

Approaching a Resolution of Autonomy-Impeding Charging Infrastructure Tradeoffs for UAVs

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Abstract

The mission scope of a UAV is limited by its airtime. Recharging stations extend that scope, but existing designs tightly couple the station to the UAV’s landing gear, size and weight, so each station suits only a narrow class of UAVs. We present a charging adapter that decouples the charging mechanism from both the UAV and the station design. The adapter serves as a switch between a UAV’s flight circuit and a charging circuit using a spring-loaded mechanism and magnetic pogo-pin contacts. It is built from cheap and widely available parts fitted into a 3D-printable chassis that we hold is easily adaptable to all UAV form factors and dimensions. We realize two prototypes and preliminary test them for a one cell Li-ion battery and a common quadcopter frame. The development of a landing mechanism was out of scope for this work.

1 Introduction

The advance of AI technologies has brought autonomous robots closer than ever, likely permitting their application outside standardized industrial settings. Among robots, UAVs have become or are becoming a key technology in many fields, and their largest bottleneck is effective airtime.

Effective airtime can naively be formulated as

$$T_{\text{eff}} = \frac{C \cdot D_T}{I_{\text{avg}}}, \quad (1)$$

where C denotes the total capacity of the power supply unit (PSU), D_T the discharge threshold and I_{avg} the average current draw. Environmental conditions impact I_{avg} significantly, leading to the well known result that effective airtime can drastically fluctuate spontaneously.

This issue can rarely be solved by changing the PSU type: Li-Po and Li-ion batteries provide high power density and reliability, but limit flight time to roughly 20 to 40 minutes, or even less for small FPV-class drones. Hydrogen fuel cells store more energy, but come with increased size, storage complexities and operating costs. Photovoltaic cells have a low conversion efficiency and require a large surface area. Additionally, they also require sunlight, making them only a partial solution even for fixed-wing UAVs [4]. The PSU choice therefore locks the UAV into an uneasy trade-off: larger capacity typically means larger and heavier PSU, decreasing effective airtime; PSU dimension differences prohibit easily retrofitting a UAV to a different PSU.

Alternatively, UAVs can be recharged during the mission, completing it over multiple flights and PSU charge and discharge cycles. In this scenario, each charging station is the centre of a circle whose radius is the UAV’s effective range. This raises two principal issues. First, the covered area grows only linearly with the number of stations, making station cost important, particularly for large areas and redundant coverage. Second, the charging functionality is split between the UAV and the station, meaning each must be designed under conditions imposed by the other.

We address the second issue. As Section 2 shows, existing stations require specific landing feet, spacing, angles, or induce size and weight limits. At the same time, the stations themselves tend to be large and hard to relocate. Consequently, the charging function dictates the platform design, and fleets mixing UAV types require either a compromise or several different station types.

We present a proof-of-concept adapter that separates the charging mechanism from the landing mechanism. It uses inexpensive, widely available materials, which mitigates the effects of the linear relation between number of stations and costs, as well as practically eliminating maintenance costs. We believe it can serve any UAV form with only minor adaptations in size, though this is a claim difficult to validate in practice.

Section 2 reviews existing approaches, Section 3 states our requirements, Section 4 presents the design, Section 5 evaluates the prototypes, and Section 6 discusses limitations. Section 7 concludes our work.

2 Related Work And Existing Solutions

[4] summarize charging approaches into four groups: the PSU is swapped manually, the PSU is swapped automatically, the PSU is charged through electrical contacts, the PSU is charged wirelessly. Manual swapping removes a UAV’s autonomy and is most time-consuming for humans, making it the least desirable solution in principle. Automated PSU swapping requires a complex system, usually a robotic manipulator. Wireless charging is generally less efficient than contact based charging and requires specific alignment. We focus on contact charging for its efficiency, potentially simple technology and therefore potentially low-cost. Its central challenge is a landing sequence that reliably closes the charging circuit.

Galimov et al. [5] classify landing stations by their positioning mechanism into five groups: stations with no positioning mechanism, stations with active positioning mechanism, stations with passive positioning mechanism, stations with active and passive mechanisms, and stations with a non-standard positioning mechanism. In their patent review from 2020, 8% of stations use no positioning mechanism, 22% an active one, 63% a passive one, and 7% a non-standard one; combined mechanisms were excluded from this distribution. Figure 1 sketches the three main classes.

