Deployable Origami Coils for Wireless UAV in-Flight Powering

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***Abstract*— The work presented in this paper demonstrates, for the first time, the combination of Origami-based solutions with wireless power transfer for the wireless charging of UAVs. The proposed lightweight, compact, yet large aperture structure is capable of delivering high efficiency power transfer links at relatively long ranges. The design features an Origami Starshade-inspired $28\,\mathrm{MHz}$ coil design fabricated on a sheet of paper using copper tape. The coil can be folded yielding at least 85% area reduction compared to its unfolded counterpart. This compactness allows the UAV to fly freely carrying a large yet compact and lightweight coil. For charging purposes, the receiving coil unfolds to match the size of the transmitting coil, enabling the delivery of high output voltages, potentially capable of charging a UAV. The proposed system was fabricated and measured, and its performance was assessed as a function of varying separation distances, folding configurations, and misalignment scenarios, demonstrating the validity of the concept.**

***Keywords*— Origami, wireless power transfer, UAV, energy harvesting, resonant inductive coupling.**

I. INTRODUCTION

Many systems such as agriculture and package delivery have found uses for aerial drones—or Unmanned Aerial Vehicles (UAVs). UAVs, however, are severely limited by short flight times of 20-40 minutes, restricting their practical application to marginal uses in these burgeoning fields [1]. To fix this, several approaches can be taken to mitigate short flight times. Firstly, the battery capacity could be heightened, however, this leads to heavier batteries and therefore decreased payload. Another solution is to implement base stations that switch spent batteries with charged batteries, however, this requires mechanical systems that can be costly and complicated [2]. Finally, UAV batteries could be recharged during intermittent ground stops or—thereby enabling their uninterrupted operation—mid-flight. This last and particularly enticing option either requires the precise and perilous attachment of the recharging (a.k.a refueling) aircraft to the receiver UAV or the employment of an efficient wireless power transfer (WPT) system. Recent advances in autonomous electronic devices (cell phones, robotics, etc.) have democratized WPT technologies–notably in its use for the charging of portable devices. While its application to the charging of UAVs has been the product of much research [3], [4], WPT solutions in air still fall short, riddled with efficiency issues and low power transfer capacity. One of the main fundamental challenges to these systems is the inherent opposition between the optimal geometries called for by electromagnetics, on the one hand, and by aerospace science, on the other: coils achieve greater charging ranges (and, therefore, larger standoffs between the UAV and the recharging aircraft) with larger footprints, while aerospace systems require lightweight, compact form factors for optimal energy efficiency. This, then, begs the question: Can we design a solution that offers the best of both worlds? Origami, or the ancient Japanese art of paper folding, significant in its ability to reconfigure planar sheets into deployable structures, has recently risen to prominence by solving several problems in science and technology [5]. Origami techniques also have the potential to provide elegant solutions to wireless power transfer in air and space, but origami for wireless systems has been largely unexplored. By investigating the properties of foldable wireless systems, lightweight, deployable, and low-cost aerospace WPT technologies can become a reality, and form a stepping stone towards the advent of uninterrupted UAV operation.

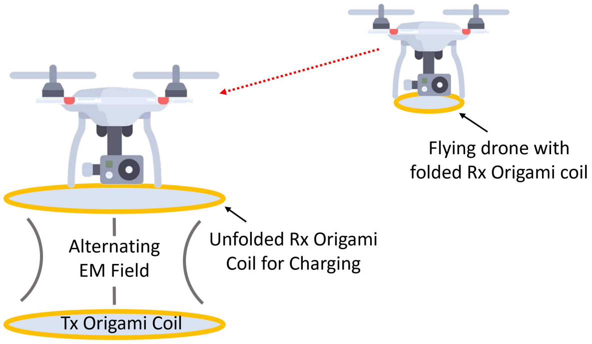
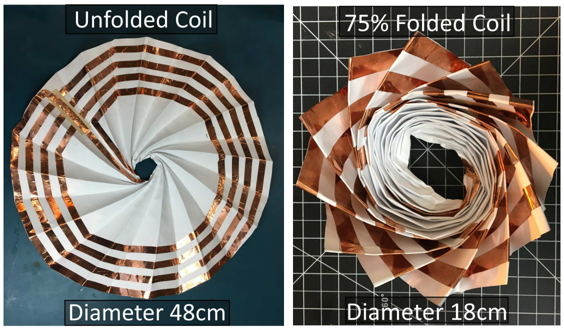


Fig. 1. Origami-based WPT system for UAV charging.

