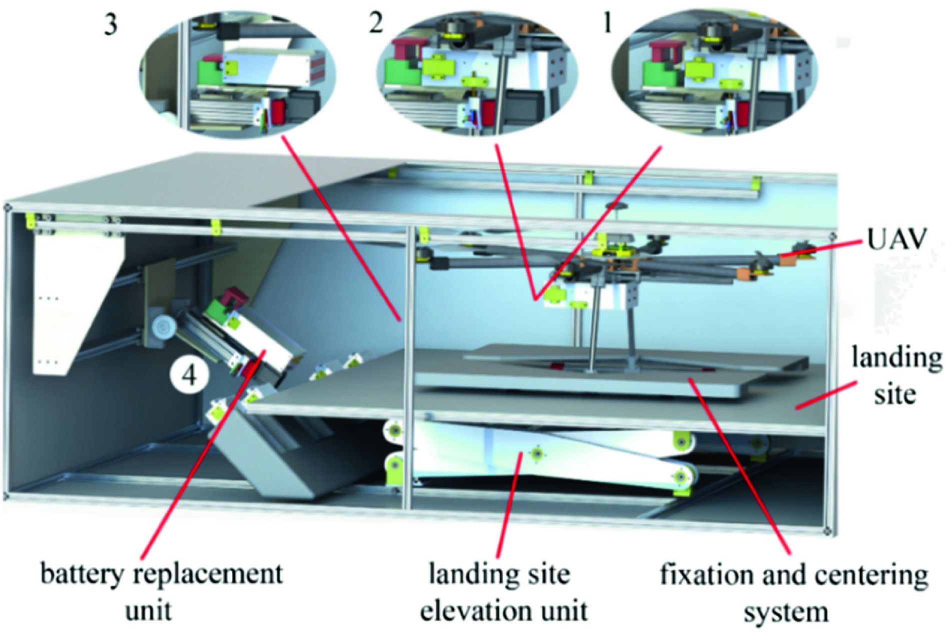

Figure 3. Fixed docking station with its subsystems from [44]. The labels (1–4) show the battery replacement mechanism in operation.

The authors used a landing system with an active positioning system that uses an elevating landing pad. An active positioning system uses V-shaped pushers which automatically move the UAV in precisely the desired position. The elevating landing pad is retracted when the UAV successfully lands. Figure 4 shows the markers used for precise landings with and without the backlight.

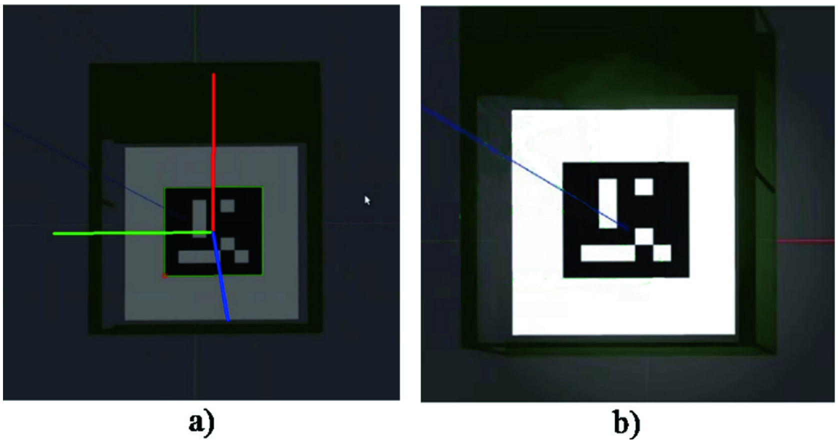

Figure 4. ArUco markers used for precise landing with (**a**) and without (**b**) the backlight turned on [44].

In the researched papers, battery replacement mechanisms are presented. In [39], the authors developed and manufactured a docking station with ability for the UAV to precisely land and a mechanism to replace the battery pack. Figure 5 shows the development of the docking station with the quadrotor used in the paper.

Figure 5. Battery replacement docking station from [39]. In the figure, the used UAV is displayed as well as the docking station final version. Furthermore, the design CAD view and the construction phase of the docking station are displayed.

In order for the docking station to be able to replace the battery, a special battery compartment was developed that can be easily attached and detached from the UAV. Figure 6 shows the battery compartment and the battery slot on the UAV.

