Verification of an EPM system for an Aerial Inspection Robot and Close-up Image Shooting

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Abstract: To develop the aerial inspection robot for infrastructures, we focused attention on EPM (Electric Permanent Magnet) as a device to stick to steel structures in past studies. Sticking ability to structures is one of the advantages of inspection robots. Although the flight experiment by a quad-rotor equipping the developed EMP unit was succeeded, the developed EPM was not able to generate enough magnetic attraction to inspect the structure. In this paper, we evaluate the effect of noise reduction in recorded images by sticking to structures and stopping rotors. The noise included in the images is evaluated based on PSNR (Peak Signal to Noise Ratio). And we develop an EPM system to stick to structures firmly, and evaluate it by measuring the magnetic attraction considering paint thickness of structures. In addition, flight experiment is carried out using the quad-rotor equipped with the EPM system to validate it.

Keywords: Aerial Inspection Robot, EPM, Quad-rotor, Maintenance Robot, Visual Inspection

1. Introduction

A lot of bridges built during high economic growth period, from the 1950s to the 1970s in Japan, get older now and require inspection and maintenance. Such bridges are inspected currently by visual inspection and hammering test by humans to detect cracks and loose bolts. The inspections of bridges and construction of the scaffold, however, bring risks of accident to working persons. Maintenance vehicles which have a long arm and a basket are used for loading workers, although the traffic lane is closed during the inspection. As a result, it triggers traffic jam. Therefore, inspection of old bridges has not progressed well. MLIT (Ministry of Land, Infrastructure, Transport and Tourism) focused attention on robots for efficient inspection of infrastructure as roads, tunnels and bridges. And MLIT set up a new committee to introduce robots for inspection and maintenance, has been advancing support for developing the robots [1].

On the other hand, studies on robots to check bridges instead of human have been progressing by researchers too. Tadokoro et al. developed an inspection multi-coper covered with a spherical shell to fly while touching on the surface of structures [2]. This multi-coper was able to take close-up pictures for visual inspection by flying near the structure. The problem, however, which taken pictures include a part of the spherical shell because of the structure is remaining [3]. An inspection robot developed by Takada et al. has four rimless wheels equipped permanent magnets to climb on steel structures [4]. The wheel is consisted of some radially-connected bars which have a magnet on the tip, and realizes running on vertical walls. Nonami et al. developed multi-copers that can gather information at disaster area and perform rescue operations [5]. A flight time of such robots, however, is as short as 10-15minutes because of the capacity of the battery and their weight.

For problems solving, we suggested an inspection robot [6] that is able to extend the flight time and to inspect the bridges in stable condition by sticking to a position where we desire (see fig.1). We constructed an EPM unit to stick on structures, and presented that an UAV equipped the EPM can fly to the target point and stick to the structure through the experiment shown in fig.2 [7]. Sticking to structures firmly and stopping rotors provide recording clear pictures for inspection. Although suggested UAV succeeded sticking to the structure, the developed EPM was not able to generate enough magnetic attraction to inspection.

In this paper, we present that attaching on structures brings noise reduction of recorded pictures, first. In the recording experiment, close-up images of the structure surface are recorded by the UAV sticking to the structure using the EPM. The UAV records them under static the condition and the condition that blades are rotating. And we evaluate of the noise included in the recorded images based on PSNR (Peak Signal to Noise Ratio). Next we develop an EPM system to stick to structures firmly, and evaluate it by measuring the magnetic attraction considering paint thickness of structures. Furthermore, flight experiment shows that the UAV equipped with the EPM system can fly, stick and take off from the steel structure.
2. Close-up Shooting Experiment

2.1 Experimental apparatus and evaluation method

When UAVs record videos and pictures for inspection, turbulence blowing around the structure, vibration of rotors and low flight stability of UAVs bring disturbance to videos and pictures. Sticking using the EPM provides stability of attitude, and reduces effects of turbulence. The vibration of rotors propagates to the mounted camera through the body. The effect of the vibration is also removed by sticking on structures firmly not to fall off and stopping rotors. In this section, we evaluate the vibration caused by rotors based on recorded images. Essentially, comparison between images recorded in flight and ones recorded in static condition is more suitable for evaluation. It is, however, difficult that flying UAVs record such images in same angle of view. Thus the experiments are started on the condition that the UAV sticks to the structure.

In experiments, first the UAV (Parrot AR.Drone 2.0) sticks on a steel plate of an experimental apparatus using the EPM similar to the inspection of bridges. Next the UAV’s camera records prepared markers in videos under conditions that the rotors are rotating and stopping. And then we evaluate sharpness of recorded images by calculating PSNR. Generally, large sized drones have gimbals and dampers to stabilize the mounted camera. To mount gimbals composed of metal parts and actuators, however, is difficult for UAVs which have small payload. Therefore the noises are evaluated by movies recorded by the camera mounted on the body directly in experiments.

