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Unmanned Aerial and Traversing Robot as Mobile Platform for Bridge Inspections

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Abstract
In this study, a bridge inspection robot deployment system (BIRDS) is designed, prototyped, and tested to facilitate the remote inspection of bridges with nondestructive evaluation tools such as microwave and hyperspectral cameras. The multimodal robotic system utilizes both flying and driving technologies. First, BIRDS as an unmanned aerial vehicle flies to the underside of the bridge to be inspected. When in position, BIRDS is engaged with the bottom flange of a bridge girder with a specifically designed roller clamping system and then traverses the bridge in a stable manner, providing high quality images from cameras. Finally, BIRDS simply detaches from the bridge as it encounters obstacles, and flies to the next area of interest. The power system of the BIRDS was designed for over one hour of operation. To meet lightweight, durability and strength requirements, the main frame of the BIRDS was made from ¼” thick carbon fiber reinforced polymer sheets. Smaller components were made with a 3D printed discontinuous fiber-reinforced nylon, characterized with tensile, compressive and shear tests. The first prototype was built and tested in laboratory. Preliminary tests demonstrated the successful engagement, traversing and disengagement of the prototype BIRDS along a simulated bottom flange of a beam. However, the four rotor arms appeared too flexible and should be stiffened to minimize any impact-induced deflection during landing.

1. Introduction

According to Federal Highway Administration, there are more than 600,000 bridges in the U.S. National Bridge Inventory. About half of the bridge populations are over 45 years old. As transportation demand continues to grow, highways and bridges must be inspected and maintained to support a steady growth of the U.S. economy. In particular, visual inspections are required for most bridges every 2 years.

A large number of elevated and complex bridges are difficult to access, requiring access trucks to complete inspections with traffic control and posing a safety threat for both inspectors and drivers. More importantly, visual inspection is subjective, leading to inconsistent results. It is thus desirable to develop robotic platforms, such as climbing robots and unmanned aerial vehicles (UAV), to support sensing systems and nondestructive evaluation devices for safer, faster, cheaper and more reliable inspections of bridges without disrupting traffic flow.

This paper reports the first study on a bridge inspection robot deployment system (BIRDS) that is designed for required functions with minimum weight, prototyped, and tested in laboratory. The BIRDS combines the flying and traversing capabilities of an unmanned aerial vehicle (UAV) and a climbing robot. It can be designed to attach to special structural elements such as flanges in I-beams or girders or any plate-like elements in civil infrastructure.

2. Practical Relevance and Benefits

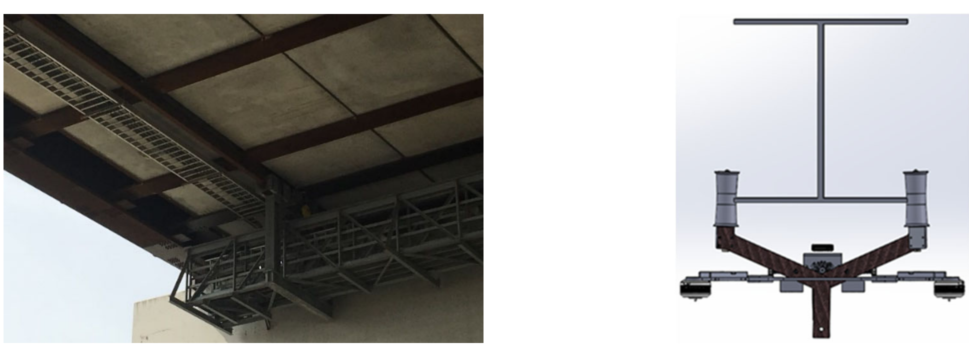
The unmanned vehicle (BIRDS) will be used to facilitate I-girder inspection and deploy climbing robots on the underside of bridge deck between two adjacent girders. The unmanned vehicle and the climbing robots together will allow the inspection and maintenance of over 90% of the bridge superstructures in the National Bridge Inventory. They can also be applied for inspection and maintenance of substructures in various types of bridges.

2.1 Dominant Uses of I-Beams/Girders in Highway Bridges

The bridges in the U.S. National Bridge Inventory can be broken down by structure types (Wu and Chase, 2010). The bridges associated with keywords (Slab, Girder and Floorbeam System, Tee Beam, Box Beam or Girders – Multiple, Box Beam or Girders – Single or Spread, and Culvert) can most likely be inspected with climbing robots based on magnetic attachments on steel components and vacuum suctions on concrete components. Together, these bridges represent 51% in number or 31% in deck area. On the other hand, the bridges associated with the keyword (Stringer/Multi-beam or Girder) represent 41% in number or 59% in deck area. The I-shaped beams or girders, both concrete and steel, are difficult for the aforementioned climbing robots to move along their cross section.

