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SENSOR PACKAGE DEPLOYMENT AND RECOVERY CONE WITH INTEGRATED VIDEO STREAMING FOR RAPID STRUCTURAL HEALTH MONITORING

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ABSTRACT

This study presents an approach for structural health monitoring (SHM) of remote and hazardous structures using unpiloted aerial vehicles (UAVs). The method focuses on overcoming the challenges associated with traditional sensor deployment techniques, which are often costly and risky due to the decaying nature of the targeted structures. Utilizing a multi-rotor UAV platform, a streaming camera is integrated into a recovery cone to aid in visual alignment during deployment and retrieval providing a safe and cost-effective means of sensor delivery. The paper covers the design of a video-broadcasting deployment system with integrated electropermanent magnets (EPMs), housed in a 3D-printed recovery cone, supplemented by redundancy measures to enhance safety and reliability. This proposed system significantly improves the user's spatial awareness and aids in precise sensor package alignment, facilitated by multiple camera views providing a dual purpose of conducting visual inspection in addition to aiding in sensor delivery. The experimental analysis presented in this study validates the system's effectiveness, demonstrating the utility of camera-aided sensor delivery for rapid SHM applications. Navigation challenges due to proximity to metal structures and the difficulties associated with signal strength and reflections are also reported. The contribution of this work is a methodology for aerial sensor deployment and retrieval using a lightweight 3D-printed recovery cone with integrated cameras for navigation and sensor alignment.

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INTRODUCTION

Structural health monitoring (SHM) of structures is a challenging task that has been traditionally done with dedicated equipment and highly trained personnel. The deployment of sensors is made even more challenging in remote areas or when the structure is partially damaged or when other hazardous conditions exist [1]; such as following an earthquake or a wet weather emergency. The approach of sending humans out to deploy sensors can be particularly costly and dangerous at times due to the unstable nature of damaged or decaying structures. Unpiloted aerial vehicles (UAVs) come as a solution to this challenge [2]. Multirotor crafts platforms with their exceptional maneuverability and useful payload provide a cost-effective and safe method of sensor delivery without the need to rely on traditional manual sensor placement approaches.

Adopting UAVs for sensor deployment in SHM comes with its own set of challenges. UAVs are typically piloted by a line of sight user, yet this is not always the case in a SHM framework. Sensor placement can be in locations where the pilot's visibility is limited during navigation [3]. In such cases, spatial awareness is needed to ensure successful sensor delivery while avoiding collisions during approach.

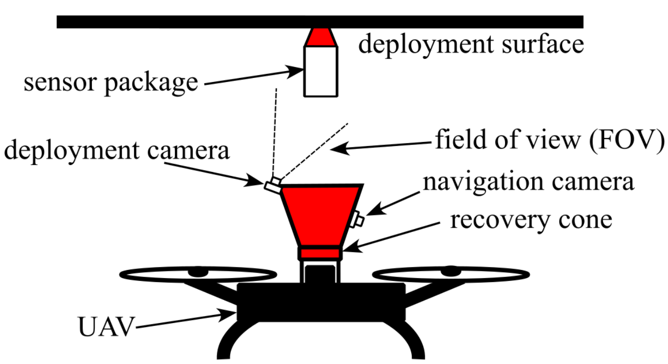

FIGURE 1. Diagram of the sensor delivery experiment with key components annotated.

Researchers have developed methods to assist in the automated deployment of sensors using UAVs. Zhou et al developed a vision-based pose estimation technique to improve the accuracy of UAV localization for sensor placement [4]. In this work, various sizes of fiducial markers were integrated into a single pattern and applied to the structure. These markers were used as precision landing targets that identified sensor placement locations. Carroll et al. developed a camera-based onboard localization technique for autonomous navigation for deploying and retrieving sensor packages to and from the underside of structures. In this work, the authors integrated an optical camera into the control system to enhance the spatial awareness of the UAV during autonomous flights by recognizing the location and orientation of a given marker. [5].

