Development of testing machine for tunnel inspection using multi-rotor UAV

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Abstract. Many concrete structures are deteriorating to dangerous levels throughout Japan. These concrete structures need to be inspected regularly to be sure that they are safe enough to be used. The inspection method for these concrete structures is typically the impact acoustic method. In the impact acoustic method, the worker taps the surface of the concrete with a hammer. Thus, it is necessary to set up scaffolding to access tunnel walls for inspection. Alternatively, aerial work platforms can be used. However, setting up scaffolding and aerial work platforms is not economical with regard to time or money. Therefore, we developed a testing machine using a multirotor UAV for tunnel inspection. This test machine flies by a plurality of rotors, and it is pushed along a concrete wall and moved by using rubber crawlers. The impact acoustic method is used in this testing machine. This testing machine has a hammer to make an impact, and a microphone to acquire the impact sound. The impact sound is converted into an electrical signal and is wirelessly transmitted to the computer. At the same time, the position of the testing machine is measured by image processing using a camera. The weight and dimensions of the testing machine are approximately 1.25 kg and 500 mm by 500 mm by 250 mm, respectively.

1. Introduction

Concrete structures, including buildings and bridges, were built in quantity during a high-economic-growth period in Japan. The percentages of these structures are approximately 40% of all bridges and approximately 25 % of all tunnels. Many concrete structures are now at least 40 years old. The deterioration of old concrete structures is a serious problem. Accidents caused by falling concrete pieces have often occurred in recent years. For example, a concrete piece fell from Kuyamakawa bridge on the Nagasaki Expressway in January 2009. The concrete piece hit a moving vehicle. Fortunately, no one was injured in this accident. However, this is a problem that must be solved immediately because falling concrete pieces have a high probability of causing third-party damage.

A reconstruction of the structure is one solution to this problem. However, rebuilding an entire structure is difficult given recent economic conditions. In addition, with regard to CO_2 reduction, repairing only the problem parts is good for the environment. Because reconstruction of the entire structure generates a great deal more CO_2 than the repair of a problem part, it have a bad influence on the environment. Therefore, a way to correctly detect a problem point is required.

The typical inspection method for these concrete structures is the impact acoustic method carried out by workers. In the impact acoustic method, the worker taps the surface of the concrete with a hammer. Thus, it is necessary to set up scaffolding to access tunnel walls for inspection. Alternatively, aerial work platforms can be used. However, setting up scaffolding and aerial work platforms is not economical with regard to time or money. Many structures need to be checked, and the inspection area is wide, so inspection methods that excel in high working efficiency is requested. As a solution to such a problem, the method has been proposed. For instance, health monitoring of structures, damage assessment using vibration data and inspection methods using a robot. Zhou et al. proposed an approach for detecting structural damage using transmissibility with hierarchical clustering and similarity analysis [1–3]. Gillich et al.

The use of robots has attracted attention as method to check large civil-engineering structures. Takada *et al*. developed a bridge inspection robot using a permanent magnet [5]. Tahara *et al*. developed a multirotor helicopter and used it for high-altitude inspections and surveys of disaster sites [6]. Some wall-climbing robots were developed that test concrete non-destructively than the above [7-8].

In this study, we developed a testing machine using a multirotor UAV for tunnel inspection as an efficient inspection method.

2. Testing machine using multirotor UAV

Figure 1 shows a schematic diagram of a testing machine that uses a multirotor UAV. The appearance of the developed testing machine is shown in Figure 2. F330 (DJI) was used as the base of the testing machine. The weight and dimensions of the testing machine are approximately 1.25 kg and 500 mm by 500 mm by 250 mm, respectively. The testing machine consists of a thrust part (to generate thrust to press the machine against the ceiling), a traversing part (to move across the ceiling), a control section such as a microcomputer, a flight controller, a wireless communication device, a measurement part such as a hammering device, a microphone, and a battery. The position of the testing machine is measured by image processing using a camera. The constitution of all parts is as follows:

