

Embedded Sensors for the Health Monitoring of 3D Printed Unmanned Aerial Systems

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Abstract—Unmanned Aerial Systems (UAS) are growing in applications every day, extending into the fields of agriculture and data acquisition. Increasingly, these systems are being designed to be low cost and affordable; although, are often required to carry expensive payloads that adds higher mission risk if the UAS faults mid-flight. Real time health prognostics of UAS capable of alerting a pilot or ground system of potential problems before they arise will decrease the associated risk of high cost payloads on lower cost UAS. In this paper, a novel strategy of embedding health monitoring systems within a 3D printed structure or airframe is presented.

I. INTRODUCTION

As the applications of 3D printing steadily increase, the aerospace and aviation industries are not far behind. Producing prototypes has been a common application for 3D printing in these industries for decades, but with the development of various polymers and printable metals, companies like Boeing [1] and Airbus [2] have expanded their horizons and begun printing parts and components for their airplanes. Today, there exists no full size 3D manufactured airplane, although Airbus has begun developing plans for 2050 [2]. A relatively unexplored practice however, is in the production of SUASs (Small Unmanned Aerial Systems) using a 3D printer. With their small size, versatility, and potential for carrying payloads, SUASs have great 3D printing potential. As of 2013, however, only 3 models have ever been printed and successfully flown [3].

The expanding development of 3D printing methods alongside the push for 3D printed planes, has led to efficient methods of low cost development of customized embedded systems. The ability to craft form fitting and replacement parts for a UAS generates a quick method to attach sensors to the system. This allows for sensors to monitor, during flight, problem areas that could lead to a UAS failure. The ability to monitor problem areas such as motor health, wing deflection, and control surface conditions are important in avoiding these critical failures that can lead to damages of high cost payload systems. The safety that these sensors can

bring to a UAS allows for lower cost systems to be utilized without the increase of risk to the payloads.

In this paper, a novel strategy of embedding health monitoring systems within a 3D printed structure or airframe is presented. The rest of the paper is organized as follows. In Section II, a fully 3D printed airframe is introduced with robust embedded sensors. In the following section, a health monitoring system for wing deflection is introduced. Section IV describes a propeller health monitoring system embedded into a motor mount. The utilization of these sensors are discussed in Section V. Finally, the future of embedded health monitoring systems for 3D printed structures is discussed with utilization of these systems, and how they will improve the reliability of UAS.

II. 3D PRINTED PLANE

Additive manufacturing, or more commonly known as 3D printing, has recently gained traction as a suitable manufacturing technique. With the advent of low cost 3D printers, it is now foreseeable for an entire aircraft to be 3D printed, either within a manufacturing plant or at home. There are several well discussed advantages towards additive manufacturing, especially for prototyping and system development [4]. However, one advantage that is not commonly investigated is the ability to embed electronics during the manufacturing process.

In traditional manufacturing, ‘embedded components’ typically involve the creation of compartments in an object, and then inserting it during postprocessing. Because it is usually subtractive, traditional manufacturing is limited in this aspect. However, advances in the field of solid freeform fabrication over the past few decades has prompted studies on the feasibility of embedding sensors, especially in layered manufacturing. This form of manufacturing builds an object from zero, so it is possible to embed components, or more practically, sensors, while they are being created and have them be permanently fixed inside the object.

The embedding of sensors is particularly ideal because it can lead to functional ‘smart’ objects and enable realtime monitoring of hard-to-reach locations within an object, not limited to ordinary surface sensors. Additionally, the sensors can be used to obtain information on performance, structural soundness and status of many components, all while being encased in the components themselves. It has been shown that embedded sensors have yielded high sensitivity and accuracy for strain measurements and had shown significant correlation with non-embedded sensors [5]. This study,

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presented in 2001, utilized large commercial manufacturing systems, but also lamented the inadequacy of the systems of the time. However, over the past 13 years, significant advances have been made in 3D printing, including the bringing of 3D printing to the home user. There have been other efforts into embedding sensors into 3D printed objects [6, 7 8], but these have focused on embedding fiber optics or printed optics rather than the embedding of sensors found in this paper.



Fig. 1. Fully 3D printed plane prototype

The new options of 3D printing have allowed for the ability to create structures embedded with sensors to place into UAS. This is achievable by embedding the sensor into the UAS by small scale printed attachments; as well as giving the option for design of entirely 3D printed UAS complete with embedded sensors within Fig. 1. A suite of robust embedded sensors were developed for this platform and embedded as seen in Fig. 2.