Proposed in this work, is a broadcasting sensor deployment system that incorporates wireless video streaming and EPMs with redundancy measures to increase the safety and reliability of the aerial deployment aspect of SHM. This system is designed to enhance the user's awareness and aid in aligning the sensor package and drone during deployment and retrieval by using a lightweight recovery cone to guide the package into the magnetic docking station. Furthermore, this camera network offers multiple views of the drone and deployment system, providing a method of delivery in addition to a means for visual inspection as shown in Figure 1. The contribution of this work is a methodology for aerial sensor deployment and retrieval using a lightweight 3D-printed guiding cone with an integrated camera for sensor alignment and navigation.

METHODOLOGY

This section explains the hardware used for UAV flight and sensor docking, as well as the experimental testing used in this work.

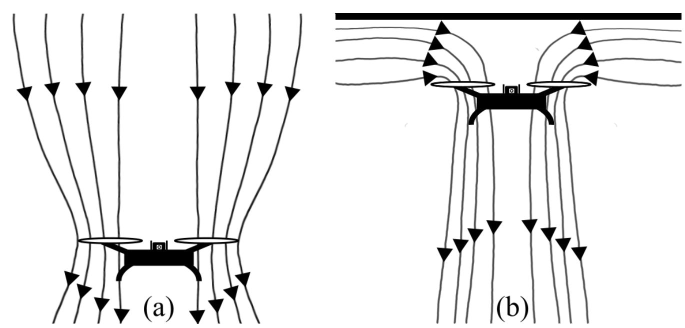

FIGURE 2. Streamlines of a UAV in (a) free stream and (b) under the ceiling effect.

UAV flight and navigation

Automation in UAV navigation is promising but encounters specific challenges when deploying sensor packages to structures like bridges. When flying close to bridge beams, the UAV's navigation precision is compromised due to multiple factors. The first of which is the proximity to the structure during sensor deployment. The impeded airflow causes a "ceiling effect", experienced as a sudden increase in lift, while the drone is directly underneath the structure. This alters propeller efficiency due to airflow disruption [6]. Shown in Figure 2, the streamline patterns during (a) flight in open stream and (b) flight under a ceiling.

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Additionally, metal structures that this sensing system typically operates under not only obstruct the direct line of sight to satellites, preventing the reception of direct GPS signals [7], but also introduce signal reflections. The inherent magnetic fields of these metal structures further contribute to making onboard compasses less precise [8]. To navigate these challenges, introducing a user in the loop equipped with multi-view video streaming significantly enhances spatial awareness in environments where traditional navigation systems fall short. This approach enables precise navigation during sensor deployment and retrieval by providing real-time visual feedback to the UAV pilot. It also improves the pilot's ability to conduct visual inspections to determine the optimal locations for sensor placement. The UAV system utilizes a hexacopter frame equipped with a Pixhawk 2.4.8 flight controller, selected for its stability and capacity to carry the necessary sensor payloads. A 120 C 10000 mAh battery is also used to provide the flight time necessary for sensor deployment missions. Such missions typically range from 1-2 minutes from take off with the package till touchdown of the unloaded UAV.

In such environments, flying in stabilize mode offers manual control over the UAV's orientation by automatically keeping the UAV level unless the pilot inputs commands. This mode is essential in areas where GPS signals are obstructed or unreliable, such as under bridges or near large metal structures. A key feature of stabilize mode is high responsiveness, allowing the pilot to make precise movements independent of GPS. This approach is ideal for navigating complex geometries with poor GPS coverage. However, stabilize mode comes with its own challenge. The drone is susceptible to drifting since it does not use GPS for position holding, requiring constant pilot corrections to maintain the UAV on course.

