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研究課題名（和文）Hybrid Robot for Bridge Inspection

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研究成果の概要（和文）：飛行と歩行ができるハイブリッドロボットを開発し、適応制御に基づく3次元飛行動作を実現した。 提案したハイブリッドロボットの飛行性能と一般的な無人機との比較をシミュレーションで検証した。 さらに、ロボットが打撃試験を行いながら鋼板の上を安定して歩行するように、永久磁石による反重力運動を実現した。 ロボットの脚を鋼板から離すため、振動を与えることで引力が低減できることを実験により確認した。 最後に、ロボットの遠隔操作を改善するためにロボットがぶつからないような視点や開けた場所を提示するVRインタフェースを開発した。

研究成果の概要（英文）：We have developed a flying and walking hybrid robot prototype and implemented 3D flying motion based on adaptive control. The flight and stability performance of the proposed hybrid robot and a typical drone was verified by simulation. Furthermore, we have developed anti-gravity motion based on the permanent magnet at the end effector of the robot leg. We verified that by applying vibration at the contact point between an end effector and the steel surface, the attractive forces can be reduced significantly. Finally, we have developed a new Virtual Reality interface that adaptively searches for the viewpoint of an open space and also warn the user when a robot will hit the obstacle.

研究分野：Robotics

キーワード：hybrid robot　robot control　motion planning　flying robot

１．研究開始当初の背景

Steel bridges make up much of the primary infrastructure for transportation all over the world. As time passes, these structures need maintenance and inspection in order to ensure that they remain safe. According to the Japanese Society of Steel Construction, costs of bridge inspections and maintenance as related to human resources exceed 12 billion yen per year and are expected to increase annually as bridges age over time. In terms of operations, the tasks involved are very risky to a human operator as they need to climb up a complex 3D steel structure as presented in Fig. 1(left). Furthermore, steel bridge inspection includes bolt inspection using a hammer as presented in Fig. 1(right). Human operators have to perform blot inspections one by one, which is tedious and highly time consuming. Robotic technology is clearly suited to this kind of application.

For inspection and maintenance on steel surfaces, wheeled robots based on magnetic power were introduced. However, it is difficult for a wheeled robot to move on a non-flat surface. On the other hand, many types of leg robots, powered by electro-permanent magnet, sticky elastomer adhesives, wheel-legs and micro-structured adhesives, and gecko adhesives force are introduced for a higher degree of freedom of motion in climbing and upside-down walking on different types of surfaces. Unfortunately, the application is limited to sticky cases where a robot can move in a specific direction. As a bridge is a quite large structure, moving from one point to another point by walking on the steel structure is also time-consuming.

There has been much recent active research in the field of multi-rotor unmanned aerial vehicles (UAVs). Typically, a parallel-rotor UAV platform (for example a quadrotor) is used in many applications such as search and rescue, and exploration and surveillance. Based on the simplicity of its dynamic model, the robot can only translate and rotate with a limited degree of freedom. It is hard for typical drones to navigate without a collision inside complex steel bridge structures and therefore typical drones can only inspect the steel structure from the outside.

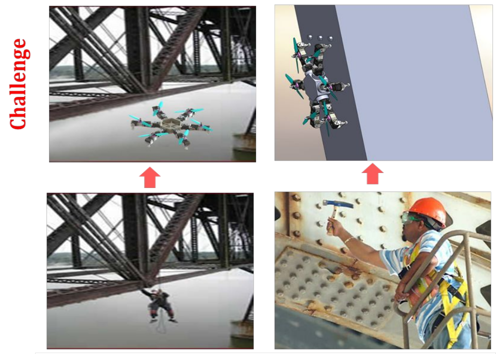

Fig. 1: Dangerous task for human like bridge inspection should be replaced by hybrid robot.