Stations without positioning mechanism expose contacts that are numerous, large, or both, so that no precise landing is needed. Active mechanisms push the UAV into position via actuators, and passive mechanisms use the UAV’s weight and vertical motion to guide it into position. Because exact details of mechanisms are rarely published, we cannot verify a one-to-one correspondence with recent commercial examples, [1–3], but they exhibit the same issues.

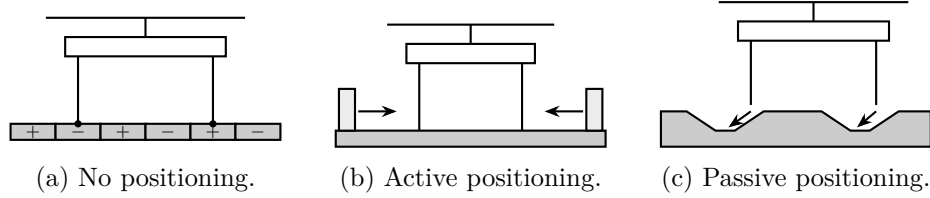


Figure 1: Following [5]: (a) Contacts on the landing site and on the UAV legs, without UAV positioning. (b) Pushers move the UAV into position after landing. (c) Funnels convert the UAV’s vertical motion into horizontal motion

Across all classes, the stations we know of place demands on the UAV such as:

- a given size, or a landing-feet geometry (spacing, angle);
- feet with conductive ends that fix polarity;
- a specific landing sequence, including a vertical approach;
- cameras for computer-vision-guided positioning.

These design decisions establish a key-and-lock relationship between the charging station’s and the UAV’s geometries. As a result, an existing UAV cannot be easily retrofitted to a station it was not designed for, implying cost occurring as a consequence of UAV or station adaptation or replacement. For a mixed fleet, either all UAVs have to be restricted to work with one specific station, or multiple stations have to be used, again incurring downstream costs and limitations.

3 Requirements

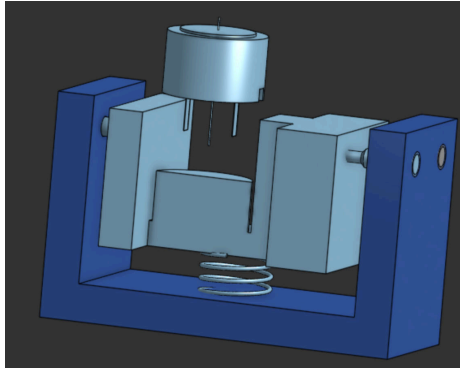
While the key-lock relationship cannot be removed in principle, it can be made more or less restrictive in practice. Based on our observations of existing systems, we derive the following requirements for our design:

- R1. Low coupling.** The mechanism can be added to a UAV or a station without major changes to either design.
- R2. Low cost.** It uses parts that are cheap, widely available, and mostly 3D-printable.
- R3. Low drone-side burden.** The mechanism does not change UAV properties, especially weight, significantly.
- R4. Minimal assembly.** It requires only a minimal number of manual assembly and processing steps, e.g. gluing or soldering.

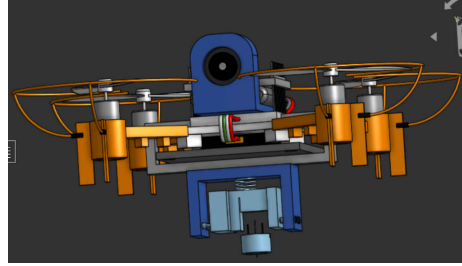
R5. Easy manual processing. Wherever it requires manual processing, e.g., gluing or soldering, it is easy to do.

At their core, all of our requirements follow the principle of minimalism, and therefore try to make explicit the general approach of demanding as little as possible of the UAV and the station alike.

4 Adapter Design



(a) Onshape Mechanism Assembly



(b) Mechanism under UAV.

Figure 2: Virtual mechanism representation.

4.1 Concept

The adapter consists of two parts: a drone-side interface (Fig. 2) and a station-side interface. Functionally, it consists of two circuits and a switch between them (see Fig. 3).