Sensor deployment and recovery system

To aid in sensor drone stabilization during docking and sensor delivery, electropermanent magnets are utilized in the system. An electropermanent magnet is a type of magnet that creates a controllable magnetic field. Unlike traditional electromagnets, which use electric currents to generate magnetic fields, EPMs can turn the magnetic field on and off through the application of a high-voltage pulse. Once the magnetic poles' direction is changed, no further current is needed, and the external magnetic field is maintained in one of two states: on or off [9]. EPMs are particularly useful for docking sensor packages to civil structures for structural health monitoring, allowing for the convenient attachment and detachment of these packages. This versatile system provides a compact and power-efficient solution for use in sensor packages as well as in a UAV docking system. In this paper, an augmented EPM system is leveraged to achieve neutral buoyancy for efficiency and stability during UAV deployment [10].

For guidance and safe delivery and retrieval, a 3D printed

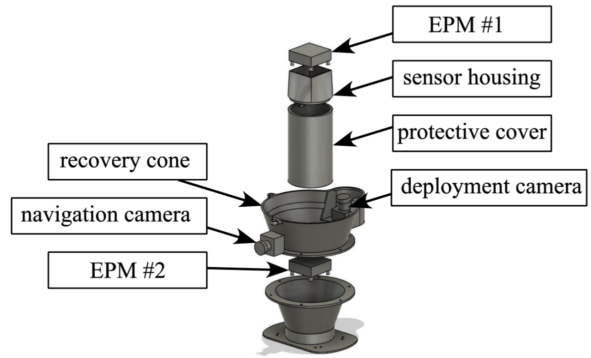

FIGURE 3. Sensor package design along with the aerial deployment system with key components annotated.

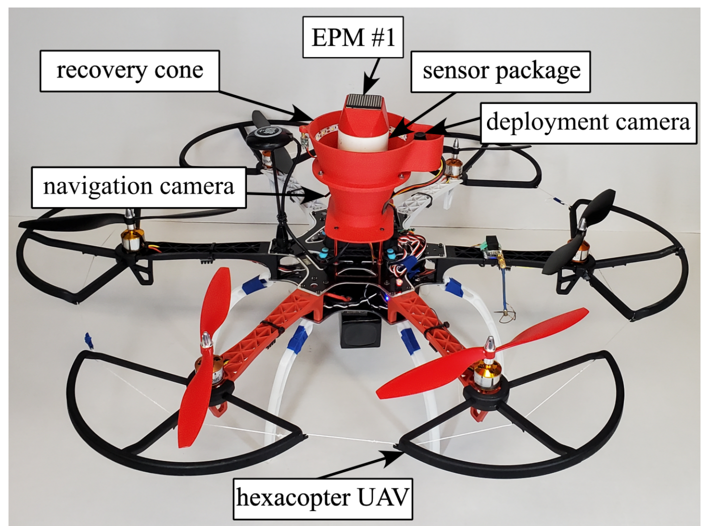

FIGURE 4. Aerial deployment system with key components annotated.

cone made of PLA is secured onto the UAV, which includes an EPM at the bottom to secure the sensor package during flight. This setup is shown in Figure 3. Additionally, a camera mount is fixed within the cone with its viewpoint oriented upward; as shown in Figure 4. This approach aids in alignment and provides a streamlined path for sensor packages away from the spinning propellers and delicate electronics. The PLA material used in manufacturing the cone and its mounts offers the benefit of being lightweight, which minimizes the impact of the cone on the UAV's payload and flight dynamics.

During the deployment phase, the UAV carries the sensor package to a designated location using the deployment/recovery cone. EPM #2, fixed to the bottom of the cone, is turned on during flight to hold the package securely. Upon reaching the target docking point, EPM #2 is turned off, while EPM #1, on the

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sensor package, is turned on simultaneously. This disengages the UAV from the package, resulting in the deployed sensor package shown in Figure 1. The retrieval of the sensor package involves the reversal of the deployment process. The UAV recovery cone is aligned to the sensor package. Then, EPM #2 on the cone is activated, securely attaching to the sensor package's bottom, while EPM #1 is deactivated, detaching both package and UAV from the structure [11].

