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Hybrid sensory-motor control for the recovery from reduced flight stability of an antenna-ablated hawkmoth

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1 Introduction

Flying insects perform sophisticated flight maneuvers using fast sensory-motor control. The challenge to achieve insect-sized flapping robots is how to build and implement the sensory-motor feedback into their small bodies. The neural basis of the sensory-motor pathways in insect flight has been reported in several species. For example, flies have a gyroscopic organ (haltere) on the thorax. The haltere is originally the hindwing and oscillates during flight. The mechanoreceptors at its base detect Coriolis force when the body rotates. The fast sensory feedback from haltere can alter the wing kinematics within 15 ms [1]. The gyroscopic organs are also found in hawkmoths, and locate at the base of antennae [2]. On the other hand in robotics, Ma et al. [3] succeeded in flight control of an insect-sized flapping robot using optical motion tracking which enables feedback control of wing flapping within a time delay of 12 ms. Furthermore, the onboard photosensors inspired by insect ocelli or a small inertial measurement unit (IMU) have been tested for autonomous flight control [4,5]. These studies also suggest that the artificial sensory-motor control will be comparable to that of flying insects. Therefore, we hypothesized that the antenna-ablated hawkmoths can recover the flight stability with an artificial sensory-motor control consists of an IMU and electrical stimulation to flight or abdominal muscles (Figure 1). In this presentation, we report the concept of this hybrid flight control, kinematical analysis of hawkmoth free flight with the IMU, and the controllability of abdominal movement by muscle stimuli.

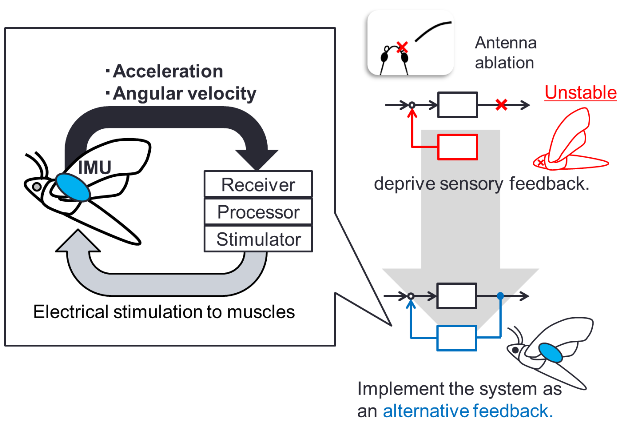

Figure 1: Concept of hybrid control.

2 System design

We used a nine-axis IMU (MPU-9250, Invensense, CA, USA) as an alternative gyroscopic sensor of antenna-ablated hawkmoths, *Agrius convolvuli*. The IMU chip sized 3 x 3 mm was soldered on a flexible board and attached onto the dorsal thorax of the hawkmoth. The mass of the board was less than 40 mg. The wires (φ0.1 mm) for I_2C bus and power supply were attached to the board. The signal from IMU was sent to a microcontroller board (Arduino Uno, Arduino, Italy), and the acceleration and angular velocity were obtained. The electrical stimulation to the abdominal muscle, a candidate of the motor output of the gyroscopic sensing of the moth [6], was controlled by the IMU output. Thus, this closed-loop enables us to test various controller models *in vivo* and during free flight.

3 Verification of IMU and muscle stimulation

3.1 Kinematic measurement with IMU

We compared the angular velocity acquired with the IMU and high-speed cameras during tethered and free flight. We accessed the time delay between signals from IMU and cameras during tethered flight, and found that the IMU output delayed 4-5 ms from camera images.

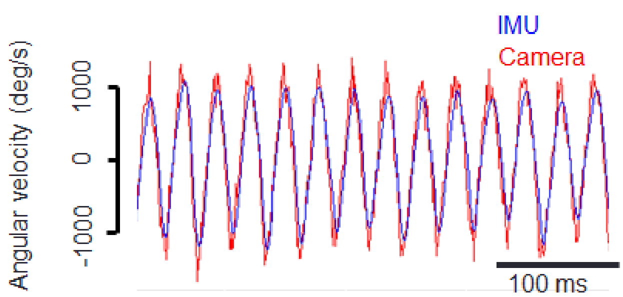

Figure 2: Abdominal pitch movement acquired with the IMU (blue) and the camera (red) during tethered flight.

Figure 2 shows a comparison of abdominal pitch movement between the IMU and a camera, indicating that the IMU could precisely measure the abdominal movement.