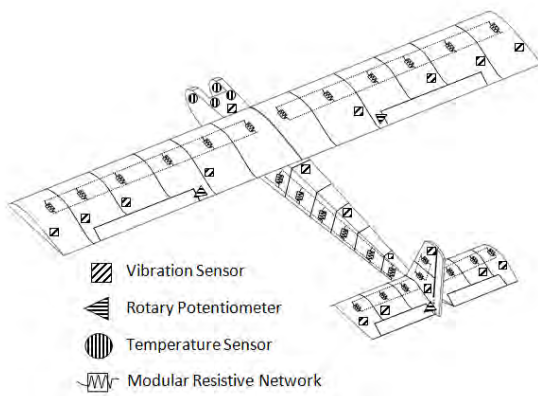


Fig. 2. Map of embedded sensors on the fully 3D printed plane prototype

A. Modular Resistive Network

One of the sensors utilized in the wing of the 3D printed plane was the Modular Resistive Network. Unlike most aircraft, the wings and fuselage were printed out in sections

to accommodate the limited printing area of the 3D printer (Fig. 2, Fig. 3). This leads to the potential problem of the segments becoming loose during flight. To address this issue, a simple modular resistive network was installed to monitor the structural integrity of the airframe.



Fig. 3. This is an inside view of the 3D printed plane wing displaying the segmented sections utilized for 3D printing efficiency, as well as allowing for ease of substituting sections with new embedded sensors

It was designed to utilize two simple electronics concepts: parallel resistors and voltage dividers. The equivalent resistance of an n number of equivalent resistors in parallel is shown in Equation 1; if many equivalent resistors are placed in parallel, the equivalent resistance will become quite low. This change in resistance can be measured using a voltage divider; the voltage at the output is shown in Equation 2.

$$R_{eq} = \frac{R}{n} \quad (1)$$

$$V_{out} = \frac{R_2}{R_1 + R_2} V \quad (2)$$

For this sensor to work properly, one resistor is placed in each wing and fuselage segment. Breakable wires are strung through the length of the wing and the resistors connected, so that they are all in parallel. A resistor is placed in series with the parallel resistor network, which is required for a voltage divider. In this particular project modular resistor pieces were glued to the interior of the wing and fuselage segments, and then connected with wires as in Fig. 4.

These resistor pieces consist of a resistor ($350\Omega \pm \%1$) and 90° headers soldered to a small piece of circuit board. The headers and resistor were connected in an H formation, such that the resistor bridged the gap between two wires. The wires used to connect to these pieces were just normal wires soldered to headers. If a wing or fuselage segment falls off the aircraft, the wire will be pulled out of the wing segment and the connection broken resulting in a measurable location of breakage. This sensor is well suited to this application. In normal aircraft production the wing is not segmented, so obvious attachment points are not available. While in a normal SUAS wing segments would be unable to detach as easily, the partial loss of a wing could still be a problem.

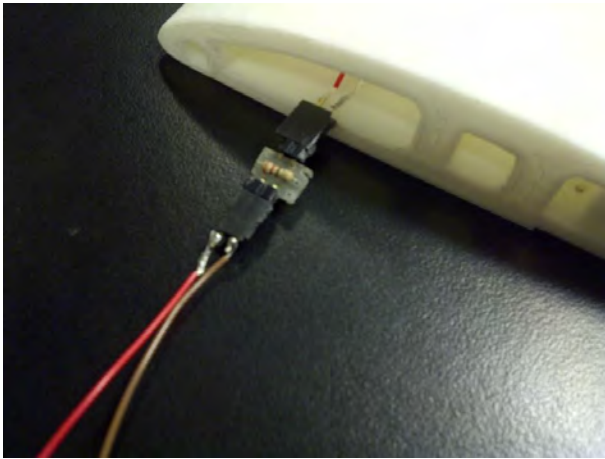


Fig. 4. This image depicts a cross section of the 3D printed plane wing. The sensor shown is part of the Modular Resistor Network.

