Biased Electropermanent Magnetic Docking Design for Neutral Buoyancy UAV Deployment

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This paper introduces a novel approach to enhance the docking mechanism of sensor packages deployed on bridges using unmanned aerial vehicles (UAVs). The current electropermanent magnet (EPM) system faces challenges in achieving efficient and stable docking due to factors such as airflow, GPS stabilization, and the time required for EPM activation. To address these issues, a biased EPM design is proposed, utilizing additional permanent magnets to achieve neutral buoyancy during UAV deployment. This design optimally balances the weight of the drone and sensor package, providing advantages such as improved stability against external factors and reduced pilot fatigue. Experimental results demonstrate the feasibility of the proposed design, indicating enhanced hold force and an extended range for efficient docking.

I. Nomenclature

UAV = uncrewed aerial vehicle
EPM = electropermanent magnet
FEMM = finite element method magnetics

II. Introduction

The advancement of uncrewed aerial vehicle (UAV) technology has opened new possibilities for monitoring the structural health of bridges. One innovative approach involves the deployment of sensor packages onto bridges using UAV drones. These sensor packages, equipped with a magnetic attachment mechanism that can be conveniently turned on and off, also known as an electropermanent magnet (EPM), provide a flexible and non-intrusive solution for gathering critical data on bridge conditions. The sensor packages on bridges are typically fitted with accelerometers to study the effects on the bridge or an ultrasonic sensor to measure water height if the bridge crosses a river or stream [1]. Solar panels and wireless communication subsystems have also been developed to extend package lifetime [2]. By combining UAVs with an array of deployable sensors, this technology offers an efficient and cost-effective means of bridge inspection, enabling timely maintenance and ensuring the safety and longevity of these infrastructure assets.

The action of docking sensor packages to steel structures is a somewhat arduous task, complicated by several factors including the interaction of airflow with the structure (ceiling effect), challenges using GPS stabilization around large steel structures, and a pilot's line-of-sight with the UAV [3]. Furthermore, the activation of the EPM from an off state to an on state can take approximately three seconds and must be in contact with the metal structure to activate; thereby requiring the UAV pilot to maintain the UAV in a stationary location for at least three seconds [4]. To increase the deployability of the sensor and reduce pilot fatigue during sensor deployments, this work proposes the

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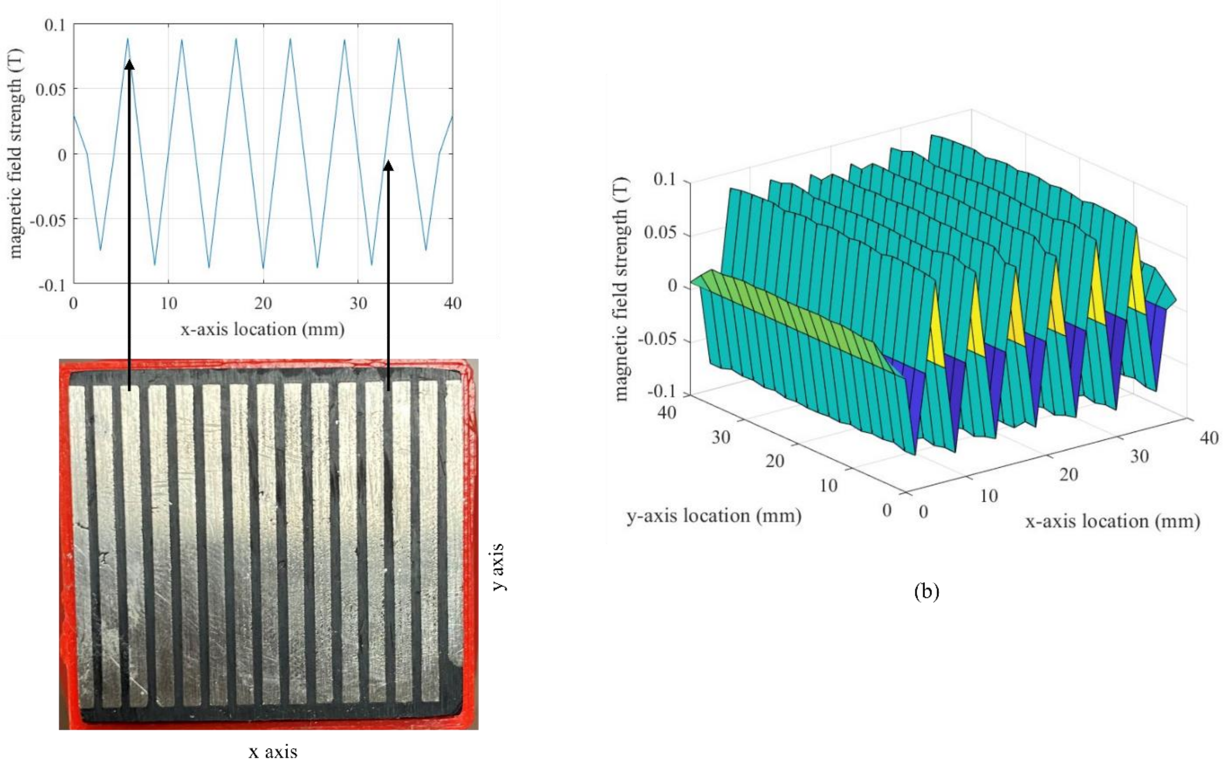
development of an EPM biased with extra permanent magnets to lightly attach the UAV and sensor package to the structure during the three seconds that the EPM requires to engage. By carefully calibrating the magnetic force, the system can achieve neutral buoyancy, effectively counterbalancing the weight of the drone and the attached sensor package with the permanent magnetic force bias of the docking mechanism. Achieving neutral buoyancy through the magnetic docking system offers multiple practical advantages. The neutrally buoyant system minimizes the impact of external factors such as wind gusts or vibrations, further enhancing the overall stability of the drone during the inspection or monitoring tasks [5]. Stability is also needed in case the drone must remain attached to the package to transfer data, which could take several minutes depending on file sizes and transfer rates [1].