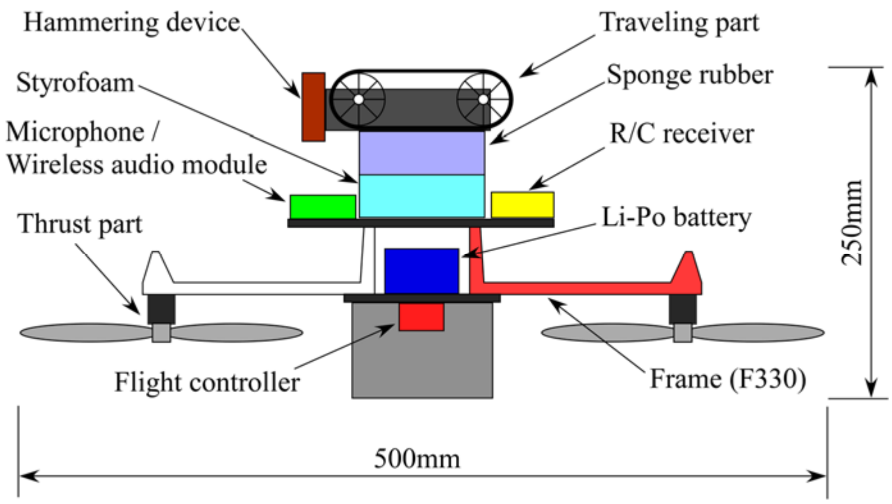


Figure 1. Schematic diagram of testing machine.

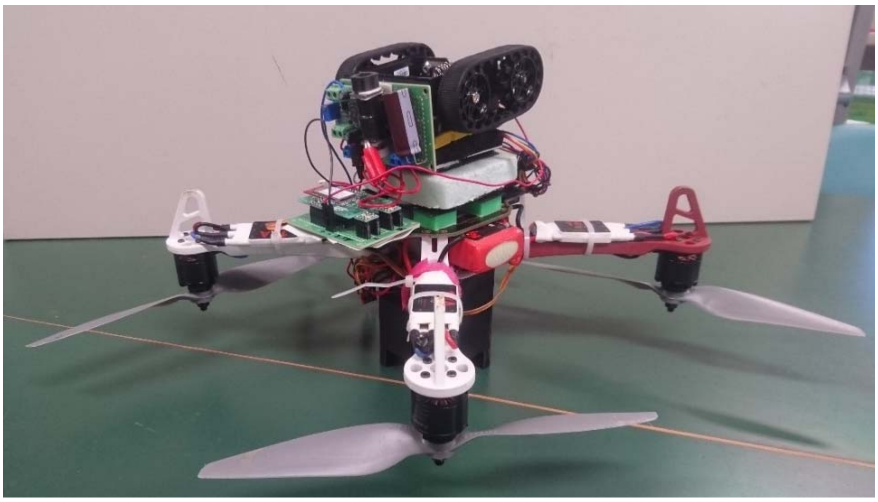


Figure 2. Appearance of testing machine.

2.1. Thrust part
The thrust part consists of four sets of propellers and brushless motors. The brushless motors are controlled by the speed controller. An electronic scale (with a smallest indication of 1 g) was used to measure the thrust. Figure 3 shows a schematic diagram of the thrust measurement. Electric power was supplied by a DC switching power supply (12 V, 1 kW), and the electric current was measured using a clamp-type ammeter. Testing machine was inversely fixed on an electronic scale. The throttle of the controller was adjusted, and the thrust and electric current were measured. The relationship between the electrical current and thrust are shown in Figure 4. From Figure 4, the maximum thrust of propeller 1 (8 × 4. 5) was 16.9 N, and that of propeller 2 (9 × 4. 5) was 22.45 N. Therefore, propeller 2 was adopted for use.