In this work, and for the first time, we combine the art of Origami foldable structures with wireless power transfer techniques to enable a lightweight, scalable, and efficient wireless charging solution, potentially capable of charging a UAV in-air at relatively long distances. The concept is described in Fig. 1 where a UAV flies carrying a folded compact Origami coil, then unfolds this coil for wireless charging when positioned on top of a charging station with another transmitter coil. The coils presented in this work are fabricated on paper substrate using copper tape, and folded following the Starshade model, delivering optimal compactness. This solution overcomes the drag potential accompanied with fixed large aperture coils and delivers an elegant, compact and, efficient wireless power transfer solution for UAV powering.



(a) (b)

Fig. 2. Fabricated coil with copper tape on paper: (a) Fully-unfolded with 48 cm diameter, (b) 75% folded with 18 cm yielding more than 85% area reduction.

II. COMPONENTS OF THE WPT SYSTEM

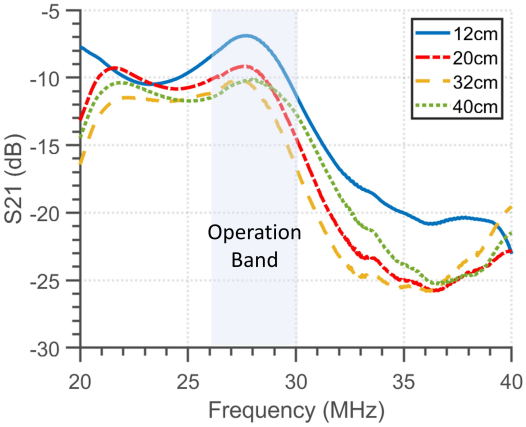
A. *Origami Coil on Paper*

The architecture of the coil is at the core of the design of a near-field wireless power transfer system. Researchers have studied the impact of coil size, shapes, and ratios on the transfer efficiency, and robustness to separation distance and displacement [6], [7], and concluded that misalignment and larger distances can result in a rapid loss of efficiency [8]. While a wide range of solutions have been proposed to improve the wireless power transfer efficiency [9], the design of a deformable, deployable coil remains largely unexplored. By making the coil on the UAV deployable, the coil can be much larger, allowing for higher power transfer efficiencies at longer ranges, and higher displacement tolerances.

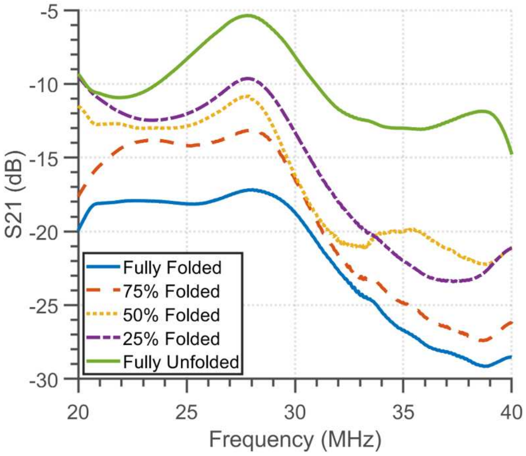
Origami presents an elegant solution for deployable structures, with the Jet Propulsion Laboratory's Starshade design being one notable example [10]. The origami structure designed in this work is inspired by the Starshade design. As seen in Fig. 2, it starts with a flat, circular sheet of paper with a diameter of 48 cm that can collapse into a much smaller shape with a diameter of 18 cm, resulting in more than 85% area reduction. To enable wireless power transfer, the coils were created by placing copper tape on the sheet. The geometry of the coil was determined by the modified Wheeler equations for planar spiral inductors [11]. These equations are used to calculate the inductance of the coil using parameters such as the inner and outer diameters of the coil, the number of turns and gaps between them, and the turn width. The proposed coil parameters are shown in Table 1. Since the coil can be modeled as an LC circuit, a capacitor can be added in parallel to tune the resonant frequency, which, for these coils, is around 28 MHz. Fig. 2 shows the final coil design fully unfolded (left), and 75% folded (right).