B. Piezoelectric Vibration Detection

Piezoelectric vibration sensors generate a current when they are vibrated which is directly related to the direction and magnitude of the vibrations [9]. The data collected from the vibration sensor can be analyzed to determine the frequency of oscillations mid flight. This allows the UAS to monitor the vibration frequencies and look for harmful resonant frequencies that would indicate an unhealthy operating system and inform the autopilot to land or warn the current operator of a prospective problem [3]. When used with a printed plane these sensors can be embedded directly into the wing structure. This allows for better sensing and prevents the vibrations from damaging the sensors connection to the wing.

C. Potentiometers

Another sensor type to be embedded into the 3D printed plane prototype were potentiometers. They were used to measure the position of control surfaces, such as ailerons, elevators, and the rudder. It is vital to know if these parts are working and have their full range of motion during flight [3]. The potentiometers are fixed to the areas of interest in the aircraft and placed so that their knobs are in line with the axis of rotation of the control surfaces. Although in this situation the sensors were directly embedded into the printed airframe, this method can still be utilized in other systems with custom made parts.

The choice to use potentiometers over encoders is due to their low cost and robust monitoring method in flight. An issue that potentiometers may encounter is their friction generation compared to encoders, another types of position sensor. The use of low friction potentiometers, combined with the use of powerful servos to move the control surfaces, this potential issue with potentiometers can be ignored with only minor costs of power increase on the servo draw.

D. Temperature Sensing

Temperature sensor were placed in the airframe to monitor high temperature due to the motors and electronic speed con-

trollers. The temperature sensors used in this prototype, the Microchip MCP9700A, are based on a thermistor integrated circuit. The sensor outputs are linear, allowing for simple data analysis and low resource onboard computing. High heat can posses possible problem for printed materials as well as indicate problems for the individual components. Monitoring these temperate locations in real time gives the UAS another avenue to avoid critical failure mid flight and return to landing. The printed nature of the UAS allows temperature sensors to be attached within the materials, removing sensor attachment considerations.

III. WING DEFLECTION MONITORING

Wing deflection during flight is a common problem in low cost UAS built from materials such as foam and bamboo. When the system is active the ground station often has a difficulty discerning the amount of stress being applied to the wing during rolls in moderate to high wind conditions. Underestimating the deflection applied to the wing in these conditions will often lead to UAS failure causing in the loss of the system and damage to any payload.

Current methods of deflection measurement rely on sensitive measures of wing deflection, such as fiber Bragg grating (FBG). These sensors rely on precise measurement and high quality parts for utilization in modern-day planes are impractical to be applied to low cost UAS. FBG sensors are targeted at larger vehicles, data recovered from small planes or UAS were used for purpose of scale testing, not as an end goal [6].

Creating a deflection detection method that is low cost, easily embedded, lightweight and robust enough to handle in flight vibrations of UAS was needed. The flex sensor system are utilized to allow pilots on the ground to monitor wing stress when the UAS is out of easy visual detection range. This allows pilots to change flight patterns when strong winds become an issue and can be integrated into an autopilot system to allow it to adjust for a weak wing or stronger than expected air currents. The sensor can also be used to predict failure, allowing the pilot to react in time to prevent the failure.

A. Wing Deflection System Design

The system utilizes a deflection sensor crafted using low grade light pipes, LEDs, and basic light sensors. It works by measuring the loss of intensity of an optical signal through the light pipe. It is lightweight and responsive allowing for accurate data collection while allowing UAS payloads to remain unchanged. The utilization of low cost light pipe allowed for variable length pipe sections that could be more easily suited to a variety of UAS, though larger sections did increase inaccuracy of measurement using basic sensors. Due to this the sensor was aimed at monitoring stress concentrators.

The sensor is designed to be easily embedded deflection sensor for any wing configuration. The sensor consisted of a light pipe stretched between two mounts. One side has an embedded IR sensor while the other has a red LED

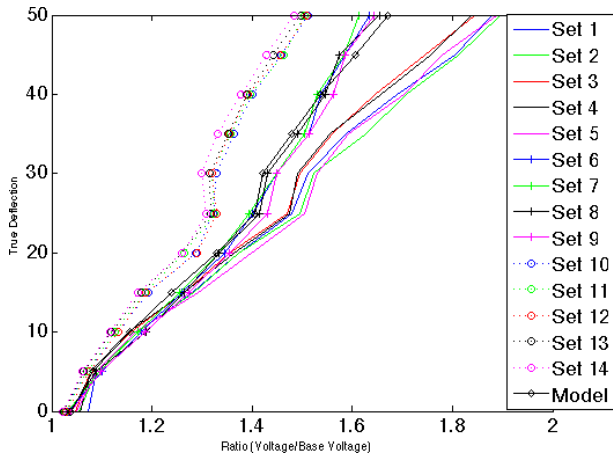


Fig. 5. The graph measures a ratio of first reading to subsequent readings, plotted against the true deflection