EXPERIMENTATION

In this experiment, the camera-aided sensor delivery system is examined. The goal of this test is to validate the reliability of the proposed system by simulating an SHM sensor deployment mission. A structure is built, as shown in Figure 5, to mimic the bottom section of a civil structure, where those sensors are typically mounted. Utilizing the Hexacopter UAV, the user approaches the structure safely while making use of the various streaming cameras, indicated in Figure 1, navigates to the desired sensor location, establishes contact, finally, initiates the docking sequence to disengage the package leaving it behind. For retrieval, the user approaches the structure again while aligning the sensor package with the retrieval harness using the upward camera viewpoint. This is designed to aid in EPM alignment during docking. Once that is established, the retrieval sequence is initiated, and the system disengages the structure with the sensor package on board to return to base. This experiment is designed to aid in optimizing the camera locations to provide the user with the most useful viewpoints to navigate challenging terrain.

RESULTS

Two main viewpoints of the camera are found to be the most useful. The frontal camera, shown in Figure 5 (b), is positioned in a way to allow the pilot to view the geometry of the drone while still pointing toward the horizon. This aids in avoiding obstacles and visually locating the target structure. Once the drone arrives at the waypoint, the deployment camera shown in Figure 5 (c) is used to visually inspect the structure and locate the optimal sensor placement. This camera further helps in aligning the drone with the package when sensor retrieval is required. By keeping the package in the top camera frame, the recovery cone guides the sensor to EPM #2, shown in Figure 3, securing it for retrieval. EPM #1 is then detached from the structure and the UAV is disengaged. In this experiment, the low-latency camera broadcasting demonstrated great potential in aiding in the safe deployment of sensors with minimal added payload and power draw.

Presented in Figure 6, a deployment mission where the UAV pilot approaches the structure 6 (a) while identifying a desired location to deploy the sensor. Using the deployment camera, the pilot validates that contact has been established with the structure 6 (b). The EPMs are then toggled to secure the sensor onto the

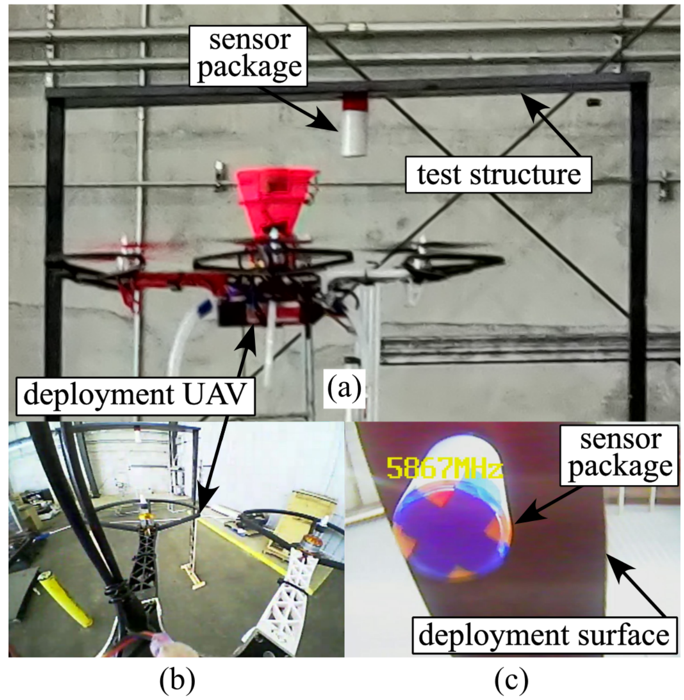

FIGURE 5. Optimal camera viewpoints for safe sensor deployment with key objects identified.