Table 1. PROPOSED COIL PARAMETERS

Number of Turns	Outer Diameter	Inner Diameter	Turn Width	Gap between Turns
4	48 cm	30 cm	1.3 cm	1.3 cm



(a)



(b)

Fig. 3. Measured coils S21 performance: (a) Measured S21 of the two fully-unfolded coils vs frequency for varying separation distances, highlighting the coil's operation band around 28 MHz, (b) Measured S21 of the two coils vs frequency at a distance of 5 cm for varying receiving coil folding configurations.

The transmission efficiency between the two coils was then assessed by looking at the transmission coefficient S21.

Fig. 3a plots the measured S21 performance of the fully unfolded coils with respect to frequency and at varying separation distances. The peak transmission appears within the expected band around 28 MHz with a recorded S21 of -7 dB at 12 cm. What is important to highlight here is that the S21 drops only by 3 dB at more than 3x the starting distance, which emphasizes the robustness of this coil to increasing distances, and its suitability for UAV applications where the TX to RX distance could be difficult to maintain, like in an in-flight UAV charging context.

The impact of folding on the S21 performance was also assessed. The transmitting coil was kept unfolded at 5 cm away from the receiving coil that was folded over five stages from 0% to 100%. Fig. 3b shows that the transmitted powers drop by at least 10 dB for extreme folding scenarios. This is

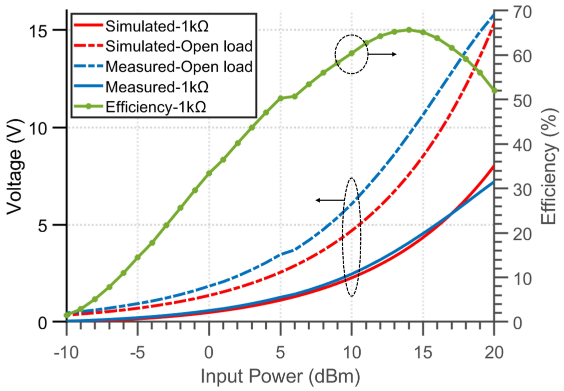


Fig. 4. Simulated and measured voltages and efficiency results vs input power for 1 kΩ and open loads.

mainly due to the reduction of the mutual inductance—and thus their mutual coupling—following the folding.

B. Voltage Doubler Rectifier Circuit

A key characteristic of the rectifier desired for the proposed WPT system is its ability to handle typical testing input powers and deliver easily measurable output DC voltages. In order to achieve this desired performance, we choose to design a voltage doubler rectifier circuit using the SMS3922 Schottky diode. The design consists of two diodes placed in a voltage doubler configuration, in addition to a simple LC matching network to match the input impedance of the diode to that of the receiving coil. The simulated and measured DC voltages at 1 kΩ and open loads, in addition to the measured efficiency, are shown in Fig. 4. The rectifier is capable of reaching voltages above 15 V at an input power of 20 dBm with a peak efficiency of 68% at 14 dBm. It should be noted that while the design presented in this work is minimalistic, the literature presents a myriad of solutions to improve the output voltage and power handling of such systems, in addition to more advanced reconfigurable matching networks [12] to adapt to any variations in the input impedance of the coil due to misalignment, changing distance, or even (in our case) folding status.

III. WIRELESS CHARGING WITH ORIGAMI COILS

After finalizing the coil and rectifier designs, the system was ready for the wireless power transfer test shown in Fig. 5. To do so, we placed the transmitting coil on a table and connected it to an RF signal generator, via an amplifier to deliver high enough power. The maximum transmitted power in this work was 20 dBm and all the voltages were measured at an open load. Facing the transmitting coil, we suspended the receiver coil connected to the rectifier at a distance of 50 cm.