embedded. Both the sensor and the emitter are directly connected to the light pipe. The light pipe is then mounted either across an open space for testing or along a wing in flight. In the case of open space testing one end is secured to a flat table while the other end is rotated in a flat plane. A protractor is used for calibration and testing. In the case of in-wing operation the pipe is stretched across a stress concentrator built into the wing. This concentrator ensures maximum bending occurs in the sensor, though care must be taken to avoid unduly weakening the wing during creation of the stress concentrator. Two methods were used to read the data. The first method took a baseline reading and computed a ratio between the base and a current reading. This was done to account for data to day variability present in many samples.

Using a ratio method lacked appropriate definition in the range of interest but was consistent over multiple trials (Fig. 5). The inaccuracy in predicted deflection was too severe and the method was switched to a pure sensor reading. The sensor reading resulted in excessive day to day variation rendering the sensor useless. To counteract the fluctuations the tube was then wrapped and the sensors permanently affixed to eliminate ambient light pollution and relaxation and shifting of the light pipe. The wrapping material served to insulate the pipe and eliminate frustrated internal reflection (FTIR) as noise generated from FTIR easily overwhelmed the useful data.

Using the wrapped pipe setup the model was able to predict angular deflection to within two points in testing on data sets not used in creation of the model (Fig. 6). This accuracy was variable based on exact setup and testing conditions, suggesting that calibration is required based on environmental conditions, however the data was very consistent even during repeated stressing during testing and little noise was observed. This indicates that after calibration of the software based on application the sensor is robust enough for operation on UAS.

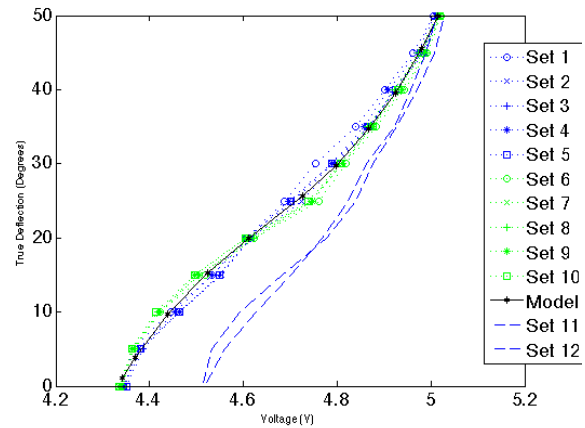


Fig. 6. This plots the voltage of the sensor against the test deflection angle. In this graph the data is from two separate test days.

IV. PROPELLER HEALTH MONITORING

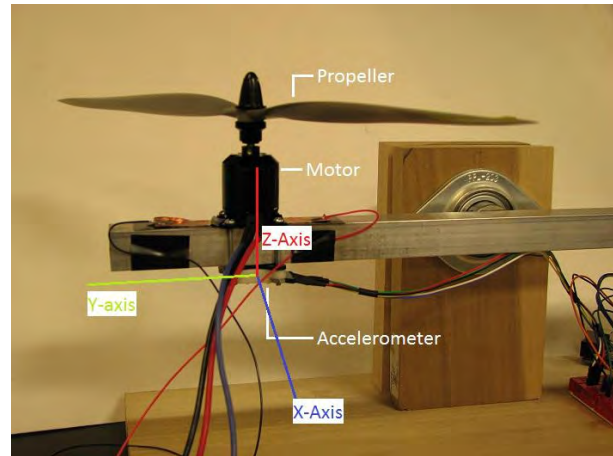


Fig. 7. Propeller Health Monitoring System Test Bench

Accurate knowledge of the health of a propeller is vital to understanding the overall health of a small UAS. The propeller health monitoring system described in this section is intended for use in a 3D printed SUAS by embedded an accelerometer into the motor mount. For the development of this system, a test bench was utilized (Fig. 7). This system aims to quantify the health of a propeller into three categories: healthy, slightly damaged, and completely damaged. Healthy propellers were tested from 5% all the way to 100% throttle, testing every 5%. Damaged propellers were tested every 5% of throttle until vibrations became too large, or the test become unsafe due to the imbalance of the propeller. For completely damaged propellers, this occurred at only 10% throttle, while for a propeller with 2 cm removed from one blade, 20% throttle was a more reasonable limit.