For UAVs to maneuver inside complex 3D structures, modified versions of multi-rotor vehicles have been proposed. Multi-rotor UAVs with tilting propellers are proposed. The vehicle arms can be rotated around the main axes therefore the arrangement of the rotor can be adapted. As a result, the thrust direction is not always parallel but can be pointed in arbitrary directions. Furthermore, hexacoptor vehicles with tilting propellers design have been proposed. For this design, a pair of actuators are aligned in three different directions. Hence, the robot can translate and rotate in 3D space based on a combination of three different direction of thrust and torque. In addition, a cube-shaped omni-directional multi-rotor UAV which can translate and accelerate in any direction at any altitude have been proposed. In contrast, for inspection in complex 3D structure where it is too difficult for a robot to avoids collision,

Lately, there is a concept of collision resilience, which means a robot with a protective cage that is capable of making contact with the environment without falling down. However, UAVs are still not an optimal solution for a steel bridge inspection application since UAVs cannot attach to the steel surface as would be required in order to maintain stability and perform bolt inspections while flying in strong winds.

In order to perform practical bridge inspection, a robot is expected to be able to navigate to the target location in a complex 3D structure, to attach tightly to the steel surface and to perform a steel and bolt inspection while walking. In this research, we propose a concept of hybrid robot (the integration of walking and flying robot)

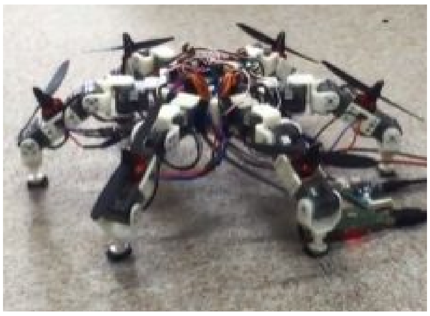

Fig. 2: Hybrid robot prototype.

which not only combines abilities but also enables new innovative abilities for carrying out a practical inspection of a complex 3D steel structure.

2．研究の目的

We achieved 3 challenging explorations which are

2.1 We developed Hybrid robot and implemented 3D flying motion based on an adaptive control. A comparison of flyability of our proposed hybrid robot and typical drone was verified in the simulation.

2.2 We implemented anti-gravitational motion based on air-pressure and permanent magnet for a robot to walk and stabilize itself on a steel plate performing hammering test. In addition, we also implement an attractive force control of permanent magnet based on a vibration for releasing a robot leg from a steel plate.

2.3 We developed a new interaction paradigm that provides adaptive views for improving drone teleoperation. This interface can also be used to augment systems that navigate open spaces with unrestricted viewing angles like forests or mountain sides and could be adapted for other freely controllable robot interfaces.

3．研究の方法

3.1 Hybrid Robot Development

Firstly, we have to develop the prototype parts using a 3D printer. We used a microcontroller board for the flight controller and the locomotion motion was controlled by a computer.

We utilised DYNAMIXEL XL-320 motors as a joint actuator to drive each leg motion of the robot. A servomotor with a reduction

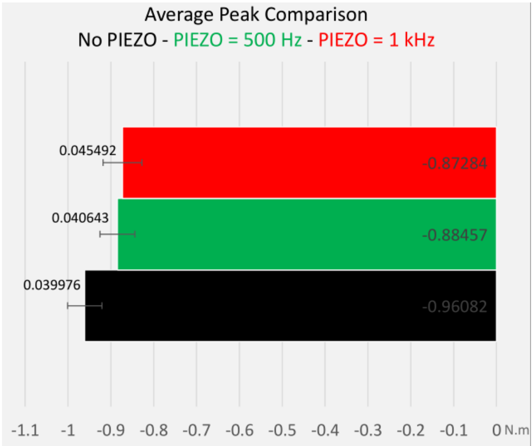

Fig. 3: The effect of different frequency of vibration applied to the surface of the steel.

gear, a control unit and a communication interface is integrated to a compact module for providing a feedback. The control unit monitors the angle for position control and provides force feedback to the main controller. The robot is connected by wires to a computer and a power generator. The board and the motors communicate with each other using an m-bed LPC1768 connector. After the computer generates the robot motion and posture, it converts higher level command to lower level command of PWM to the reference joint angles.

An Atmel 644PA microcontroller as the flight controller contained the gyroscopes, measuring the angle of the robot. Encoders are used to measure the spinning velocities of the propellers. The microcontroller coordinates the desired position and speed and converts the data as spinning velocities to brushless propeller motors (DYS BE1806-13) and propellers (Gemfan 5045). Thrust analysis indicates that the thrust from all motors can lift weights of up to 3.2 kg.