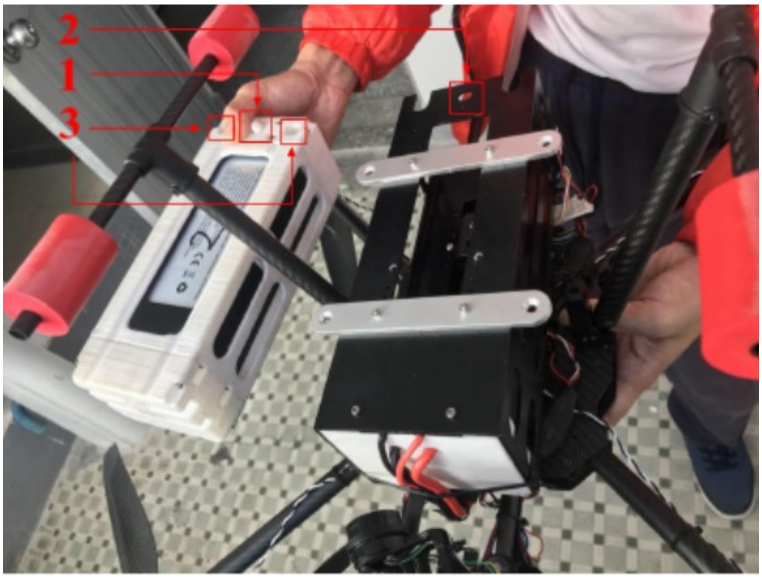

Figure 6. Battery compartment and the battery slot on the UAV [39]. Label 1 and 2 on the figure show the positioning system which is composed of a pin (1) that pops out to be locked in the hole (2). The two holes (3) on the battery compartment are used to push the battery compartment out.

Earlier work showed the use of a robot arm that can manipulate battery packs [40]. The authors developed a battery charging system and the novelty is "hot battery swapping", which is a method to swap a battery while the electronics are continuously powered. Figure 7 shows the docking station developed by the authors from [40].

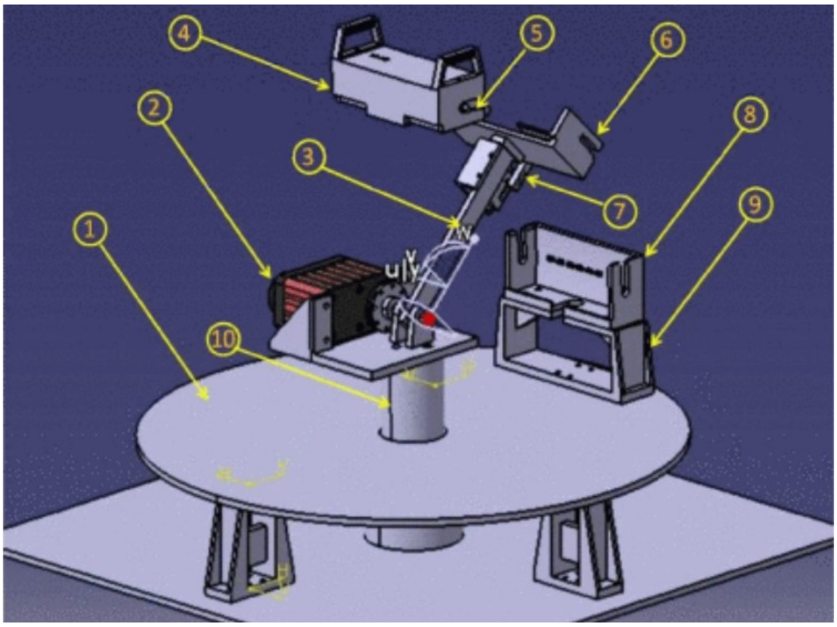

Figure 7. Robot arm for battery pack manipulation in [40]. The different parts are described in the paper as: Carousel (1), Servo Motor (2), Rocker Arm (3), UAV Battery Holder (4), Battery Bracket (5), Arm Battery Holder (6), Finger with motor (7), Bottom Battery Holder (8), Carousel Bracket Height (9), and Shaft (10).

In [42], the authors present another solution for a fixed docking station with battery replacement mechanism. It uses an active mechanism for positioning the UAV that uses orientation arms. The results show successful precise landings and battery replacement. Figure 8 shows the presented UAV docking station in operation.