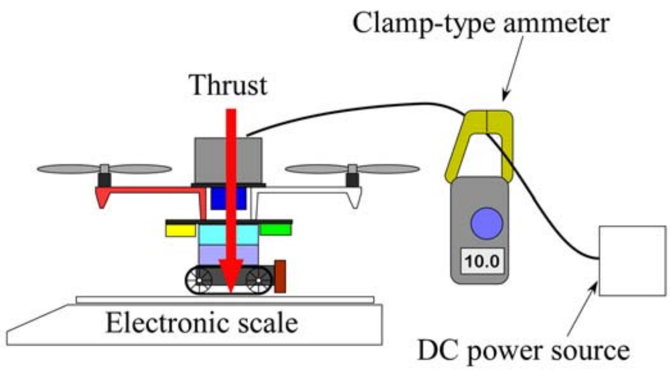


Figure 3. Schematic diagram of thrust measurement.

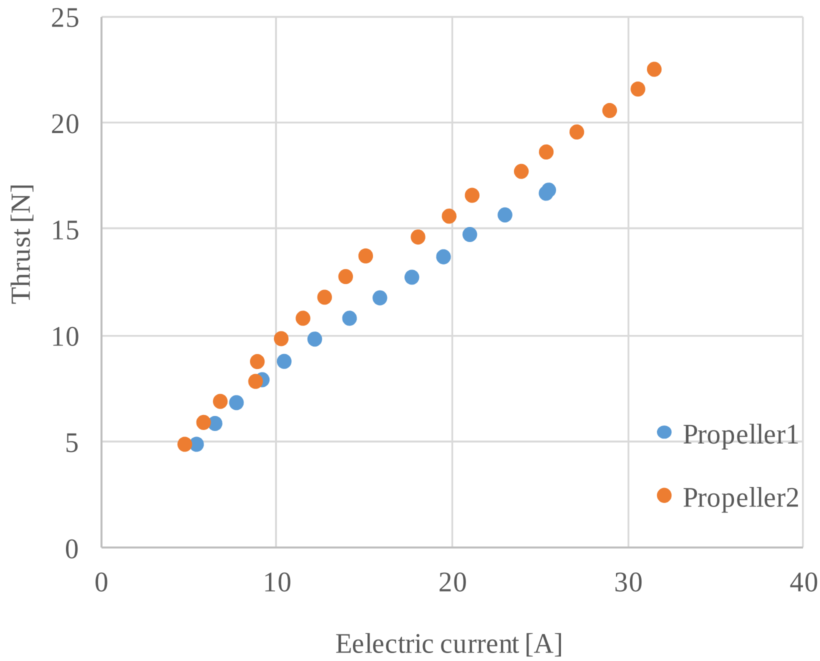


Figure 4. Relationship between electric current and thrust.

2.2. Traveling part
A tracked robot platform (Zumo robot by Arduino, Popolu) was used for the traveling part. The traveling part was forced into the ceiling by thrust, and it drives a crawler and moves the robot. Turning is also possible.

2.3. Control part
A flight controller (NAZA-M Lie, DJI) controls the brushless motors to produce stable flight. In addition, a microcomputer controls the tracked robot platform. A radio control system was used for the remote control of each controller.

2.4. Measurement part
The measurement part consists of a hammer to make an impact, and a microphone to acquire the impact sound. A push solenoid (CB0730, Takaha Kiko Co., Ltd.) was used for the hammer. The measurement value is converted into an electrical signal, and is transmitted to a computer using the wireless audio module (CPI-WAM001, CPI Technologies, Inc.).

2.5. Positioning system
The positioning system consists of a camera and a personal computer. First, a picture of the testing machine with a motion marker is acquired using the camera. Next, the location of the marker is estimated by image analysis. NI LabVIEW was used for image analyses.

3. Verification of traveling performance
To verify the traveling performance, a movement test was carried out using inclined composite panels. Figure 5 shows a schematic diagram of a moving test, and a situation for a moving test is shown in Figure 6. A movement test includes the following three patterns: (1) movement in horizontal direction (x-direction), (2) movement in the inclination direction (y-direction), and (3) turning movement. The results are as follows. When the steerability is sufficient, the results are good. The case in which the robot can move barely is poor. Control impossibility is N/A. The results of a verification test for traveling performance are listed in Table 1.