For free flight experiment, we attached the IMU and a tracking marker on the dorsal thorax (Figure 3), and measured free flight behavior in a flight arena sized 900(D) x 900(W) x 900(H) mm. We captured three dimensional flight behaviors with two high-speed cameras (Fastcam SA3, Photoron, Japan) at a frame rate of 250 fps. The timing of IMU sampling was synchronized with frame capturing of the cameras. Figure 4 shows the comparison between yaw, pitch and roll acceleration acquired with the IMU and cameras. Both recordings generally corresponded to each other though there were some differences, which might be due to the potential misalignment between the IMU and the tracking marker on the thorax. These results indicate that the IMU has a capability to measure the insect body kinematics during free flight within a time delay of 5 ms.

3.2 Electrical stimulation to the abdominal muscle

Although the muscles that act as an actuator of the gyroscopic sensory-motor pathway has not yet been identified, it is reported that the compensatory abdominal movement in response to pitch rotation disappears after the ablation of the antennae [6]. We therefore investigated the function of the dorsal longitudinal muscle (DLM) in the first abdominal segment which locates the joint between the thorax and the abdomen. The electrical stimulation to this muscle elevated the abdomen, and its elevation angle was modulated by stimulus frequency (Figure 5). These results indicate that the abdominal DLM is one of the candidates of actuators of the gyroscopic sensory-motor pathway.

4 Conclusion and future work

We proposed the novel hybrid flight control to investigate the sensory-motor system for insect flapping flight. We showed that a small-sized IMU can be used for acquisition of angular velocity during free flight. We also showed that electrical stimulation to the abdominal DLM modulates the elevation angle of the abdomen. For future work, we will identify kinematical cues of the instability induced by the antenna ablation from IMU output, design a stimulus controller, and close the feedback loop during free flight.

Acknowledgement

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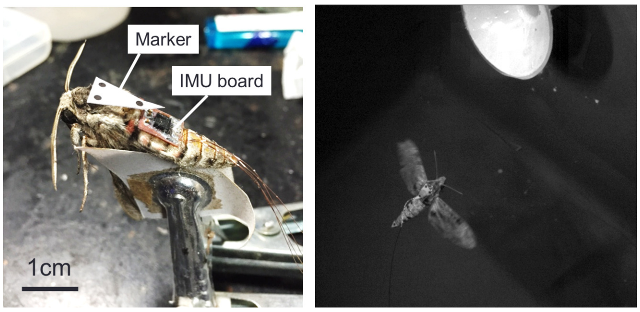

Figure 3: Animal preparation and flight with IMU. Note that the IMU is on the abdomen to visualize.

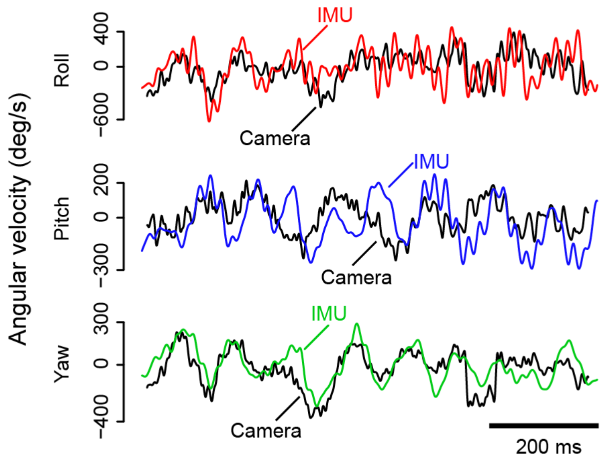

Figure 4: Angular velocity acquired with the IMU (colored) and cameras (black) during free flight.

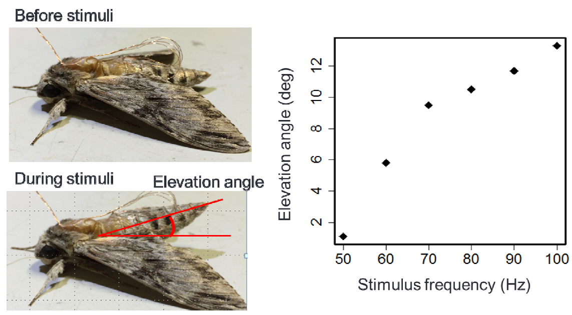

Figure 5: Modulation of the abdominal elevation angle by electrical stimulation.

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