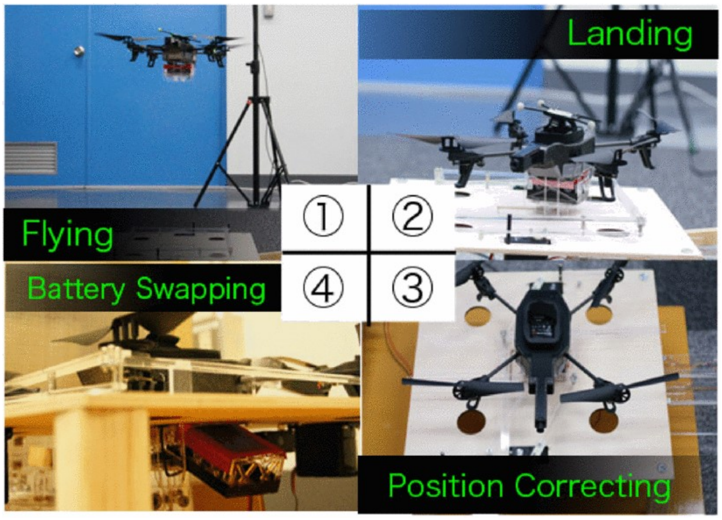

Figure 8. Endless Flyer [42], docking station with battery replacement mechanism. The labels in the center show the different landing stages and the order in which they are realized.

The Intelligent Self-Leveling and Nodal Docking System (ISLANDS for short) is a docking station system presented in [28]. The paper presents a landing pad for use with autonomous helicopters. It incorporates a method to precisely land on an actively tilted landing pad that has the ability to precisely position the helicopter and to lock it in place. The active tilting is used to level out the landing pad. It uses a pneumatic piston as an actuator. Figure 9 shows the fully assembled ISLANDS system.

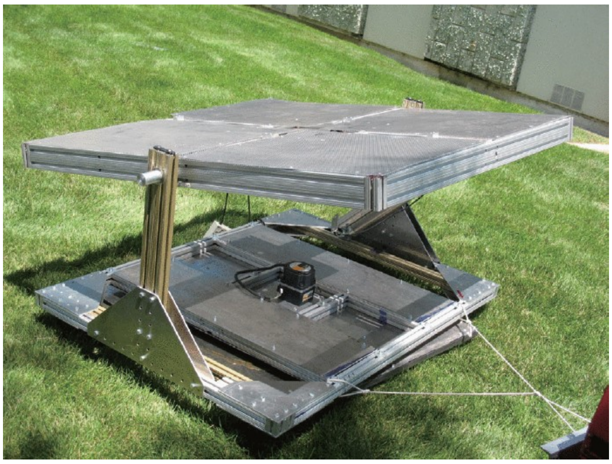

Figure 9. ISLANDS [28], assembled docking station with actively tilted landing pad.

Finally, in [31], a system that uses a custom-developed UAV is presented. A landing pad is developed which enables the UAV to operate for up to four hours with no human interactions. It consists of a charging pad shown in Figure 10. The landing system is used to transfer data from and to the UAV, thus contributing to its autonomy. The control and guidance methods for the UAV were developed. The optimization of the layout of the markers was presented in the paper since an array of AprilTag markers can be used for precise landings.

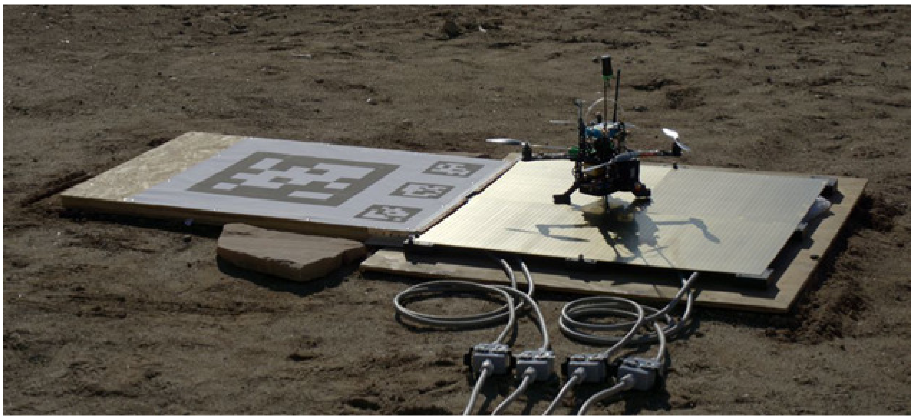

Figure 10. Docking station with recharging pad with the custom made UAV from [31]. In the figure, the QR codes used in the approach and landing phase can be seen.