'Flight mode' denotes the state in which the circuit between the flight controller and the PSU is closed. 'Charge mode' denotes the state in which the circuit between the PSU and the charger is closed. The modes are separated, as only one circuit is closed at a given time (see Fig. 3) The PSU remains connected to the drone-side interface in both modes. The switch disconnects either the flight controller (FC) or the charger.

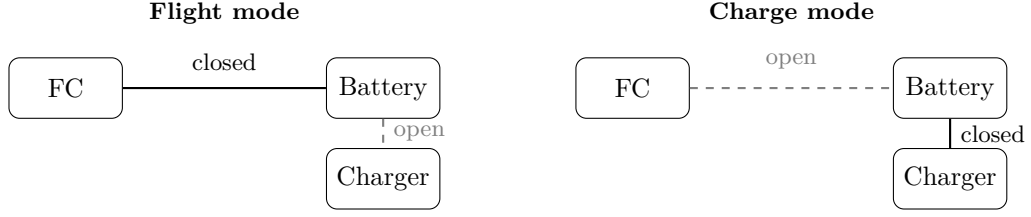


Figure 3: The two circuits.

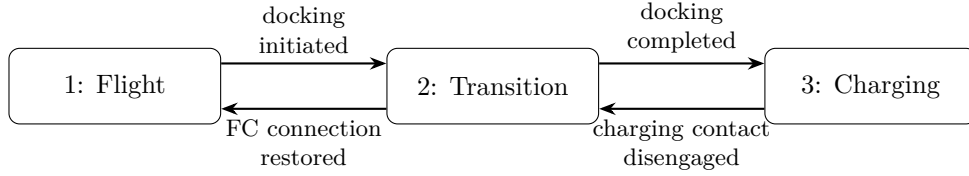


Figure 4: The adapter's three states and their transitions.

4.2 Mechanism

We implement the charging circuit with a magnetic pogo-pin connection. The male pin belongs to the drone-side interface, and the female pin to the station-side interface. This order can be switched and is not crucial to the concept. The magnets help to align the pins and keep the contact stable after it was made.

The switch is realized as a spring-loaded carriage in the drone-side interface. In flight mode, the FC to PSU connection is closed via a polarity plate. When the male-female pogo pin connection is made, the relative motion displaces the carriage by either compressing or stretching the spring. This displacement removes the pogo pin that connects to the negative polarity plate and the FC from the polarity plate, thereby opening the FC–PSU circuit. The male-female connection closes the PSU–charger circuit.

At the charging station, a sensor continuously measures the charging circuit's current. A microcontroller interprets a current above a certain threshold as the signal that charging began, and a drop below that same threshold for more three consecutive seconds as the signal that charging is nearing completion. This follows the constant-current/constant-voltage (CC/CV) protocol for Li-ion batteries. In our implementation, the threshold was set to 400mA.

The microcontroller activates two bistable solenoids that push away

the spring-loaded carriage, breaking the magnetic pogo pin connection and therefore opening the PSU–charger circuit. Moreover, the spring changes back into its original state, reconnecting the FC pogo pin–polarity plate connection and thus closing the FC–PSU circuit.