III. Current Sensor Package Docking Mechanism

The current sensor packages are fitted with a singular EPM (Nicadrone.com) with face dimensions of 40 × 40 mm and a weight of 108 g when placed in the 3-D printed housing. The device requires a 5 V power supply and is controlled by a standard PWM input to turn the magnetism on and off. The weight of the delivery UAV is estimated to be 11 kg. To further understand and characterize the EPM, tests were performed to examine the field strength at the face of the magnet and the relationship between force and distance to a metal target. The face of the EPM can be seen in Fig. 1 (a). The device utilizes NIB magnets, Alnico magnets, and copper wire to magnetize 15 iron pole pieces approximately 1.75 mm wide with 1 mm of separation in between each [6]. Each consecutive bar is magnetized antiparallel to the last, with the polarization axis going into and out of the page. The magnetic field lines stay contained close to the surface of the EPM due to this geometry. The field strength at the surface of the EPM was manually mapped using a DC gaussmeter and can be seen in Fig 1.



(a)

(b)

Fig. 1: EPM face showing: (a) the field strength measured at the surface across the x-axis (probe placed in the center of the y-axis), and (b) field strength mapped across the entire surface of the EPM.

The strength drops to 0 Tesla in between the magnetized bars, which is expected due to the flipping of the magnetization vector at every iron pole. The max strength reached about 0.09 T as shown. The EPM was simulated using Finite Element Method Magnetics (FEMM) to gain a better understanding of the field lines, and the results are shown in Fig. 2 [7].

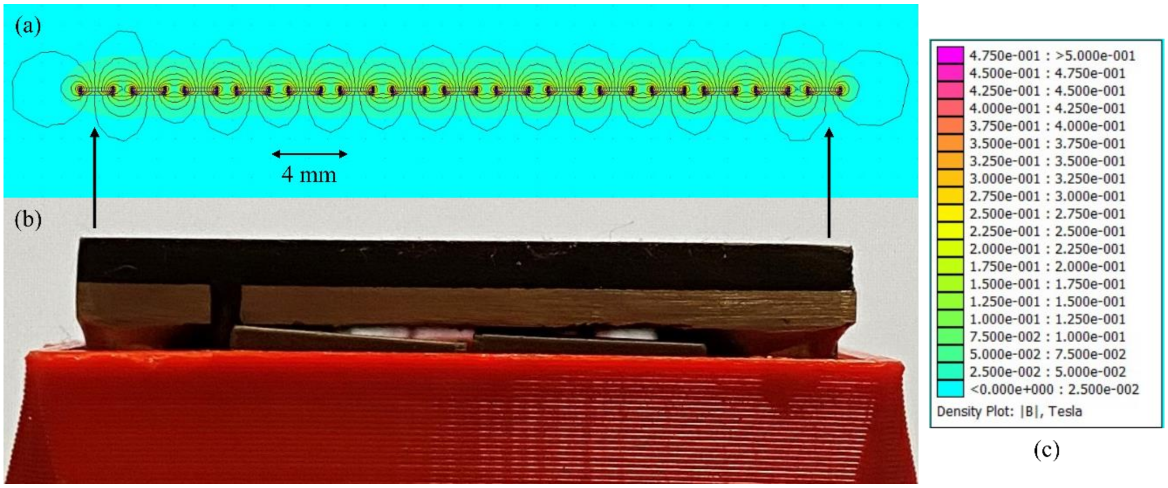


Fig. 2: Simulation of the magnetic field generated by the EPM, showing: (a) FEMM simulation results; (b) side view of the surface of the EPM, which is held in a 3-D printed housing, and; (c) Flux density of the simulated field in T.