4. Mobile Docking Station

This group of docking stations consists of a platform that is mobile during the landing operation. These include UGV–UAV (Unmanned Ground Vehicle–Unmanned Aerial Vehicle), USV–UAV (Unmanned Surface Vehicle), and even Airborne UAV–UAV interaction systems. These can be docking stations as described before, but some can have only some of the subsystems mentioned above. These include UGVs, which are capable of moving to the desired landing position and exchanging the batteries.

Mobile docking stations require different software solutions for precision landing systems. The main requirement is robustness, meaning the ability to land in the presence of various disturbances. Papers dealing with disturbance rejection are [49–51]. Visual-based trajectory planning is the basic method for landing on a moving platform. Such methods are described in [52–56]. More advanced controllers such as deep learning and Fuzzy Logic algorithms are used in [57,58]. Mathematical approaches with simulation results are presented in [59–62]. Other works concerning landing on a moving platform consist of fixed-wing UAV landing systems such as [63] and algorithms for landing on platforms situated on a water surface—[4,64].

Movable docking station systems can be classified into three different groups depending on the medium they are operating in and an additional group which can be a part of the other three. The first ones are ground-moving docking stations. Some of them are Unmanned Ground Vehicles which have landing systems mounted on, like in [65–71]. The UGV can be used to swap the battery of a UAV, like in [72] or to wirelessly charge the battery—[35,73,74]. The UGV solutions for mobile docking stations are the most often used solutions since UAVs are mostly used above land. UAVs should be used and are being used for short ranges because they lack better power supplies. Because of the above-mentioned reasons, UGV docking station solutions are the most important group of stations.

The second group are airborne docking station solutions as in [75–78]. These solutions are the most rarely used, but they can be a great method to transport small UAVs over larger distances to be used in most remote areas. There are solutions such as [79] that are only used to deliver and change a battery using another UAV. It is a good solution where the main drone is used for a specific operation and must stay airborne during the operation.

The third group are water surface moving docking stations. They are described in [5,80,81]. These are good solutions when UAVs have to be operated above water, but it can be challenging to design a robust docking station which can be used in severe wave conditions. They are best suited for small water surfaces with calm water conditions.

The last group is composed of docking stations, which can be used like a fixed docking station as well as mounted on a manned vehicle, like in [82]. These can be useful for bigger vehicles which have a UAV system support mounted on top.

The authors of [83] present a helicopter tethered to a moving landing platform. Systems that use tethers to supply a UAV with electrical energy significantly improve flight endurance, but they lack the ability of a UAV to freely move. It is a great solution where viewpoints from a higher position are required.

Other designs found for this review are systems for multiple smaller UAV landings and docking, like in [84]. These can be used for drone swarms which are used for the same operation.

Another solution for landing purposes is described in [85], which is a landing gear robot that can be attached to a UAV. The robot described in the article is fully adaptable to different terrain configurations. The same is found in [86], where a mobile adaptable platform is described. These do not strictly belong to docking station solutions, but they are mentioned since they can be used in future projects as supporting technology.

Finally, conceptual work was found in [87]. The authors propose a cooperative robotic system using UGV and UAV to accomplish a specific task. The system is simulated using Gazebo simulator (ROS interface). Here, work currently being carried out in this field is mentioned and shown. The reader is advised to pay attention to the work being carried out in the future.

Detailed Overview

In this section, a detailed overview of the selected work carried out in the field of moving docking stations is given.

In a recent paper [65], a controller design was proposed for a cooperative UGV–UAV system. In this paper, QR codes were used for precise landings. The mathematical approach and the docking station system were presented. This docking station solution uses a simple box that can be closed so the UAV can be protected from various environmental conditions. It even consists of a battery replacement system which is displayed in Figure 11.

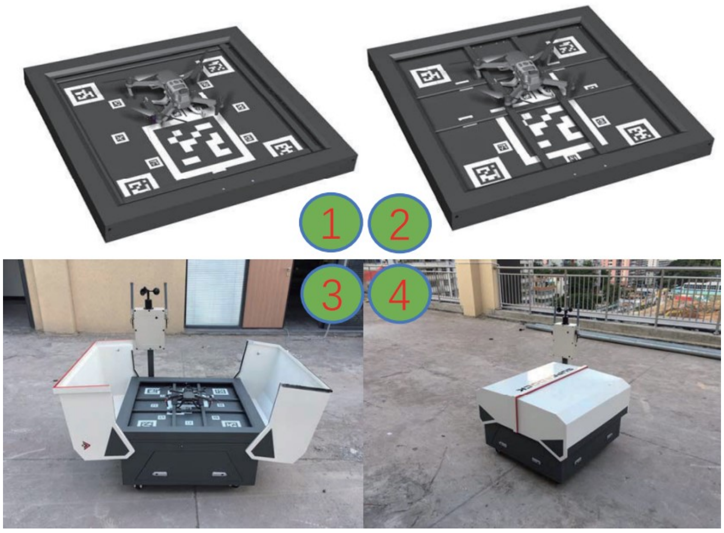

Figure 11. Moving docking station with storage system and battery replacement system [65]. Labels in the figure (1–4) show the order in which the active positioning mechanism and storing mechanism take place.