3.2 Permanent Magnet-based walking motion

We developed robot leg with permanent magnet at the end effector for robustly move on the steel surface. Also, we use the PIEZO actuator which can generate high frequency vibration to reduce attractive force at a contact between permanent magnet and steel plate.

3.3 User Interface

The prototype system was built using LSD-SLAM running on the Robot Operating System (ROS). To build this model, we used OpenCV to collect and undistort the video feed from a Wide-FoV lens. This was fed into an LSD-SLAM server in real time, which then builds a 3D pointcloud of the environment and streams updates to the user's view. The user can then view this environment using the HTC Vive (though any VR device would suffice) and can control both the drone and free-view using the two controllers included for interaction.

For consistency, we calibrate both scale and orientation of the 3D scene using ARToolkit by starting scene reconstruction from an AR marker in the view of the camera. After obtaining a number of frames, we calculate a transformation matrix from LSD-SLAM's arbitrarily chosen coordinate system and convert it into real world coordinates based on the marker's known dimensions. Although other methods are available for computing absolute scale, this marker approach gave us a simple way to compute correct scale for the purposes of quickly creating point clouds for testing.

Both experiments involved navigating a virtual flying drone through a series of predefined courses, with the 2D and 3D experiment utilizing different courses. Participants were instructed to focus on avoiding walls while making their way from the start to the goal, but they were not told to finish as quickly as possible. When a participant collided with a wall, the view turned red and the drone was moved backwards (the opposite direction of motion at the time of collision) slightly after a wait period of several seconds. This occasionally led to the virtual drone immediately hitting another wall and counting another collision, but all such cases were noted and removed from the data. Participants could see their collision number as they navigated through the course. During the experiment, we recorded the number of collisions, number of interactions with the viewing window, and time to completion.

Both courses included narrow corridors, wide open areas with smaller obstacles throughout and a single small exit,

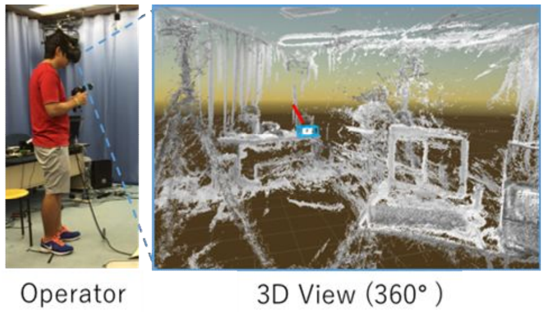

Fig. 4: Human operator control robot in VR environment

sections where vertical movement was required, and sections with a 90 degree turn. Both courses began very simple, to make sure participants had time to learn the controls and view behavior, but gradually increased in difficulty further in. During the priminary experiment (Section 3.3), we were able to observe what structures tended to give participants difficulty and use this knowledge to create the two courses for the experiments described in this section (Section 5).

４．研究成果

4.1 Vibration-based Flying motion

Our developed hybrid robot is presented in Fig. 2. Also we present two simulations that were performed based on vibration control and flying motion control. The vibration control simulation is designed to see how the LQG control can be used to solve problems with two commonly occurring vibrations of impulse and sinusoidal profile. Afterwards, we compare the hybrid robot flight performance with and without LQG control in a flying motion control simulation. Our simulations were implemented in MATLAB/Simulink running on Windows 10 on a PC (E5-1620 3.50 GHz Xeon CPU, 16384 MB RAM, NVIDIA Quadro K2200 graphics card).

4.1.1 Vibration Control Result

The system was tested with two vibration profiles of impulse and sinusoidal disturbance. These two profiles are the most commonly occurring, based on our observations in the preliminary experiment which are the vertical displacement and vertical velocity results of the system with and without LQG control disturbed by impulse and sinusoidal vibration, respectively. Clearly, with the LQG controller, the impulse is compensated by 33.52% and 89.83% (0.0812 cm on average) for the sinusoidal vibration. In addition, the system with LQG control maintains 0.0092 cm vibration from the beginning of the simulation and remains constant through to the end of simulation. This differs from the system without LQG control, which has 0.0904 cm of average vibration throughout the simulation.