Fig.3 shows the experimental apparatus, and its length, width and depth are 1000 mm, 1000 mm and 1120 mm. The distance from the floor to the UAV is 800 mm which is the altitude in usual hovering for the UAV after taking off by the automatic control. The distance between the camera and markers is 140 mm. The camera records full-color video to AVI format at 30 fps, and the number of pixels is 640 x 480. Each pixel is recorded at 8 bit. Fig.4 shows two kinds of markers put on the ceiling of the apparatus.

The camera shoots a crack gauge and printed cracks in the figure. From experimental results, it is clear that PSNR is greatly changed and decreased because of noise caused by not only vibration of rotors but change of attitude by turbulence. UAVs include more noise caused by not only vibration of rotors but change of attitude by turbulence. Therefore, it is difficult to mutually compare the No.1, No.2, and No.3 markers in Condition 1 and Condition 2.

To evaluate of noise in the video, we dissolve the video into each frame. And PSNR between the first frame recorded in static condition and other frames is calculated by the following equations:

\[
PSNR = 20 \log_{10} \frac{2^n - 1}{\sqrt{MSE}} \tag{1}
\]

\[
MSE = \sum_{j} \left( \frac{f_{ref, red}(i, j) - f_{red}(i, j)}{f_{ref, red}(i, j)} \right)^2 \tag{2}
\]

\[
+ \sum_{i} \left( \frac{f_{ref, green}(i, j) - f_{green}(i, j)}{f_{ref, green}(i, j)} \right)^2 \tag{2}
\]

\[
+ \sum_{i} \left( \frac{f_{ref, blue}(i, j) - f_{blue}(i, j)}{f_{ref, blue}(i, j)} \right)^2
\]

where \( n \), \( i \) and \( j \) are bit number of pixels, the number of horizontal pixels and the number of vertical pixels. \( f_{ref, red}(i, j) \) means the pixel value of red in the first frame, and \( f_{red}(i, j) \) means the pixel value of red in the other frames. MSE (Mean Square Error) of the pixel value is calculated from using the pixel values red, green and blue. In above equations, each parameter is set as \( n=8 \), \( i=640 \) and \( j=480 \).

2.2 Experimental results

Fig.5 shows PSNR of marker no.1 and vertical acceleration of the UAV measured by the mounted acceleration sensor. After the experiment started, the rotors had stopped in first 10 seconds. Therefore the acceleration was approximately-constant. The rotors began to rotate at 10 second, and the acceleration sensor measured the vibration generated by the rotors. PSNR was greatly changed and declined, due to the noise caused by the vibration. The value recovered, however, after the rotors stopped at 23 second.

Fig.6 shows frames recorded on condition that rotors stop and rotate. The marker of fig.6-left is clear. On the other hand, the marker in the right figure is blurred, and sharpness is lower than the left one. PSNR of the right figure is the lowest in the experiment.

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Y. HIGASHI, S. AKAHORI, A. MASUDA and K. TAKEUCHI
Fig. 7 shows PSNR of marker no. 2 and vertical acceleration. When the rotors are rotating, PSNR is decreasing. PSNR recovered, however, after the rotors stopped similar to the experiment for marker no. 1.

![Fig. 7 PSNR and vertical acceleration for marker no. 2](image)

Fig. 8 shows the frames recorded on condition that rotors stop and rotate. Sharpness of fig. 8-right blurred by the vibration is lower than fig. 8-left. PSNR of the right figure is the lowest in the experiment.

The UAV shoots a crack gauge and printed cracks in the next experiment. Fig. 9 shows PSNR of the picture of cracks and vertical acceleration. While rotors are rotating, PSNR decreases similarly to previous experiments. And the crack gauge in fig.10-right is too blurry to recognize it. The right figure has the lowest PSNR in recorded frames.

From experimental results, it is clear that PSNR is greatly changed and decreased because of noise caused by the vibration. Therefore, it is expected that recording close-up videos while sticking to structures provide effective inspection, because recorded images and videos by flying UAVs include more noise caused by not only vibration of rotors but change of attitude by turbulence.

3. Development of the EPM System

3.1 Attraction mechanism of the EPM

The EPM in past studies [7] couldn’t generate enough attraction to inspect. Thus we develop the lightweight EPM for UAVs. The EPM is a device that can tune the magnetic field on and off by supplying a pulse current. The magnetic field in the EPM is generated by two permanent magnets differently from electromagnets which the magnetic field is generated by electric current [8]. The EPM uses only a pulse current to magnetize one of the magnets in a desired direction. After changing the direction of the magnet, the EPM needs no current. The EPM is consist of two magnetic materials, one magnetically hard (e.g. Neodymium) and the other semi-hard (e.g. Alnico), magnetically soft material such as steel and a coil. The amount of magnetization is driven to zero by an external magnetic field in the opposite direction. The amount of reverse driving field required to demagnetize it is called coercivity. Table 1 shows coercivity and residual induction of Alnico, Ferrite and Neodymium. Table 1 means that Alnico magnet is a strong magnet, but Alnico is easily changed its magnetic pole by external magnetic field.

