論文の内容の要旨
Abstract of Dissertation

Failure-Tolerant Control and Vision-Based Navigation for Hexacopters
（ヘクサコプターのための耐故障制御と視覚に基づくナビゲーション）

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The research summarized in this thesis is motivated by the events at the Fukushima Daiichi nuclear power plant that resulted from the 2011 Tohoku earthquake and tsunami. Those events exposed the need for an autonomous vehicle that can be deployed remotely to closely inspect a facility that is no longer accessible by personnel. Two key elements of this mission have been identified as requiring further research. First is the need to improve safety to avoid risk of damage or injury due to a crash while in transit to the remote location. Second is the need for a sensor that can provide position measurements with much greater precision than GPS or in environments where GPS is not available.

I. Outline

Chapter 1 introduces the hexacopter rotorcraft configuration and compares it to other types of hovering aircraft. Previous research on the subjects of fault-tolerant control of multicopters and vision-based navigation Is reviewed.

Chapter 2 introduces the equations of motion that describe hexacopter flight. The various forces and moments that are applied to the hexacopter are cataloged and modeled. A linear model is developed for use in designing a simple Linear Quadratic Gaussian (LQG) controller.

Chapter 3 proposes an adaptive controller that can simultaneously estimate and adapt to changes in actuator effectiveness with guarantees on speed of estimation. An error projection operator is proposed for projecting 4 error measurements to the 6 motors/propellers of the hexacopter. A method for smoothly reconfiguring upon detection of total loss of effectiveness is discussed.

Chapter 4 introduces the PTAM algorithm, which is the basis for the proposed vision-based navigation. The merits and limitations of PTAM for vision-based navigation are discussed. Several improvements are proposed to enhance the utility of PTAM for robotic navigation. Extensions for control and communication with an embedded attitude controller are presented.

Chapter 5 introduces the flying testbed that was used for control and navigation experiments. It is composed of a Mikropkopter Hexa XL hexacopter paired with a custom computer-vision package based on a Mac mini computer. The experimental embedded software that was developed to facilitate this research is discussed in detail.

Chapter 6 presents data collected from simulated and real flight tests to evaluate the performance of the methods and systems described in the preceding chapters. As a first step, a baseline controller is evaluated. Next, test results that demonstrate the precision of vision-based position estimation are presented. Then, data recorded from a successful indoor autonomous navigation task is shown. Finally, a series of simulated trials demonstrate the ability of the failure-tolerant controller to adapt to a total propeller failure and compares its performance to the baseline controller in normal operation or when subject to disturbances.

Chapter 7 concludes the thesis with a discussion of the proposed failure-tolerant control and high-speed vision-based navigation system. The merits and deficiency of each are summarized and suggestions for future work are listed.

II. Failure Tolerance of a Hexacopter and its Relatives

Some common configurations for hovering rotorcraft are: traditional helicopters, tricopters, quadrotors, hexacopters, and octocopters. Of these, only the hexacopter and octocopter configurations remain controllable after any single actuator failure. For hexacopters, the propeller opposite the one that has failed must be operated near zero speed in order to maintain control, so that the weight of the vehicle is carried primarily on four of the six propellers. A few select configurations are shown in Figure 1.

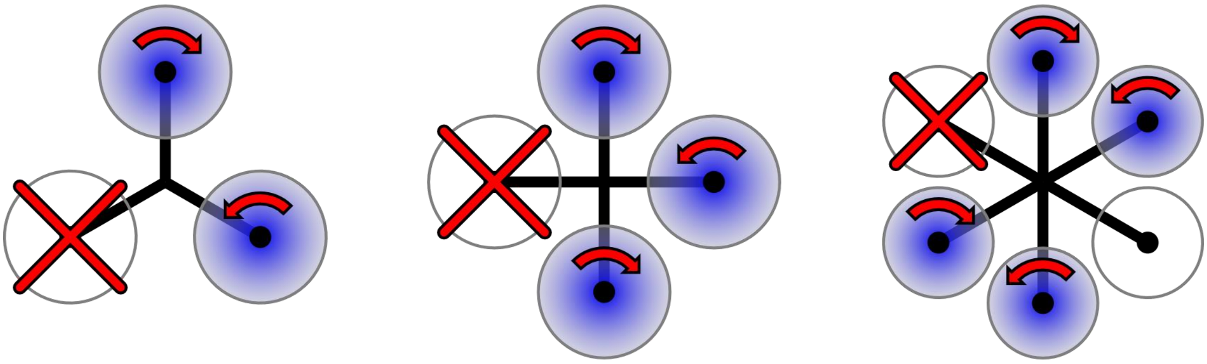

Figure 1: A failed propeller in the case of a tricopter, hexacopter, and hexacopter.

III. Control of a Hexacopter

For a traditional helicopter, control of the roll, pitch, yaw, and vertical accelerations is decoupled through clever mechanical design. In the case of quadrotors, hexacopters and octocopters, decoupling is typically accomplished through the use of a signal processor that actively converts decoupled body-axis moment and thrust commands into individual propeller speed commands by inverting the system dynamics. For a quadrotor, this inversion is straightforward since the 4 propellers each orthogonally affect the 4 degrees of control freedom, so the actuation matrix is square and invertible. A hexacopter however, is an over-actuated system (it also has only 4 degrees of control freedom, but has 6 actuators), so the actuation matrix is not square and cannot be inverted. Rather, there exist an infinite number of pseudo-inversions. Taking the Moore-Penrose pseudo-inverse results in propeller speed commands that are symmetrically distributed.

With the dynamics decoupled, feedback control can be applied separately to each degree of control freedom. In the case of attitude control, typically only angular rates are measurable from the IMU, but the other states are observable, so an observer (e.g. a Kalman filter) may be used to estimate the other states in order to arbitrarily place the poles of the closed-loop dynamics with state feedback.