4.1.2 Flying Motion Control Result

We developed the flying simulation in order to evaluate the performance of our controller system. We tested a hybrid robot with a ground truth as a sinusoidal trajectory with some inconsistencies. The robot was assigned to fly from the top position to the ground position as shown in Fig. 5. This trajectory involves a vertical transition along the Z axis and many turning points, which is a good test route to visualise the position error induced by arm vibration and how the LQG controller with active vibration improves the robot's motion.

Figure 5 shows a comparison of the robot trajectory with the LQG controller and without the controller. Both were disturbed by a sinusoidal vibration profile. The sinusoidal vibration generates high noise levels that make it difficult for the robot to follow the reference trajectory with the overall error of 0.0071, 0.0077, and 0.0079 m along the X, Y and Z axes as presented in Fig. XX. The hybrid robot with the LQG controller can follow the trajectory with an acceptable average error of 0.0015 m.

4.2 Anti-gravitational Walking motion

Apart from using air pressure from rotor to fly, our innovative solution is to use air pressure and permanent magnetic for anti-gravitational motion. Once the robot fly to the surface, controlling robot to stick with metallic plate and perform hammering test is challenging. We apply the hovering backward as we want air pressure power vector perpendicular to the surface to support permanent magnet while receives a feedback from pressure sensor to balance itself on the steel. We realized that vibration can actually reduce attractive force at a contact between permanent magnet and steel plate (presented in Fig. 3) similar to the process of reducing friction force.

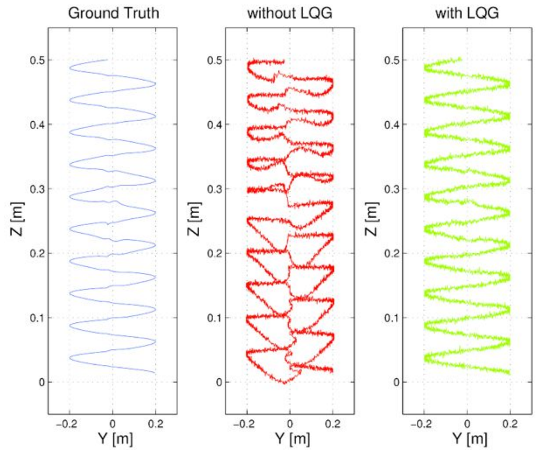

Fig. 5: the result of flying motion compared with ground truth

4.3 User Interface Testing

We have developed system interface as shown in Fig. 4. For analysis, we conducted one-way repeated-measures analyses of variance (ANOVA) and followed with paired t-tests (Bonferroni-corrected) as necessary.

4.3.1 Collisions

Participants with access to our adaptive view (AV) had a smaller average number of collisions than those using a first or third person view. Paired t-tests confirmed a significant effect of method for FV vs. TV (t_{11} = 1.76, **:$P < 0.05$), for FV vs. AV, with (t_{11} = 7.52, ***: $P < 0.01$) and TV vs. AV, with (t_{11} = 10.87, ***: $P < 0.01$).

For 3D experiments, having access to the 3D immersive view helped participants avoid collisions. We found significant effects for 3DV vs. 3DAV, with (t_{11} = 1.93, *: $P < 0.1$). Participants who utilized the adaptive view exhibited less collision variance compared to 3DV. Being able to view from multiple angles also likely contributed to the consistent collision errors.

4.3.2 Time

In the 2D experiments, participants with access to our adaptive view (AV) had a smaller average time-to-goal than those using a first-person view but larger than those using a third person view. We found a significant effect for FV vs. AV, with (t_{11} = 15.86, ***: $P < 0.01$) and FV vs. TV, with (t_{11} = 8.60, ***: $P < 0.01$). However, no significant effect found for TV vs. AV, with ($t_{11} = 0.37$, $P = 0.35$). This might be expected, as participants were told to focus on avoiding collisions and not to care about how much time they took. One possible explanation for this is that participants appeared to be more careful in the adaptive view case and would often wait for the camera to finish moving to make a decision. This was especially true when they neared walls, which may have added overall time to reach the goal. This will likely vary based on use case.

For 3D experiments, we found a significant effect for 3DV vs. 3DAV, with ($t_{11} = 4.35$, ***: $P < 0.01$). Participants with access to our 3D adaptive view (3DAV) had a smaller average time-to-goal than those using a 3D view.

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