<table>
<thead>
<tr>
<th>Coercivity [kA/m]</th>
<th>Residual Induction [kG]</th>
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<tbody>
<tr>
<td>Alnico 5</td>
<td>12.5</td>
</tr>
<tr>
<td>Grade Y30BH Ferrite</td>
<td>235</td>
</tr>
<tr>
<td>Grade N40 Neodymium</td>
<td>1000</td>
</tr>
</tbody>
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Fig. 11 shows the operation of the EPM. When the EPM is in the resting phase, the Neodymium and Alnico magnets are oppositely magnetized. Therefore, the magnetic flux circulates inside the EPM. On the other hand, when the EPM is in the operating phase, the Neodymium and Alnico magnets are magnetized in the same direction by a pulse current. This is because that the flux of the Neodymium is always in the same direction, since the Neodymium magnet has a very high coercivity. Therefore, the flux crosses through the steel core and the steel structure as shown in fig. 11-(b).
The UAV which had used for past flight experiment in [7] was a quad-rotor that can be steered in smartphones and tablets. The weight of the quad-rotor was including the battery 466.5 g. Considering the payload, we determine types and size of magnets to make the EPM within 100 g. Table 2 shows the magnets to be used in the EPM.

### Table 2 Two magnets for the EPM system

<table>
<thead>
<tr>
<th>Magnet type</th>
<th>Size [mm x mm x mm]</th>
<th>Weight [g]</th>
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<tbody>
<tr>
<td>Alnico 5</td>
<td>10 x 10 x 10</td>
<td>7.0</td>
</tr>
<tr>
<td>Grade N40 NIB</td>
<td>10 x 10 x 10</td>
<td>7.5</td>
</tr>
</tbody>
</table>

To improve the magnetic attraction, we design and make the EPM on the basis of these magnets. Fig. 12 shows designed EPM and developed it. Steel plates 6 mm thick are used to improve the attraction. Its attraction is 211.8 N.

### 3.2 Pulse current generator

It is necessary to pass a pulse current to the coil by a pulse current generator in order to tune the magnetic field of the EPM. Accordingly, we developed a pulse current generator controlled by a microcomputer Arduino. Fig. 13 shows overview of the EPM controller and fig. 14 is a circuit diagram of the pulse current generator.

The EPM controller consists of the pulse current generator for supplying a pulse current to the coil and a microcomputer, Arduino for controlling the pulse current generator. The pulse current generator is an LC circuit, and it can flow a pulse current to the coil and change the direction of the pulse current by supplying current from the microcomputer. Switching the direction of the pulse current is controlled by using a relay in the circuit. The weight of the whole EPM controller is 71.0 g.

The strength of the magnetic field generated by the coils can be determined by solving the differential equation. The equation of the LC circuit is represented as follows:

$$\frac{d^2Q(t)}{dt^2} + \frac{Q(t)}{LC} = 0$$

where $L$ is the inductance of the coil, $Q(t)$ is the electric charge in the capacitor, $C$ is the capacitance of the capacitor.

On condition that $Q(t) = Q_0$ and $I(t) = 0$ this gives:

$$Q(t) = Q_0 \cos(\sqrt{\frac{1}{LC}} t)$$

The current $I(t)$ and the field intensity $H(t)$ are written as:

$$I(t) = \frac{dQ(t)}{dt} = -\frac{Q_0}{L} \sqrt{\frac{1}{LC}} \sin(\sqrt{\frac{1}{LC}} t)$$

and

$$H(t) = \frac{n I(t)}{L} \frac{l}{\sqrt{a^2 + (l/2)^2}}$$

where $n, I$ and $a$ denote the number of turns of the coil, the length of the coil per unit length, and the radius of the coil. From the eq. (6), the maximum intensity of the magnetic field that the coil can be generated is

$$H_{\text{max}} = -\frac{n Q_0}{L \sqrt{1 + (l/2)^2}}$$

If this value is stronger than the coercivity of alnico magnet 48 kA/m [9], it is possible to switch the EPM. In order to prevent the resonance, the actual circuit requires the flywheel diode.