Extensive work was carried out in [74]. In this paper, simulation results and real test results of an autonomous UGV–UAV system are presented. This docking station solution focuses on Search and Rescue missions. It is fully autonomous; thus, it could be very helpful in such conditions. Simulation results show the ability of the UAV to perform multiple landings and take-offs from the proposed UGV. Figure 12 shows the proposed system.

Figure 12. UGV–UAV proposed moving docking station solution from [74].

In [72], another cooperation between UGV and UAV systems is proposed. The UGV, with a mounted robotic arm, can find and retrieve a UAV. The proposed system is capable of swapping a battery. Figure 13 shows the operation of the described system and Figure 14 shows a detailed view of the custom-made UAV with a replaceable battery.

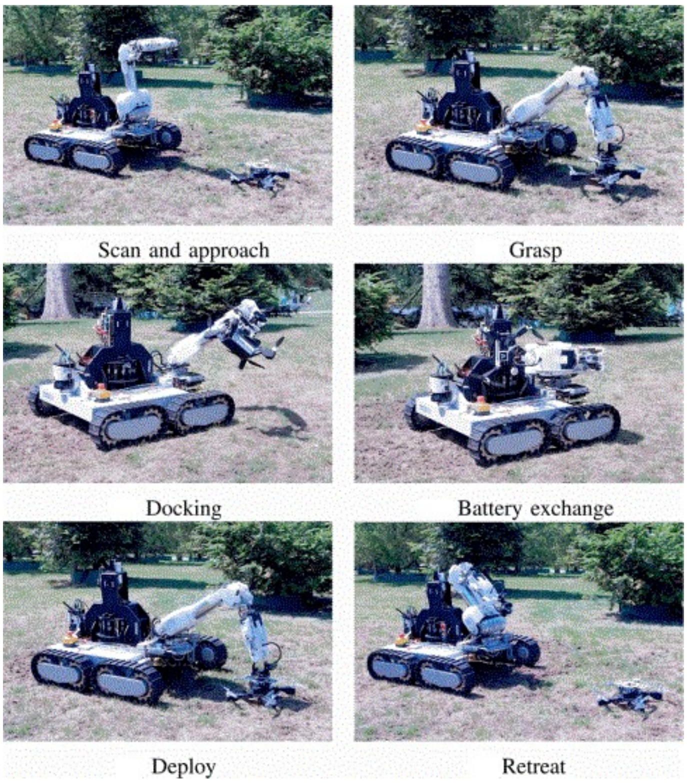

Figure 13. Operation of the proposed UGV–UAV system from [72].

Figure 14. Wasp [72]—custom-made UAV with replaceable battery system. All the stages of battery replacing operation are labeled on the bottom of every sub-figure.

The second group of moving docking station solutions are the USV–UAV systems. The earliest paper found proposes a docking station solution that can be mounted on a moving ship [5]. In the paper, a helicopter was used for testing purposes. The system consists of a helipad that can be tilted to allow the landing pad to be leveled out.

More recently, a custom-made USV was presented in [81]. In the paper, a mathematical approach is presented with the simulation results as well as real test results. Figure 15 shows the proposed USV–UAV cooperation landing system.