Up to an angle of inclination of 15º, all tests were good. At more than 20º, the y-direction movement and turning movement were poor. Because the crawler only partly contacts a composite panel in this case, contact areas necessary for movement are not sufficient, as shown in Figure 7. Furthermore, if the angle is greater than 45º, only movement in the x-direction is possible. Finally, when the angle was at least 55º, steering was impossible.

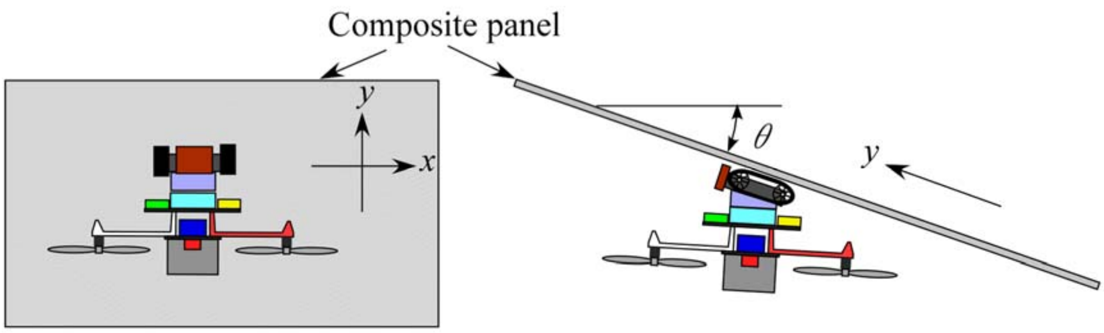


Figure 5. Schematic diagram of moving test.

Figure 6. Photograph of moving test.

Table 1. Results of verification test of traveling performance.

Angle of inclination θ [º]	x-direction movement	y-direction movement	Turning movement
0	Good	Good	Good
10	Good	Good	Good
15	Good	Good	Good
20	Good	Poor	Poor
25	Good	Poor	Poor
30	Good	Poor	Poor
35	Good	Poor	Poor
40	Good	Poor	Poor
45	Good	N/A	N/A
50	Good	N/A	N/A
55	N/A	N/A	N/A

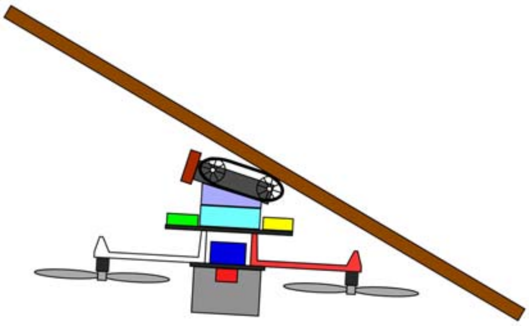
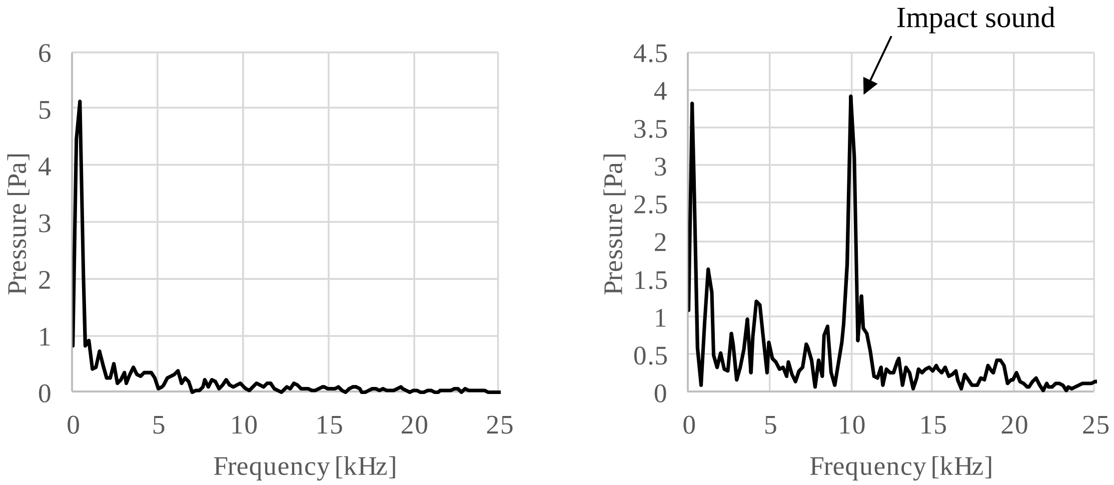