When the charge voltage of the capacitor changes, initial electric charge $Q_0$ changes. Therefore change of charge voltage changes maximum current from the eq. (5). We investigated the relation between attraction force of the EPM and charge voltage for capacitor based on experiments. Fig. 15 shows the apparatus for measurement experiments. The magnetic attraction of the EPM is measured by the force gauge every 2 V from 10 V to 30 V. The results are shown in fig.16. Since attraction is saturate at approximately 22 V in the graph, the results show that the magnetic polarity turns over completely at 22 V. The maximum current in the pulse current generator at 22 V is 232 A calculated by eq. (5). Discharge time $t_d$ is a quarter of a cycle of a LC circuit. Discharge time $t_d$ is calculated as...


\[ t_d = \frac{1}{2} \pi \sqrt{\frac{L}{C}} = 1.04 \times 10^{-3} \text{ sec.} \] (8)

Here inductance \( L \) and capacitance \( C \) are 100 \( \mu \text{H} \) and 4400 \( \mu \text{F} \).

4. Verification of Developed EPM System

4.1 Energy consumption of the EPM

Sticking to structures by the EPM has merit the EPM doesn’t consume electric energy. It uses, however, electric energy to change magnetic polarity. We evaluate energy that the EPM consume to change magnetic polarity. Charged energy \( W \) of the capacitor is calculated as

\[ W = \frac{1}{2} C V^2 = 1.06 \text{ J.} \] (9)

This value means that developed system requires 1.06 J to switch the EMP. Because the battery of the UAV is 11.1 V, 3000 mAh Li-Po battery, charged energy \( W_{\text{battery}} \),

\[ W_{\text{battery}} = 11.1 \times 3000 \times 10^{-3} \]  
\[ = 33.3 \text{ Wh} = 1.2 \times 10^5 \text{ J.} \] (10)

The UAV in flight consume the energy in approximately 15 minutes. Therefore energy consumption of the EPM is sufficiently small for the energy for flight.

4.2 Measurement of magnetic attraction of the developed EPM

Actual bridges are coated to protect from corrosion. The surface of old bridges, however, is rusty and bald. Generally, magnetic attraction is affected by the surface properties of the suction surface and the distance between the suction surface and the EPM. Therefore, we investigate the effects of the paint thickness on the magnetic attraction by measuring the magnetic attraction of the EPM under several conditions of the paint thickness.

On bridges, welds and bolt joints tend to broken. It is necessary to attach the probe foot to such places in order to examine the damage. Each the paint thickness of the outer surface, the welds and the bolt joints are 0.265 mm, 0.295 mm and 0.445 mm according to the paint guide book published by Nippon paint [10]. Thus, the horizontal attraction and the vertical attraction with respect to suction surface are measured under conditions that the distances between steel surface and the tip of the probe foot are 0.00 mm, 0.25 mm, 0.30 mm and 0.45 mm using the force gauge. Fig.17 shows experimental apparatus for measurement. In this measurement, we use tape instead of paint.

Fig.18 shows measurement results of the vertical magnetic attraction and the horizontal one in relation to 0.00 mm, 0.25 mm, 0.30 mm and 0.45 mm. The vertical magnetic attraction is about 300 N when there is no paint thickness. This value is approximately two times larger than the design value. And, results show that the magnetic attraction becomes the lower rapidly, the thicker the paint thickness becomes. The horizontal magnetic attraction becomes the lower rapidly. The lowest attraction is 15 N in a horizontal direction at paint thickness 0.45 mm. Since the weight of the quad-rotor is 466.5 g, when the quad-rotor sticks to the side as in fig.1, the EPM can support the airframe in each of the conditions. Therefore, results show that the developed EPM system can provide enough magnetic attraction.
4.3 Flight and sticking experiment using the developed EPM

To validate the developed EPM, we mounted it on a quad-rotor and carry out a flight experiment. The pulse current generator and the microcomputer are mounted on side of the quad rotor shown in Fig.19. Fig.20 shows the experimental results. The quad-rotor flew and approached to the steel structure (the steel plate) by manual control, first (fig.20-1, 2). Next, the quad-rotor stuck to the steel plate while the EPM was turned on (fig.20-3). And the rotors are stopped (fig.20-4). After 15 seconds, the rotors rotated again. Finally, after the quad-rotor was separated from steel plate (fig.20-5), we returned the quad-rotor to the original position (fig.20-6). It is validated that the EPM is lightweight enough to mount on the quad-rotor, and it can generate enough attraction to stick on structures.

5. Conclusions

In this paper, we presented that sticking to the structure realized stopping rotation of rotors, reducing vibration on the body and recording clearly images for inspection. And the lightweight EPM for the quad-rotor was developed, and its attraction was evaluated through experiments considering paint thickness of the suction surface. The results showed that the EPM was able to stick on structures in case that the paint thickness is 0.45 mm. In addition, we succeeded the flight experiment that the quad-rotor equipped with the EPM system flew, stuck to the structure and took off from there.

Acknowledgement

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References