IV. Adaptive Control

IV.A. Adaptation to Control Effectiveness

For a critically actuated system such as a quadrotor (where the number of actuators matches the number of degrees of control freedom), an adaptive law is proposed that simultaneously estimates and adapts to changes in actuator effectiveness. This is achieved by comparing the measured state rates to those predicted by a model of the system. The error between the two is projected back to the actuators by inverting the actuation matrix. A combination of the projected error and the actuator command is then used to drive the effectiveness estimate for each actuator. The model actuation matrix combined with the estimated effectiveness is then inverted to compute a new control signal. The control inversion and adaptive law are structured such that, under nominal conditions (i.e. the system is well modeled, the real actuator effectiveness is not changing, and the propeller speed commands are away from zero), the effectiveness estimates will approach their true values exponentially with a time constant that is the reciprocal of the adaptive gain.

IV.B. Sensitivity

The adaptive law described in the above section is analyzed for sensitivity to disturbances, measurement noise, and modeling uncertainty. It is found that a fundamental trade-off exists between the speed of convergence and the sensitivity to disturbances, noise, and uncertainty in the state function, especially for small actuator commands. A sufficient condition that guarantees stability in the presence of modeling uncertainty remains an open area of investigation.

IV.C. Extension to the hexacopter

In the case of a hexacopter, even with perfect measurement of the state and state rates and perfect knowledge of the propeller speeds, it is not possible to determine the effectiveness of 6 actuators from only 4 measurements. Rather, there exists an infinite possibility of combinations of actuator effectiveness that could result in the measured error. Some extra information is required to find a unique solution to this system, which has six unknowns with only four relationships.

This thesis proposes applying likely constraints in order to make the problem solvable. For example, it could be assumed that 5 of the 6 actuators are performing close to design effectiveness and only 1 actuator is deviant. This constraint effectively reduces the number of unknowns from 6 to 1. When examining each possible deviant propeller, there are 4 equations and only 1 unknown. Each set of 4 equations can be solved for each propeller, and the propeller with the least variance in its solutions is guaranteed to be the propeller with the most deviant effectiveness. However, no information is learned about the effectiveness of the other propellers.

Another possible constraint could be to assume that 3 propellers have some nominal deviation from design effectiveness and the remaining 3 have unique deviations from design effectiveness. This constraint reduces the number of unknowns from 6 to 4. While it has the potential to give much higher fidelity in the effectiveness estimates for each of propeller, it turns out that many of the possible scenarios are not testable due to symmetry in the actuation matrix which leads to singularities in many cases.

Several other possible constraints lie in between the two mentioned above. It is determined that the only practical constraint is to assume that 5 of the propellers have some nominal deviation from design effectiveness and 1 propeller is uniquely degraded. This constraint allows for adaptation to uniform differences in actual performance and allows detection and adaptation to partial or total degradation of a single propeller.

Replacing the projection of measured error through inversion of the actuation matrix with the projection operator described above effectively extends the adaptive law to the case of the hexacopter.

V. Vision-Based Navigation

V.A. PTAM

Parallel Tracking and Mapping (PTAM) is an algorithm developed by Klein and Murray at the University of Oxford for the purpose of simultaneous localization and mapping (SLAM) for augmented reality. As its name implies, this algorithm divides the localization task and the map building task into separate parallel threads to improve performance. "Map building" refers to the process of storing the location of observed features for future comparison, even after those features have exited the field of view. "Localization" refers to the process of matching currently observed features to those stored in the map to attempt to determine the current position and rotation of the camera relative to the origin of the map.

V.B. Modifications

The PTAM algorithm was originally designed for use with augmented reality, where the position of a camera is tracked so that artificial objects can be superimposed onto the scene of the real world. Several modifications have been made to adapt the algorithm to the task of autonomous navigation.

PTAM arbitrarily sets the orientation and scale of the map upon initialization. Some extra information is required to align PTAMs map with world coordinates. The ability to recognize a fiducial marker of known size was added so that origin and scale of the map could be aligned to the marker.

In the case of augmented reality, it is not expected that the camera will move large distances, but that is not true for navigation. An expanding map consumes increasing computation time and memory and will saturate at some point. To alleviate this risk, additions to the database were made more judicious.

For augmented reality, much of the computation is involved in rendering the scene. For navigation, rendering is only necessary for visual confirmation of proper tracking and therefore can be made much lower priority. To increase performance, rendering and some other functions, were split into separate threads of execution so that tracking could be performed as quickly as possible.

VI. Experimental Results

VI.A. Failure-Tolerant Control

Unfortunately, it was not possible to perform flight tests with the adaptive controller that is proposed in this thesis. However, its performance was tested extensively in simulation. Results are presented that show that this method can quickly recover in the case of a single propeller failure. It can also accurately estimate the changing effectiveness of several propellers. However, it is also shown that typical performance is degraded compared to the baseline, non-adaptive, controller. Furthermore, strong disturbances may cause instability. The hexacopter is particularly sensitive to yaw disturbances with this control scheme.

VI.B. Vision-based navigation

A pair of experiments compares the precision of position estimates from PTAM to those from GPS and a high-precision motion capture system. In these experiments a camera recorded downward-looking video aboard vehicles whose positions were tracked either by GPS or a motion capture system. The recoded video was post-processed with PTAM and the resulting trajectory was compared. It was found that the system is capable of accuracy on the order of a few centimeters.

Another experiment investigated the ability to perform indoor autonomous navigation using the proposed vision system. In this experiment, the hexacopter autonomously repeated a circuit of takeoffs and landings at 3 waypoints. The circuit was repeated 5 times. It was found that the navigation was drift free and landing was accurate to within 20 cm.