Utilization of an Arduino Uno microcontroller to collect data from the 3-axis accelerometer simulates the ability of an on board processing capabilities of a UAS. The accelerometer used is a 3-axis accelerometer based on the ADXL335

accelerometer chip. This system can handle baud rates up to 115200 baud, which is ideal for fast data collection in real time.

A. Data Analysis

Frequency analysis for this project was performed in MATLAB using the function `fft()`. This function, was used to find an n -point discrete Fourier transform (DFT) of a small sample of vibration data when the motor was spinning at the desired throttle level. The sample was chosen by looking at the graph of acceleration vs. time, and choosing a section of about five to ten seconds where the motor was at its desired throttle level. The n -point FFT function was then used, and the absolute value of the result graphed in a magnitude vs. frequency plot. For n -point FFT calculations, choosing a value for n is important. If n is a real power of 2, the calculation will be executed much quicker than if n were not a power of 2.

For this project, a value of $n = 1024$ was usually used for readability purposes. While higher values could potentially be more precise, the lower value made the graphs much easier to read, while not negatively affecting the qualitative data. The DFT of each axis of the accelerometer was used in each graph, with the x -axis shown in blue, the y -axis in green, and the z -axis shown in red. Fig. 8 is an example of the magnitude vs. frequency plots calculated for each test. The graph is from a test at 50% throttle with a healthy 10-inch propeller 8.

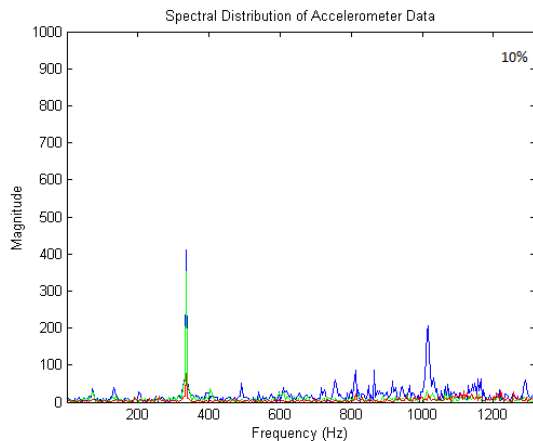


Fig. 8. Magnitude vs Frequency plot of a healthy 10-inch propeller

When the throttle level is increased, the frequency of this spike slowly increases until, at the 50% throttle test seen in Fig. 9, the frequency begins to stagnate just below 400 Hz, then decrease. In early tests, this frequency spike was to be used to determine the health of the propeller: if it was present, there was no damage; if it was not, the propeller was damaged. However, as the throttle level is increased further, this frequency spike diminishes and seems to randomly move to different frequencies. Because of the changing frequency, and because the amplitude drops, using this frequency spike to monitor health would be problematic.

As can be seen in the graphs of slightly broken propellers, large amplitude frequency spikes appear around 75 Hz to 100 Hz. These same frequencies are also characteristic of completely damaged propellers (Fig. 9).

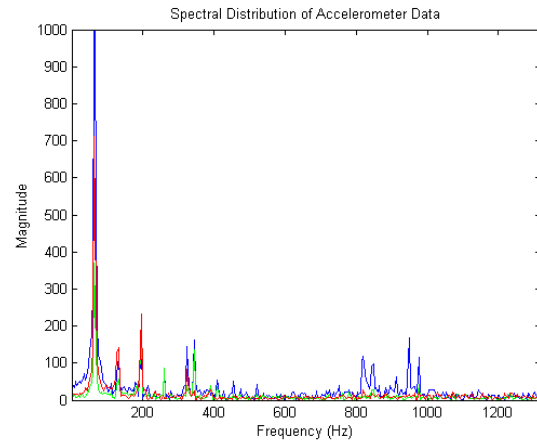


Fig. 9. Magnitude vs Frequency plot of a damaged 10-inch propeller

The major difference between these two damaged states is that the frequency spikes in the completely damaged propellers have much larger amplitudes, and start at lower throttle levels. The completely damaged propeller already has a large low-frequency spike at 10% throttle, while the slightly damaged propeller has a very small, almost insignificant low-frequency spike. By focusing on these low frequencies, the health of the propeller can be determined by the amplitude of oscillations.