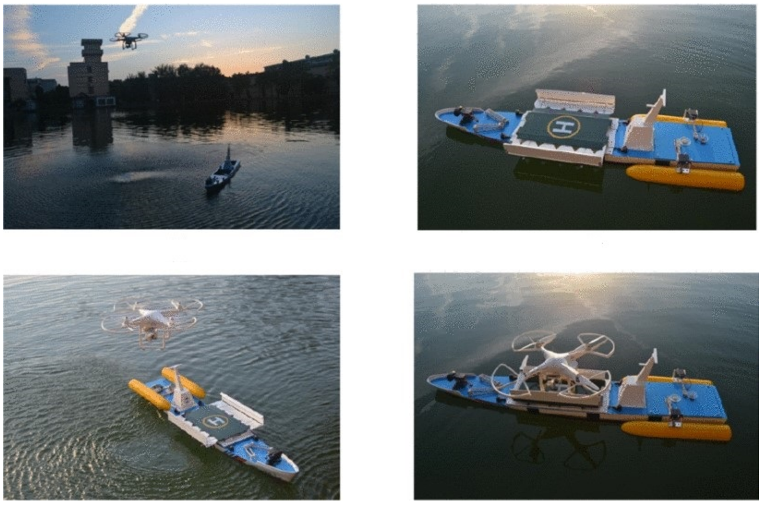

Figure 15. USV–UAV landing system proposed in [81]. The whole landing operation is shown.

The most recent paper published in 2020 [80] proposes a fully autonomous solar-powered USV. In the paper, a conceptual design of such a system is given and a 3D model is presented. It would be mainly used as a UAV recovering system. Figure 16 shows the presented conceptual design of the USV.

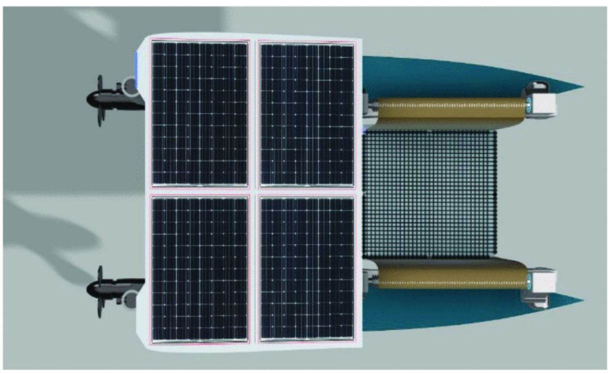

Figure 16. Solar-powered USV for UAV recovery from [80].

In the last few years, solutions for airborne docking stations started to arise. In 2018, a paper was published that proposes a solution for docking a multirotor UAV to another multirotor UAV [75]. Figure 17 shows the concept of such a system.

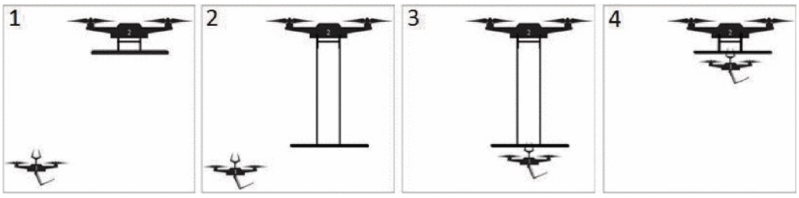

Figure 17. Concept of a multirotor UAV transportation system [75]. The numbered labels (1–4) in the figure show in which order are the individual landing stages happening.

Its primary task is to transport another working multirotor UAV. The docking station consists of a winch mechanism and a bar that can be lowered so the transported UAV can dock. Simulation results of the controllers are given in the paper, and real experiments were conducted. Figure 18 shows the system in operation.

Figure 18. Multirotor UAV docking station [75] in operation. The numbers in the picture show all the different landing stages during a test. The first series of figures (1–4) show the approach and docking of the UAV while the bottom figures (1–4) show the un-docking and the separation process.

A more recent paper [78] proposes an airborne docking station that is mounted on a fixed-wing UAV or airplane. In this system, a custom multirotor UAV with a docking and locking mechanism mounted on is used. It can be used for fully autonomous flights in which the fixed-wing UAV can circle above the operation zone where the multirotor can detach and fly the mission and later dock to the same airborne base. The paper mainly focuses on the docking mechanism, and the tests show the validation of such a system. Figure 19 shows the conceptual design of the proposed docking station system.

Figure 19. Fixed-wing UAV docking station with the multirotor UAV locking system [78]. The figure shows the concept CAD design of the fixed-wing UAV and the multirotor UAV with the docking mechanism monted on.

Figure 20 shows the concept of operation of the proposed system.

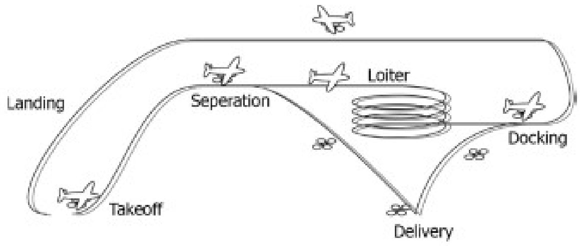

Figure 20. Operation concept of the proposed fixed-wing and multirotor UAV cooperation system from [78].