A. Impact of Separation Distance

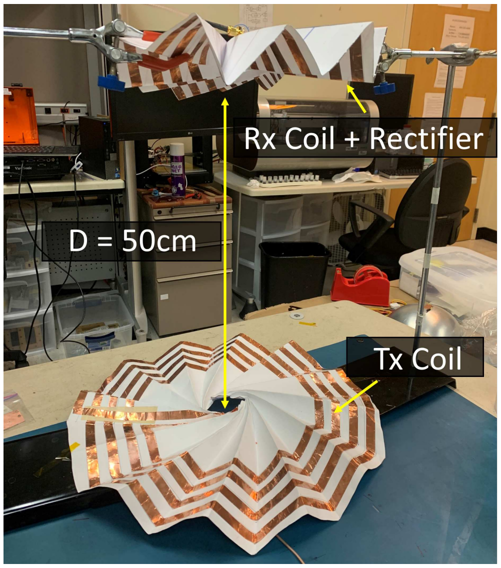


Fig. 5. Wireless power transfer setup with TX coil, and RX coil connected to a rectifier with a separation distance of 50 cm.

For our first evaluation, we looked at the output DC voltages at varying distances and with different folding architectures. In this test, the TX coil was always kept unfolded while the RX coil was being folded up to 75%. The experiment results, presented in Fig. 6, show that while the folded structures outperform the unfolded at shorter ranges, the fully-unfolded Rx coil achieves significantly higher output voltages at longer ranges, demonstrating the advantages of large aperture coils for long range wireless power transfer. Here it is important to note that this experiment was performed at three distances only: 10 cm, 20 cm, and 50 cm. Therefore, the displayed shape is an interpolation of the data and does not necessarily reflect the exact values at all distances.

B. Impact of Coils Misalignment

The second evaluation looked into the impact of TX-RX center-to-center (C2C) misalignment on the measured output voltages at 50 cm. In this test, the receiver coil was slightly moved horizontally away from the transmitter coil, creating a displacement similar to that with a UAV not landing in the correct spot for charging. The experiment compares the unfolded and the 75% folded Rx coils for zero, 6 cm, and 20 cm misalignments. The measured results, shown in Fig. 7, display an expected drop in output voltage with a higher displacement. However, it is interesting to note that the folded structure shows a less severe drop. This is due to two reasons: 1) the starting voltage is already low, 2) since it is very compact, the folded structure almost fully remains within the electromagnetic field of the TX coil even at large displacements. This effect could be easily mitigated through the use of a TX with larger dimensions than its folding RX counterpart.

IV. CONCLUSION

This work offers a stepping stone for efficient, lightweight, and compact wireless charging solutions for flying UAVs.

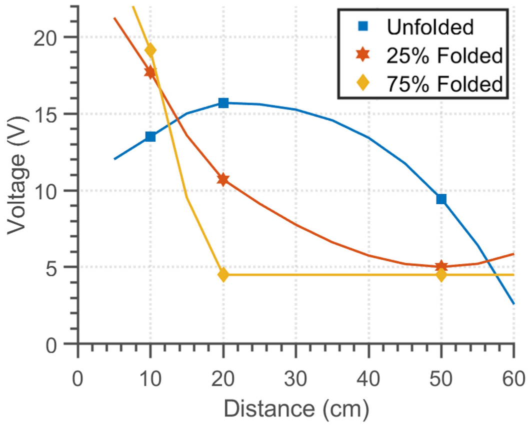


Fig. 6. Measured open load DC voltages at the receiver coil with different folding conditions for a transmitted power of 20 dBm and for varying distances in a fully-aligned configuration.

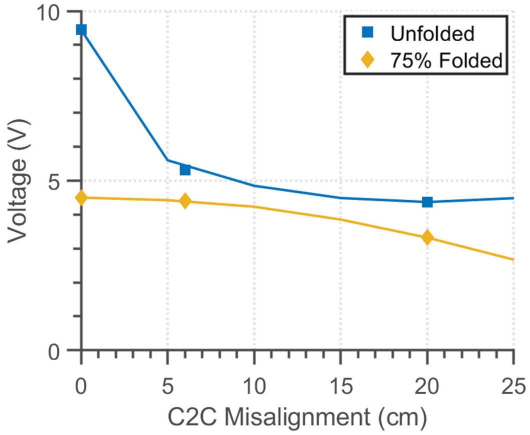


Fig. 7. Measured open load DC voltages at the receiver coil with different folding conditions for a transmitted power of 20 dBm and for varying TX-RX center-to-center (C2C) misalignment distances and 50 cm vertical coil-to-coil distance.

Inspired by the Starshade design, large Origami coils can be easily folded and carried by a flying UAV, before being deployed, using one of several mechanisms [13], when placed in the vicinity of a recharging aircraft to receive power and recharge the battery.

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