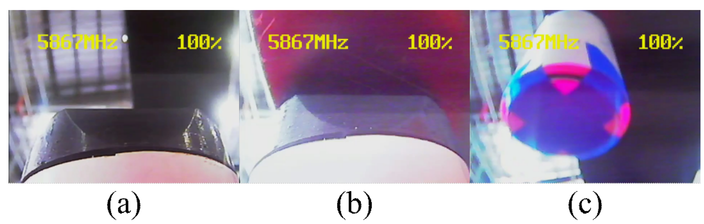

FIGURE 6. Sensor deployment mission with the UAV (a) approaching the structure, (b) establishing contact with the structure, and (c) UAV disengaging the sensor, leaving it attached to the structure.

structure, disconnecting it from the UAV as shown in Figure 6 (c).

To enhance the stability of the UAV during deployment, the center of mass was strategically shifted below the propeller line, creating a self-stabilizing pendulum effect that helps counteract disturbances from turbulent air around the recovery cone. The flight controller has also been tuned to handle these forces effectively on the pitch and roll axes, and the system's effectiveness is currently being evaluated under various wind conditions. Preliminary results have shown that the UAV maintains stable and favorable flight characteristics, even in light wind gusts encountered during field tests.

Using the same UAV flight controller, commands are issued by pilots to control the EPMs during both deployment and re-

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trieval. This integrated control system, along with the deployment camera, not only enables pilots to locate the optimal sensor placement but also engages sensors already fixed on the structure for retrieval. To facilitate precise alignment and guide the magnetic elements to their intended positions, the fringing magnetic fields of the EPMs work in conjunction with the recovery cone. During contact with the structure, a command loop overlaps the magnetic states of both EPMs to increase reliability and prevent mistriggers during the magnetization sequence of deployment and retrieval. This increases the redundancy of the system by ensuring that the sensor package remains securely magnetized to at least one surface to prevent loss.

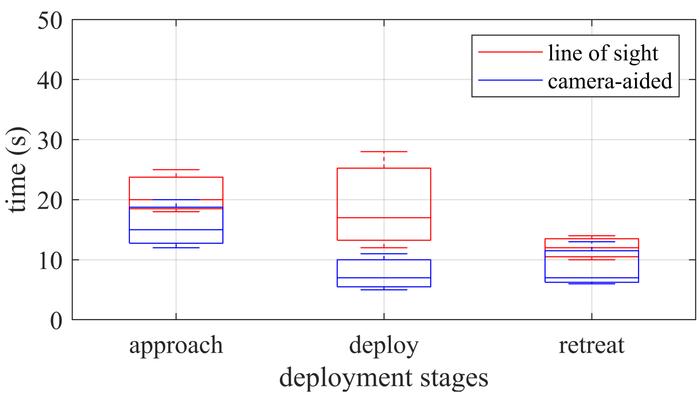

FIGURE 7. Timing report of the three stages of sensor delivery.

For a numeric comparison of performance, the deployment mission is categorized into 3 stages, approach, deployment, and retreat. The first stage includes the UAV taking off with the sensor package onboard. After identifying the desired sensor location, Stage two starts. This includes sensor alignment and initiating the EPM deployment sequence. Once the sensor package is released from the UAV, the third and final stage of disengaging the structure and landing is executed. As a comparison, trials of deploying the sensor through the line of sight and the camera-aided system are timed, with the timing report presented in figure 7. The results indicate an average decrease in mission time of over 38% between line of sight and camera-aided deployment methods.

CONCLUSION

This study introduces a method for structural health monitoring of remote and hazardous structures through the use of unpiloted aerial vehicles, addressing the limitations of traditional sensor deployment methods on decaying infrastructures. By employing multirotor UAVs equipped with wireless video streaming and electropermanent magnets, enhanced by redundancy measures, this approach improves safety, cost-effectiveness, and precision in sensor delivery. The system notably enhances spatial awareness and facilitates accurate sensor package alignment during deployment and retrieval through multi-view camera feedback, which is essential for navigating near metal structures where GPS-based stability is limited and visibility issues can lead to collisions. The integration of these technologies offers a solution for sensor delivery challenges typically encountered in rapid structural health monitoring. This work provides both, a system for aerial sensor deployment and retrieval along with means to demonstrate the system's utility.

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