The results of the simulation can be used to predict the range at which the magnet will begin to exert a force on another ferromagnetic object, which it shows is about 3 mm in this case. To verify the prediction, an experimental setup was created to test the force the EPM exerts on a block of 1018 steel at varying distances. A three-axis gantry was used to mount a displacement sensor, load cell, and EPM above the piece of steel. This setup allows the arm's vertical height to be precisely moved and held in place when needed. This device, along with the force vs distance curve produced when the EPM is turned on, is shown in Fig. 3.

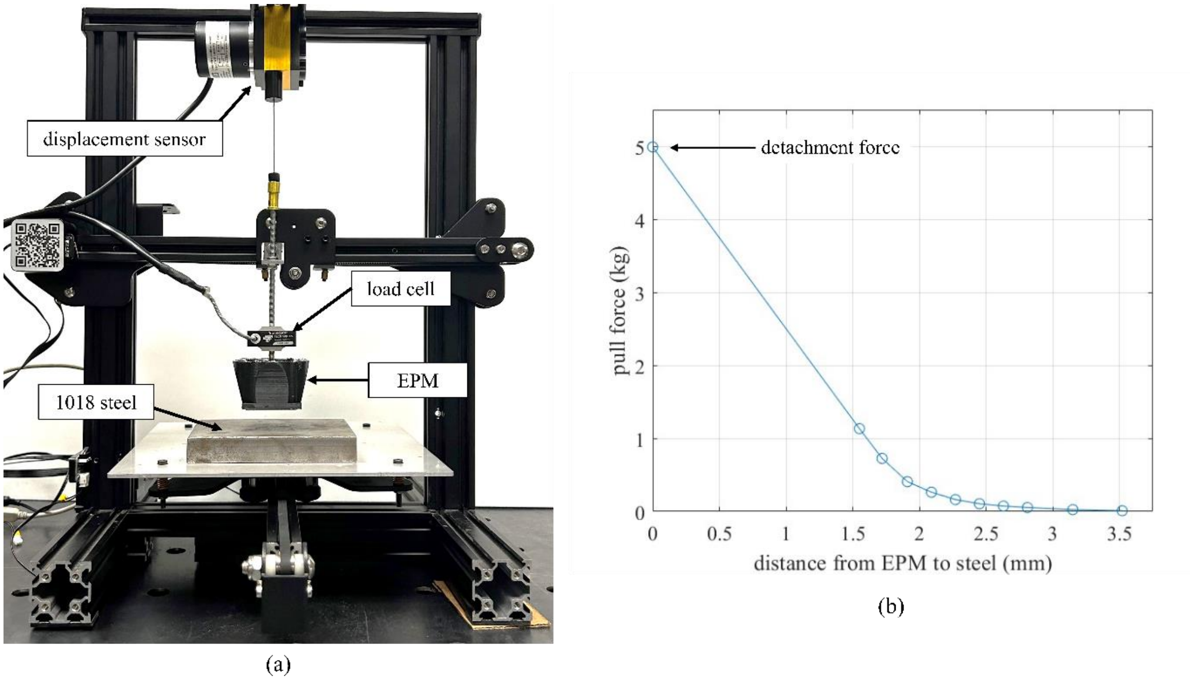


Fig. 3: Measurement of magnetic pull strength, showing: (a) three-dimension gantry setup used for testing, and; (b) pull force measured vs distance.

The detachment force of the EPM, shown as the force at 0 mm, is the force required for the magnet to break free from the steel after being fully attached. As shown in the curve, the distance at which noticeable force is measured by the load cell begins at around 3.5 mm and rises as the magnet gets closer to the block. The detachment force could also be thought of as the maximum holding force of the EPM, and in this case, it is far from being able to hold the weight of the UAV.

IV. Proposed Design to Provide Neutral Buoyancy

To reliably hold the weight of the drone and to help provide an easier docking method, the EPM can be optimized by adding extra permanent magnet blocks in line with the iron poles. Two 2.9 g, NdFeB, Grade N42 permanent magnet blocks 40 mm long, 6.35 mm wide, and 1.6 mm thick were selected to be placed on both sides of the EPM. The 3-D printed housing for the EPM was modified to allow for the addition of these blocks and to ensure smooth testing with the current setup. The added force from the extra permanent magnets will allow the weight of the drone to be balanced when the EPM is turned off, but it will not be so strong that the package is difficult to remove. It will also extend the distance of the pull force from the sensor package to a structure, making attaching the packages to structures with a UAV significantly easier. The prototype EPM housing with the added magnets is shown in Fig. 4, along with a simulation in FEMM of the added magnets (with the EPM off), and the results of testing the force vs distance in the same manner as before.