Using the conclusions reached above, a health monitoring system can be created using a low-pass filter with a cutoff frequency between 100 and 150 Hz. This setup will permit detection of low frequencies characteristic of damaged propellers, while filtering out the high frequencies more characteristic of healthy propellers. The amplitudes of vibrations can be used to determine the relative health of damaged propellers; high amplitude vibrations at low throttle levels would indicate a completely damaged propeller, while lower amplitudes would indicate a propeller that is only slightly damaged.

V. UTILIZATION OF EMBEDDED SENSORS

The embedded sensors discussed in this paper all provide a method for in-flight diagnostics and operational failure prevention. This type of failure prevention is important in this setting because of the price difference between payload and UAS. Each provides a solution to a type of failure that can occur during a UAS operation. These solutions are often unique to UAS applications, either because of construction methods or size.

A. Modular Resistive Network

The modular resistive network is a system of sensors that can be used in segmented aircrafts. It allows for in-flight warnings of loss of wing segments and requires a

pre-flight check of fully assembled wing segments required for proper operation. This system is easily expanded to fit any number of wing segments and is suitable for any length as the parallel network will not suffer detection problems at increased length. The segments allow other sensors to be embedded more easily so having a method of ensuring reliable connection is important to the continued use of segmented wing structures.

B. Piezoelectric Vibration Detection

The piezoelectric vibration sensor is connected to the autopilot controls and to the transmitter to send the data back to the pilot. This information allows the pilot to notice the developing vibrations and attempt to correct the flight pattern to reduce them. This allows flights to continue more safely, and if the vibration do not subside this allows the UAS to land before catastrophic failure occurs. This sensor prevents unseen vibrations from ruining the scientific mission as well, recording the vibrations allows the pilot to know if pictures or other data being gathered will be affected by the vibrations.

C. Potentiometers

The utilization of potentiometers to monitor ailerons and other servo controlled devices in-flight allows for updates of current position of ailerons are sent to the ground operator. These sensors can inform the pilot of servo failure during flight to allow for landing and repair before critical failures due to an unknown servo failure. This in-flight importance of this occurs mostly when the UAS is being operated by a pilot. When an autopilot system is in use the control system will notice and correct for the failure but a ground operator might be unable to visually determine the attitude of the aileron when the UAS is operating during a mission.

D. Temperature Sensing

Embedding temperature sensors into the airframe structure is a useful method for monitoring critical hotspots in the system. Extreme temperature fluctuations warn of onboard engine problems during flight. It can also monitor battery temperatures to make sure they avoid hot or cold conditions that would reduce their reliability during flight. Knowledge of the temperature of batteries and motors would allow pilots to correct in flight problems. As in full-size aircraft, abnormal engine or battery temperatures can indicate significant problems. Proper integration of these sensors would allow immediate failsafe actions to occur, such as killing the motors and starting emergency landing procedures.

E. Wing Deflection

The implementation of wing deflection monitoring allows on the ground station members to monitor the deflection level of their UAS and make adjustments in the flight plan according to the information received. It can inform the pilot of high stress conditions on the wings during flight to allow for alternative flight paths or cancellation of the mission due to high speed winds unknown to the UAS team. It also allows

for further parameters to be passed to auto pilot systems to improve their flight capabilities, reducing the chance they damage their wings due to unsafe external conditions.

F. Propeller Health monitoring

For propeller health monitoring different propellers need to be tested in different damage states to create accurate on board analysis filters for individual UAS. The benefit of these systems allow for knowledge of damaged propeller in flight that one might not be aware of from the ground. This allows the pilot to land or switch power to less damaged propellers or to continue the flight until landing. This system also allows the operator to determine the extent of damaged incurred by a rough landing or collision.

VI. CONCLUSION

Real time health monitoring prognostics of UAS is a tool that is becoming easier to implement over time with the aid of 3D printing technologies and simple low cost sensors. These systems are capable of warning the UAS of dangers mid flight improving their reliability and allow for the system or the pilot to make corrections accordingly to avoid high cost failures. Many of these systems are easily implemented and low cost methods of securing costly payloads from avoidable dangers allowing small scale UAS to improve airworthiness and reliability [3]. Further integration of these methods will allow for low cost UAS to safely carry high cost payloads.

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