5. Commercial Docking Stations

A wide variety of commercial docking stations are currently on the market. They range from complete docking stations with custom-made UAVs up to docking stations that are compatible with commercially available UAVs such as DJI drones. These docking stations are widely used for military purposes and security systems, but some can be bought and used in civil applications. Table 1 shows some of the commercially available docking station solutions. It is important to note that the docking station solutions with storage systems are referred to as drone-in-a-box.

Table 1. Commercially available docking station solutions.

Brand Name	Setup	Notes
Airobotics [88]	drone + docking station	Fully automated drone-in-a-box solution
Nightingale security [89]	drone + docking station + AI software	Autonomous threat response (patrol, threat response, manual, AI intrusion detection)
Percepto [90]	drone + docking station	Autonomous drone solution. 4K Camera
Hextronics [91]	battery replacement station	DJI Mavic 2 Zoom/Pro/Enterprise Zoom/Dual/Advanced
Skycharge Skyport [92]	docking station	DJI Mavic and Parrot ANAFI Support
Hive [93]	docking station	Modular in construction to fit various drones
Dronehub [94]	drone + docking station + AI software	Autonomous docking station with storage system. Uses AI software for inspection
Easy Aerial [95]	drone + docking station	Military-grade autonomous drone in a box solution

Table 2 show a detailed overview of the presented commercially available docking station solutions. In the table, a plus sign shows the docking station has the implemented feature available, while a minus sign shows the feature is unavailable. The slash sign indicates that the information is unavailable for the docking station solution. It is worth noting that all the presented docking stations have got a storage system and data exchange feature, so these features are not displayed in Table 2. The last column in the table shows whether the docking station solution uses a custom-made UAV from the same company or other commercially available multirotor UAVs can be used. Table 1 shows which commercially available UAV is compatible with the appropriate docking station.

Table 2. Detailed overview of the selected commercially available docking station solutions with references.

Brand Name	Charging Type	Battery Slots	Swap Time	Payload Exchange	Custom UAV
Airobotics	swap	/	/	+	+
Nightingale security	contact charging	-	-	-	+
Percepto	charging	-	-	-	+
Hextronics	swap	6	2 min		
Skycharge Skyport	contact charging	-	-	-	-
HIVE	swap	6	230 s	-	-
Dronehub	swap	/	2 min	-	+
Easy Aerial	charging	-	-	-	+

6. Discussion

Docking stations come in different designs, and therefore, are suitable for different applications. With respect to the construction and the mobility of a docking station, there are several groups of applications and uses in which docking stations can be put.

Mobile docking stations are capable of extending the range of UAV multirotors; therefore, they are suitable for missions that combine UAV and UGV. Such UGV–UAV systems are commercially available and have certain advantages over the use of fixed docking stations. One of these systems is SHERPA mobile ground base [72]. Mobile docking stations can also be USVs, which are useful and for landing on sea and lakes. USV–UAV systems combine mobile docking stations with vessels operating on the water surface and multirotor UAVs. This kind of system can increase the safety and range of multirotor drones during missions when flying over large water surfaces [80,81].

For fixed docking stations, the main advantage is a more simple design with no need for a transport vehicle. Some of the systems are fixed to the ground, and some are portable. These docking stations can have either active or passive landing systems and different charging and battery exchange methods. A self-leveling docking station with an active landing system using the pneumatic actuators ISLANDS is described in [28]. This kind of docking station is usable in situations where the docking station needs to level its landing surface with respect to the UAV's orientation. This kind of system can be useful on uneven terrain. On the other hand, docking stations that are fixed to the ground can be connected to the electrical network for recharging and operating of a system without the need for batteries. These systems are suitable for use in cities where UAVs can deliver goods and information while avoiding traffic.

Regarding battery recharge and in-air time, docking stations can be divided into battery recharge and battery swap systems. Docking stations with battery exchange are a bit more complex in design but bring the advantage of more airborne time and less time spent not operating. Docking stations with battery charging options must include some kind of electrode for connection and charging. Further, these systems require the precise positioning of the UAV on the landing platform to achieve a battery swap or successful connection to the electrodes. Figure 21 shows different combinations of the properties and possible applications of docking stations regarding the type of charging/battery exchange and precision positioning.