5 Results

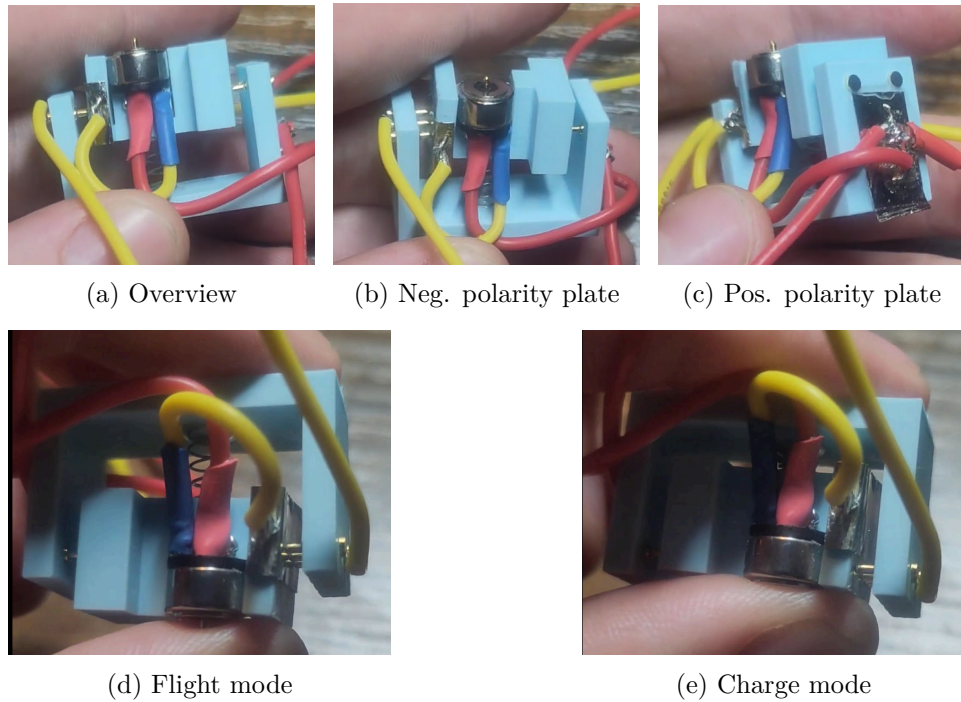


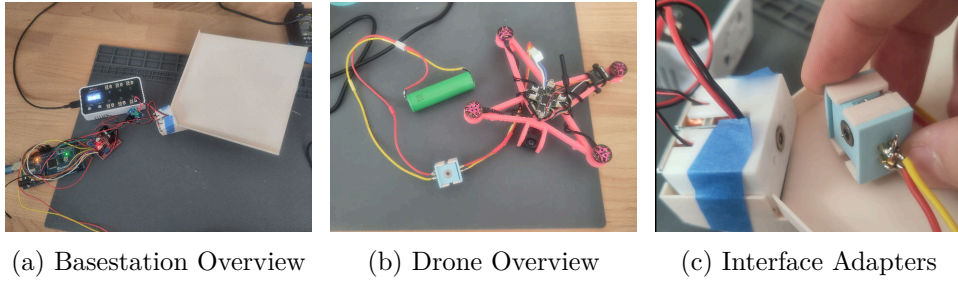
Figure 5: The minimal mechanism.

5.1 Setup

We implemented two mechanisms of the concept. The minimal mechanism (Fig. 5) consists only of a 3D-printed housing, a 3D-printed spring-loaded carriage, two polarity plates, and six pogo pins. The enclosed mechanism (Fig. 7) is designed to expose internals less.

Both mechanisms were tested under controlled conditions. Docking was triggered manually, with either the mechanism in isolation, or attached to the side or bottom of a typical quadcopter. To attach the mechanism, the FC to battery wire connection was rerouted through the polarity plates, and

the 3D printed chassis was either glued to the side of one leg or strapped beneath the UAV with a rubber band.



The station side consisted of an Arduino UNO Q microcontroller with an INA219 current sensor, two 12 V bistable solenoids for the release, and a commercial 1S charger; the battery was a 18650 Li-ion cell (3500 mAh). The full cycle of docking, charging, and current based release was run. To additionally test the stability of the mechanisms, release was initiated after 30 seconds of charging, rather than based on current. The drone side adapter then rested on the solenoid plungers, which reversed after 5 seconds to close the charging circuit. This models repeated docking and release processes and was repeated more than 10 times.

Success was judged to mean that no faults occurred, the mechanism worked without interference (except for the initial docking), the battery was charged without damage being incurred on the mechanism, e.g. through heat, and all three states were reached as intended.