2.2 Performance Requirements on an Inspection Vehicle

The above data clearly indicates an urgent need for the development of a new robotic platform to support the inspection and maintenance of a significant percentage of bridges in the U.S. National Bridge Inventory. Currently, an inspection platform as shown in Figure 1(a), costing over $1M, is often designed and built between girders in the superstructure of river-crossing bridges due to difficulty and cost associated with bridge inspection and maintenance. Such an inspection platform is quite familiar to bridge engineers and inspectors, and used in practice.



(a) Inspection platform used in practice (b) Proposed unmanned inspection vehicle
Figure 1 The current inspection platform and the proposed inspection vehicle

In this project, a hybrid aerial and traversing unmanned vehicle as schematically shown in Figure 1(b) will be developed and tested in application-like settings. Such a vehicle must be able to fly in air and traverse along a girder with an effective vehicle-bridge engagement mechanism for smooth transition from the flying to traversing mode. Design criteria of the vehicle include, but are limited to,

- In the flying mode, the vehicle is stable with necessary positioning precision and navigation guidance in a GPS denied environment.
- In the traversing mode, the vehicle with necessary positioning precision moves at a constant speed to provide a stable station for various measurements.
- In the transition period, the vehicle engages with a girder safely and efficiently.
- Overall, the hybrid vehicle must have the required payload for measurement devices and deployment of climbing robots, and the required flight time (over one hour) for bridge inspection and local maintenance.

2.3 Benefits of the Proposed BIRDS

The benefits of the proposed BIRDS include, but are not limited to:

- Increased operation time
- Stable measurement platform, particularly less susceptible to wind condition
- Ease in navigation
- Accurate positioning
- Cost effectiveness
- Improved potential use by bridge inspectors due to its analogy to inspection platform

3. Material Tests and Results

Onyx with triangular infills was used as a composite material for 3D printing of some components in the proposed BIRDS. The material was tested for the modulus of elasticity, Poisson's ratio, shear modulus, tensile strength, compressive strength, and yield strength according to various ASTM Standards.

3.1 Tensile Tests and Results

ASTM D3039 "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials" was used to determine ultimate tensile strength, yield strength, and Poisson's ratio [33]. Each specimen is 250 mm long, 25 mm wide and 2.5 mm thick. Five specimens were prepared and tested. The average values for the modulus of elasticity, Poisson's ratio, tensile strength and yield strength are 37.1 MPa, 0.472, 14.7 MPa and 3.84 MPa, respectively.

3.2 Compression Tests and Results

The ultimate compressive strength was determined using ASTM D6641 "Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture" [34]. Each specimen is 140 mm long, 13 mm wide and 2.5 mm thick. Seven specimens were prepared and tested, giving an average compressive strength of 14.8 MPa.

3.3 Shear Tests and Results

Shear tests were conducted following ASTM D7078 "Standard Test Method for the Shear Properties of Composite Materials by V-Notched Rail Shear Method" [35]. The overall dimension of each specimen is 76 mm long, 56 mm wide and 4 mm thick. Six specimens were prepared and tested, giving an average shear modulus of elasticity of 428 MPa.

4. Design, Prototyping and Initiatl Tests

The dimensions and overall shape of the BIRDS were mainly determined based on the required functions for I-girder inspection and for deployment of climbing robots. Simple calculations were conducted to ensure that the material strength is sufficient to support the weights of various components and expected cameras. A finite element model of the BIRDS was established to analyze stress distribution under different operation conditions. However, it is not included in this paper due to limited space.

4.1 Prototyping

A design prototype of the BIRDS was created to address the performance requirements as described in Section 2.2. As shown in Figure 2, the multimodal system, BIRDS, utilized the benefits of both flying and traversing technologies. Using two methods of transportation allows the design to maneuver around obstacles and over overpasses while in traversing mode. Traversing also uses less battery power, which will increase the duration of the bridge inspection that the drone can perform.

Figure 2 BIRDS Mobile Platform Prototype

Figure 3 Fully Engaged Clamping System

The proposed design used the flight capability with four brushless DC outrunner motors, each providing approximately 67 N (15 lbs) of thrust. By simply switching the 47.0 cm (18.5 in) propellers used in this design into 54.6 cm (21.5 in), the system could be enhanced to have nearly 117 N (26.2 lbs) of thrust per motor. The objective was to maintain a minimum 2:1 ratio of thrust to total weight for flight stability. The four motors were attached to four carbon fiber plate arms that were bolt connected to the carbon fiber frame of the drone. Stiffeners were added to the arms to increase rigidity during takeoff when forces were the greatest on the motor arms.