There has been a lot of research in the field of landing algorithms in the past decade, and it makes good sense to continue to improve precision landing using current vision, wireless and other systems. It is more cost-effective to improve results in precision landing using algorithms than physical constructions that are more expensive to design and manufacture. Mobile docking stations in combination with UAVs give more possibility and versatility in mission planning and can extend range, and consequently increase in-air time significantly. With more range, multirotor UAVs have more possibilities of applications. There is still room for the development of docking stations, and possibly networks of landings sites where multirotor UAVs could land, recharge and exchange information and goods.

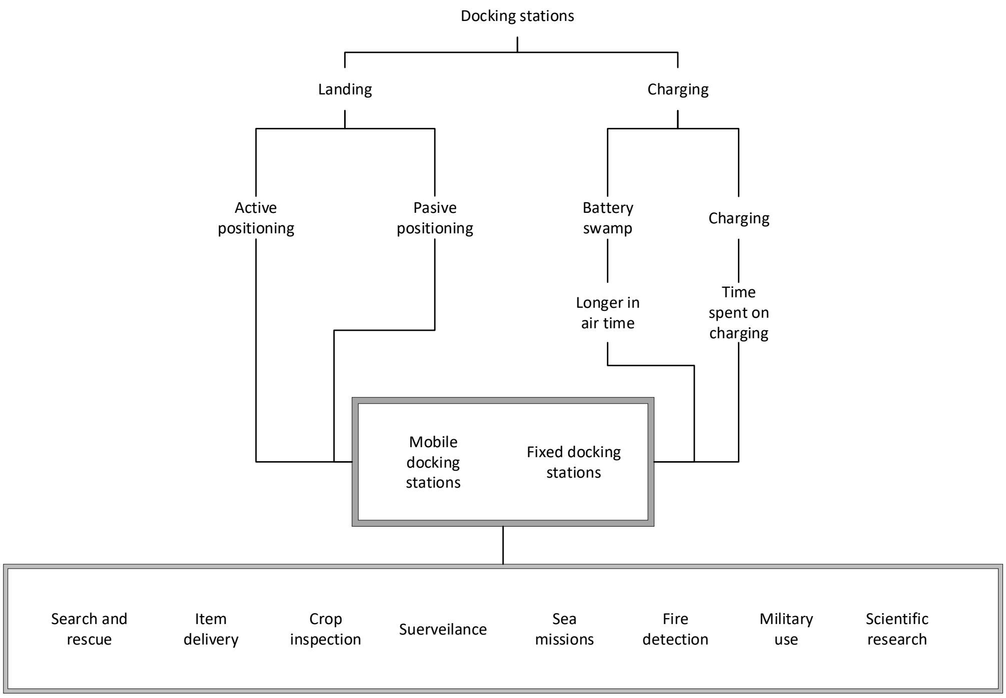

Figure 21. Combinations of properties and possible applications of different docking station systems.

7. Conclusions

As UAVs have been developed in the last decade, more and more scientific papers and patents are being published. The research and development of UAV docking stations are a consequence of fast UAV innovations. Furthermore, the need for a bigger range and more autonomous work time of UAVs resulted in developing systems for precision landing, charging, and/or battery swapping. The application of these systems can be very wide and is already used for the delivery medical samples across big cities and other fields such crop inspection or fire detection and prevention.

In the last 10 years, there has been a lot of research in procedures for precision landing, especially landing algorithms. However, this field of study may be the main direction for research and further development of landing systems.

When a UAV lands on a landing platform, it can be positioned more precisely with active positioning using pushers or other devices or with passive positioning using shapes and gravity. The more precisely a UAV lands using vision and landing algorithms, the fewer pushers and other devices need to work. So, there is a space for the development and research of landing algorithms that would put to better use the power of UAV positioning capabilities rather than relying on mechanical solutions for positioning.

UGVs are suitable for use as moving landing platforms and can be modified in many ways. There is a big potential in developing UGVs as moving docking stations in new ways. It would be interesting to see a moving landing platform that can store multiple UAVs and automatically replace batteries but that also autonomously recharges using solar energy or hybrid propulsion. There is also the possibility of automatic minor repairs of UAVs such as broken propeller replacement or other UAV subsystems. Future docking stations could be equipped with diagnosis systems for UAVs that can, for instance, detect battery health or other subsystems conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
USV	Unmanned Surface Vehicle
VLC	Visual Lights Communication
IMU	Inertial Measurement Unit
WPT	Wireless Power Transfer
GNSS	Global Navigation Satellite System
LED	Light-emitting Diode

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