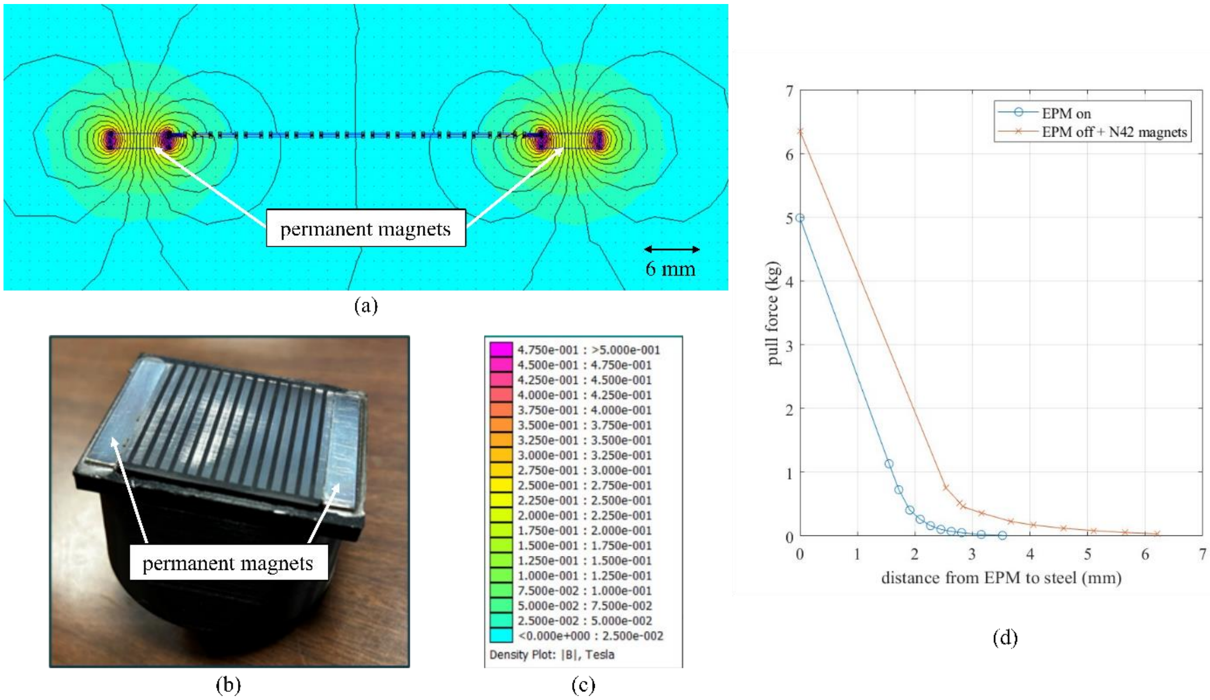


Fig. 4: Prototype results, showing: (a) FEMM simulation of the EPM with permanent magnets added to the sides and the EPM turned off; (b) modified EPM showing the placement of the N42 magnet blocks; (c) flux density of the simulated field in T, and (d) force vs distance curves for the EPM by itself and the EPM with added permanent magnets but in its off state.

Results of the modified EPM show that when the EPM is turned off, the permanent magnets will begin exerting a noticeable force on an object at an increased distance of about 6 mm, and the detachment force in this case is about 6.4 kg. This implies that when combined with the EPM in its own state, the total hold force of the docking mechanism should be just above 11 kg, which is approximately what is needed to obtain neutral buoyancy with the drone. The height of the permanent magnets can be adjusted if needed to tune the force.

V. Conclusion

This paper addresses the complexities associated with deploying sensor packages on bridges using UAVs with an EPM docking system. The current EPM design's limitations in holding force prompted the development of a novel approach to enhance its performance. The proposed biased EPM design, augmented with additional permanent magnets, demonstrates significant improvements in hold force and range, making it capable of achieving neutral buoyancy during UAV deployment. The modifications to the EPM housing and the corresponding simulations validate the effectiveness of the proposed design in providing a reliable and stable docking mechanism for sensor packages. Adjustments to the permanent magnet configuration offer flexibility in tuning the force as needed. Overall, this research contributes to the advancement of UAV-based bridge inspections, ensuring efficient and secure deployment of sensor packages for structural health monitoring.

Future work will be aimed at providing results from further testing with the EPM in its on state to ensure that the total hold force is sufficient to hold the full weight of the drone. Docking tests will also be undertaken to show that deploying sensor packages will have a much higher success rate with the addition of the modified EPM. Further permanent magnet orientations, as well as pieces that can adjust position in real-time, are being explored to allow for increased customization such that a variety of UAV weights may be easily accounted for.

Acknowledgments

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