Once beneath a bridge girder, four additional DC motors were used to engage a clamping system that consists of two scissor style clamps. With the help of beveled 3D printed Onyx gears, two lead screws on either side of the BIRDS drove the clamps inward to apply pressure against the edges of the flange. The clamps utilized a scissoring motion to maximize the range of flange sizes that a particular set of arms could engage. The proposed BIRDS was applicable to a flange range of 38-47 cm (15-18.5 in), but with a creation of various, interchangeable, custom carbon fiber scissor arms, many other flange sizes could be achieved without modification to the frame of the drone. The clamping mechanism for the prototype was position controlled by linear potentiometers. At the ends of four clamping arms were the four grips that acted as the BIRDS traversing mechanisms and were independently powered and controlled by their own DC motors. Each grip was a 3D printed onyx wheel that was overlaid with a flexible urethane coating to increase the coefficient of friction against the gripped beam to help with stability during inspection.

Speed and flight controllers, two 25V batteries, and landing gears were attached beneath the main carbon fiber frame of the drone. These batteries were used to power the flight controller and the 12V DC motors that drive the traversing and flying mechanisms. Other components on the drone that required a more rigid connection used aluminum 6061-T6. The overall weight of the BIRDS prototype was approximately 118 N (27 lbs). Using 54.6 cm (21.5 in) propellers, a payload of approximately 113 N (25.4 lbs) can be achieved while maintaining a 2:1 thrust-to-weight ratio and meeting the Federal Aviation Administration regulations. Since the major components were placed beneath the drone mainframe, inspection mechanisms could be placed above the platform, closest to the girder to be inspected. Wireless cameras were attached to two arms on either side of the drone platform and above the central housing unit to show a potential inspection technique that the BIRDS could perform. These cameras relayed real-time videos to the control station to assist with positioning of the drone during flight tests.

4.2 Preliminary Tests

A complete system test was performed to validate the BIRDS prototype. This test evaluated all current systems: flying, clamping, and traversing with a 43.2 cm (17 in) plank simulating the flange of an I-girder in bridge applications. The BIRDS launched from ground level upwards until it reached the wood plank. Once beneath the test fixture, the clamping system was successfully engaged with each wheel, as shown in Figure 3. The traversing mechanism was tested back and forth along the wooden plank to ensure it functions as designed. Motors were then throttled upwards as the clamping mechanism was slowly disengaged. Once the clamps spread past the extent of the plywood plank, the throttle was lowered until the drone landed back on the ground.

5. Concluding Remarks

Several observations can be made from the complete system test. The rotor arm flexibility concern was apparent during the initial takeoff and landing. Undesired flexing occurred at the cantilevered connection of the rotor arm to the main frame and at the ends of the slits in the main frame, which was cut to make room for the clamping mechanisms. This did not hinder the flight capabilities, but caused a slight bouncing motion to occur under landing impact loading and resulted in wire disconnection. Although clamping forces were not monitored during traversing, a large deflection of the wheels was not seen during the test. Therefore, the clamping mechanism can provide more than the minimum force necessary to clamp the BIRDS onto a girder and perform an inspection. Using a position-controlled clamping mechanism without yet establishing a relation between flange sizes and a position on the remote controller did not cause an issue during the test conducted at a close standoff distance. On real-world bridges, this would not be an option. If the size of a girder is unknown, a different positioning system will be needed to replicate laboratory results.

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7 References

ASTM (2012). "D7078/D7078-12 Standard Test Method for Shear Properties of Composite Materials by V-Notched Rail Shear Method." ASTM International, American Society for Testing and Materials.

ASTM (2014). "D3039/D3039M-14 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials." ASTM International, American Society for Testing and Materials.

ASTM (2016). "D6641/D6641M-16 Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture." ASTM International, American Society for Testing and Materials.

La, H. (2018). "Climbing robots with automated deployment of sensors and NDE devices for steel bridge inspection." Presented at the INSPIRE UTC Annual Meeting, Rolla, MO, <https://inspire-utc.mst.edu/annualmeeting/> (Aug. 14-15, 2018).

Wu, N.C., and Chase, S. (2010). *An Exploratory Data Analysis of National Bridge Inventory*. Final Report UVA-2009-03, US Department of Transportation Research & Innovative Technology Administration UTC Program.

Xiao, J.Z. (2018). "Autonomous wall-climbing robots for inspection and maintenance of concrete bridges." Presented at the INSPIRE UTC Annual Meeting, Rolla, MO, <https://inspire-utc.mst.edu/annualmeeting/> (Aug. 14-15, 2018).