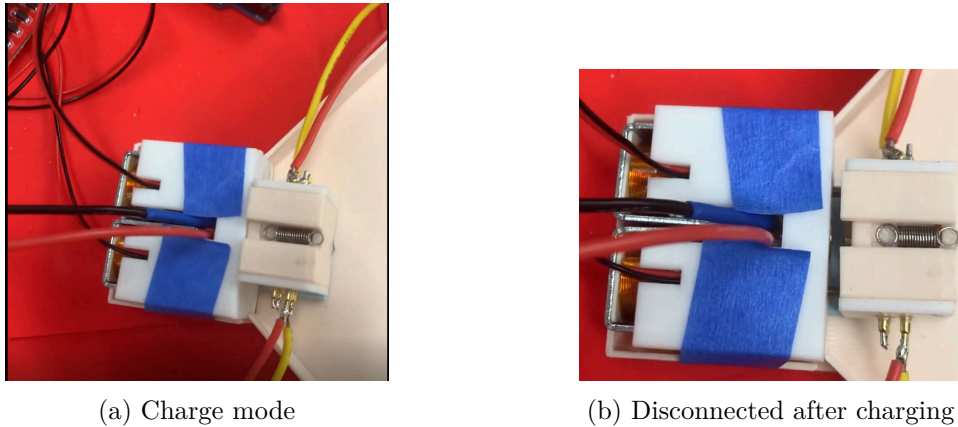


Figure 7: The enclosed mechanism.

5.2 Functional results

Both mechanisms work under the definition of success. Specifically,

- all three states (flight, transition, charging) could be reached reliably;
- transitions occurred without short circuits in the final versions of both mechanisms;
- transitions occurred reliably over more than ten consecutive repetitions.

The number of repetitions is small, but it indicates that the mechanism is robust if in a good initial state. Experiments regarding crooked positioning as a result of in-flight forces were not performed, and the general reliability can therefore not be estimated.

One short circuit occurred in an earlier iteration of the enclosed mechanism. Presumably, glue had leaked into the side plates and prevented the mechanism from moving correctly. Since the mechanism was sealed, we could not confirm this cause.

Table 1 summarizes how the mechanisms fare against requirements R1–R5. The minimal mechanism fulfils all five, the enclosed one the first three. The costs are estimates, as many required items were part of larger packages of items, without a detailed cost breakdown provided. Moreover, some material was already available, e.g. cables and PLA.

Table 1: Requirements fulfilled by the two mechanisms.

	Requirement	Minimal	Enclosed
R1	Low coupling	Yes	Yes
R2	Low cost	≈ 8 Eur.	≈ 12 Eur.
R3	Low drone-side burden	< 5 gr.	< 5 gr.
R4	Minimal assembly	< 30 minutes	> 60 minutes
R5	Easy manual processing	Mostly	Somewhat

The largest cost factor were two pairs of solenoids and the microcontroller used. We decided for these purchases to allow ourselves to focus on the mechanism, rather than the base station, which can be implemented more cost effectively. For example, simple solenoids, rather than bistable ones, could be used.

5.3 Observations on fragility and assembly

Because of the materials used and the minimal design, both mechanisms were relatively fragile to concentrated force applications. In the final iteration of the minimal mechanism, nickel strips served as polarity plates. They are difficult to grind down, which made it difficult for the FC connecting pogo pin to slide off and back onto the plate. Earlier iterations with a thin copper sheet connected and disconnected smoothly without any downsides being observed. The carriage is stabilized by pogo pins on both sides that carry no other function. This gave a surprising amount of stability against forces from the open sides. For iterations using copper plates, this appeared sufficient for reliable operation in our trials.

Assembling either mechanism required some dexterity, mostly because of the low-viscosity glue. Soldering and arranging the wires was easy with pliers for holding and bending. Tolerances are tight but not unforgiving. The supporting structure could be designed to guide the assembly further, reducing and simplifying the effort.

6 Discussion

Our design goal was that any UAV could be equipped with the adapter without major redesign. In practice this claim hinges on two factors:

1. the adapter’s 3-D printed chassis can be easily made to match the geometry of the host airframe, either via changes to the dimensions or an extension of the supporting structure.
2. the charging gear is suitable for the involved PSU.

We have shown successful integration for a typical quadcopter frame in a controlled environment. Future work should include testing on a variety of UAV types, forms and dimensions.

All experiments were performed under controlled, manual docking. Investigation into which landing mechanisms the charging mechanisms can be integrated is required. To completely solve the initially laid out problem, a landing mechanism needs to be designed to ideally follow the same constraints of being cheap, easy to assemble and largely 3-D printable.

7 Conclusion

We presented a low-cost, low-coupling adapter that separates the charging mechanism from the landing mechanism of a UAV. While the current work validates the concept under controlled conditions, real world tests are lacking. In principle, without the design of a corresponding landing mechanism, the overall goal of resolving UAV charging station trade-offs is only half solved.

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