Figure 7. Situation in which part of crawler contacts the ceiling.

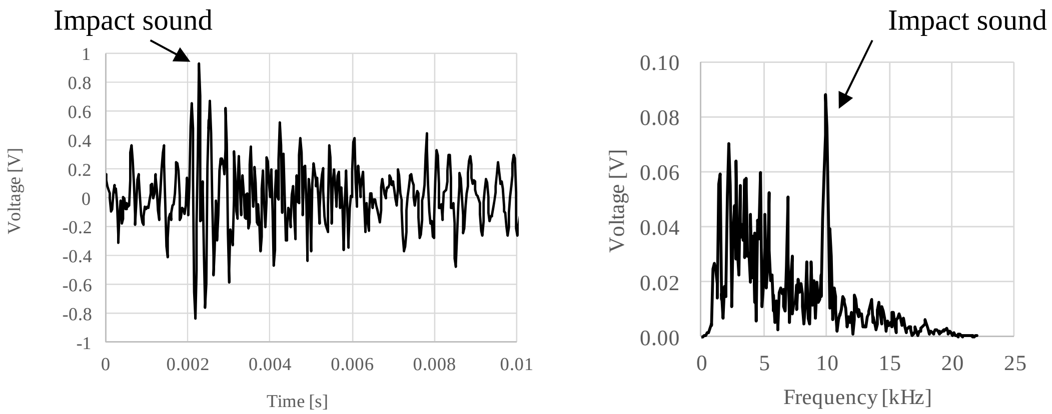
4. Verification of inspection performance

To verify the inspection performance, the propeller noise and affect sound were measured using a microphone for sound measurement. The experimental results are shown in Figure 8. Figure 8 (a) shows the frequency distribution of the propeller noise. An experimental result shows that the frequency mainly included in the propeller noise is less than 1 kHz. Therefore, if the frequency of the impact sound is higher than 1 kHz, it is possible to detect it. Figure 8 (b) shows the frequency distribution of the impact sound. It seems that this peak is a frequency of the impact sound. In addition, the measurement results of hitting concrete pieces during flight are shown in the Figure 9. Figure 8 (a) shows measurement sound, and Figure 9 (b) shows the frequency distribution of the measurement sound. To reduce the influence of propeller noise, measurement results passes a high-pass filter (cut-off frequency is 2kHz). Both figures can recognize the impact sound. Thus, the validity of the inspection performance has been confirmed.



(a) Propeller noise (b) Propeller noise and impact sound

Figure 8. Results of verification of impact acoustic test.



(a) Measurement sound (b) Frequency distribution

Figure 9. Measurement results during flight.

5. Conclusions

In this study, we developed a testing machine that can move along the walls at any angle, and mounted the inspection device for the tunnel ceiling. We obtained the following results:

(1) Using propeller thrust, the testing machine was developed to move across a ceiling. To verify the traveling performance, a movement test was carried out using inclined composite panels. As a result, up to an angle of inclination of 15º, the testing machine could move in all directions and turn.

(2) Impact acoustic test equipment that can be mounted was developed. To verify the inspection performance, the propeller noise and impact sound were measured using a microphone for sound measurement. The frequency mainly included in propeller noise is less than 1 kHz. Therefore, if the frequency of the impact sound is higher than 1 kHz, it is possible to detect it.

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Acknowledgments

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