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A quad-rotor system for driving and flying missions by tilting mechanism of rotors: From design to control

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ABSTRACT

This article presents the hybrid design and control of a quad-rotor system called Flymobile. Flymobile is a combined system of a mobile robot and a quad-rotor system aimed to perform both flying and driving tasks. Flymobile performs flying tasks in the same way as conventional quad-rotor systems while the tilting mechanism of each rotor allows Flymobile to navigate in its terrain for a driving task. The body frame with rotors is implemented by a calibration process through a test-bed equipped with a force sensor. The triangular wheel frame is designed to mimic motions of a mobile robot with three passive wheels. Sensor data of a gyro and an accelerometer are filtered and used for controlling the attitude of the system. Focusing on a practical approach of implementing a hybrid system, a non model-based approach is applied to control Flymobile. Experimental studies are demonstrated to show the feasibility of performing both driving and flying missions.

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1. Introduction

Recently, research interest in unmanned aerial vehicles (UAVs) has been enormously increased. Successful missions performed by UAVs in the war zone as a military weapon have accelerated research in UAVs in many countries. Most of successful UAVs have a conventional take-off and landing (CTOL) structure that is suitable for a long range plan such as a surveillance task at remote areas. UAVs with the CTOL structure do not concern about the space for take-off and landing since they require enough space in wide areas.

In other aspects, however, UAVs can also be used for surveillance tasks in urban areas where a lot of buildings are surrounded. UAVs are often required to navigate between buildings to obtain information. This leads to the priority of using a vertical take-off and landing (VTOL) structure of UAVs. One of UAVs with the VTOL structure is a helicopter that has been around for many years [1–5]. Miniature design of mimicking a single rotor system has been introduced [5]. Although helicopters have great advantages of VTOL and hovering posture, an abrupt change of direction is not easily maneuvered and even of danger. Moreover, the backward movement of a helicopter is difficult from the hovering posture since it is not designed for omnidirectional movements in the sky.

Since the omnidirectional movement is preferred in the narrow space, quick movements help UAVs to improve maneuvering performances greatly. This requirement leads to the usage of a quad-rotor system that has four symmetrical rotors. Using four rotors provides several advantages. Firstly, hovering control performance can be achieved more easily than a single rotor system. This enables quad-rotors to cooperate each other for carrying objects together [4]. Secondly, control of quad-rotor systems is much easier than that of a single rotor system. Movements of a quad-rotor system are generated by controlling the velocity of each rotor instead of controlling the blade. This leads to an omnidirectional structure. Thirdly, payload to lift and carry objects can be increased since more rotors are used.

In the framework of the quad-rotor system design, many control algorithms have been proposed through simulation studies [6–16]. A nonlinear control method [6], a simple linear control method [7], and an inverse dynamics control method are applied to improve control performances [9]. Intelligent control approaches using neural network have been presented as well [12,14].

In practice, physical quad-rotor systems are developed and presented [17–26]. A quad-rotor system is controlled on the test-bed with a quaternion-based feedback control scheme [18]. Aggressive maneuvering control has been demonstrated based on PIDA controllers [20]. Recent research on quad-rotor systems is focused more on autonomous navigation through localization with the help of sensor fusion [21] and vision information [22–26].

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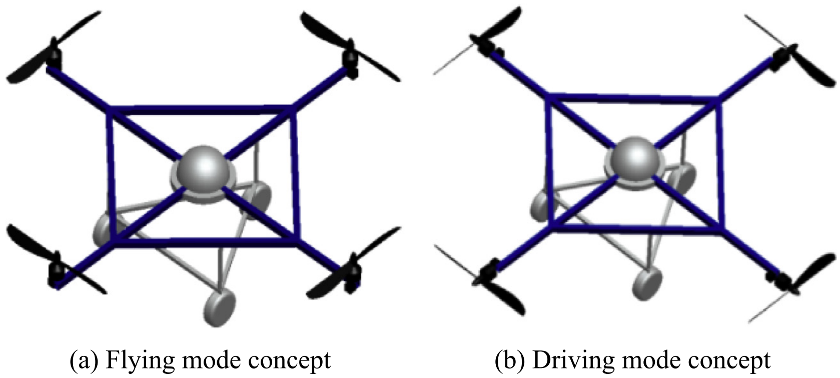

Fig. 1. Design concept of Flymobile.

All of aforementioned research topics are concerned about the flying capability of quad-rotor systems. Both driving and flying operations of a quad-rotor system are rarely considered [27–29].

In this article, therefore, a novel hybrid design concept of a quad-rotor system having both flying and driving capabilities is presented [30]. The design concept of Flymobile for flying and driving is shown in Fig. 1. Each rotor can be tilted up for the flying mode as in Fig. 1(a), and is stretched out for the driving mode as in Fig. 1(b). For a driving capability, the base of the wheel frame is designed as a triangular shape which is easier to steer since it is constrained kinematically in the lateral direction.

A gyro and an accelerometer are used for detecting angles and output signals are filtered out by the complementary filter and the Kalman filter. Filtered signals are used for linear controllers to regulate the velocity of each rotor for attitude control. Calibration of making each rotor's force even by using a force sensor is performed. Each rotor having a tilting mechanism enables both driving and flying capabilities.

Since a practical approach of implementing a hybrid quadrotor system is focused, a non model-based control method is applied. Control gains are selected by empirical studies. Experimental studies of both flying and driving tasks of Flymobile are performed to demonstrate the feasibility of the concept of a future flying automobile.

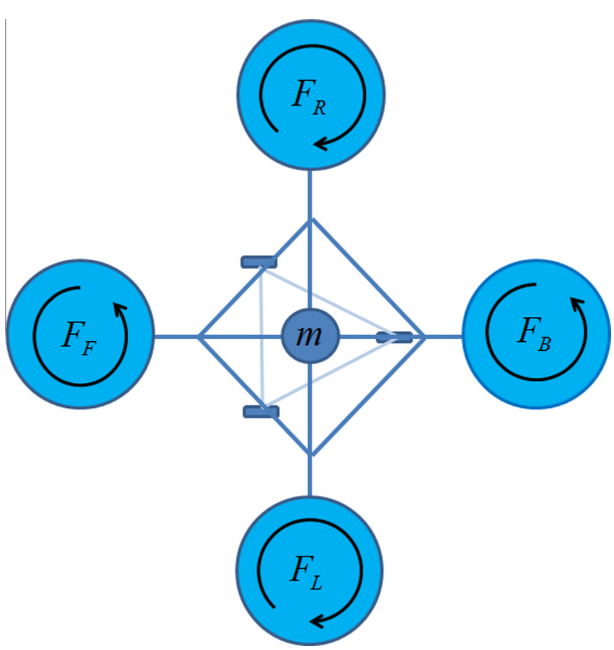

Fig. 2. Flying operation of Flymobile.

2. Operation of a quadrotor system

2.1. Flying operation

Flymobile has a symmetrical structure and four rotors are assumed to produce an equal thrust force as shown in Fig. 2. A pair of front (F) and back (B) rotors rotates in the counterclockwise direction and a pair of left (L) and right (R) rotors rotates in the clockwise direction to prevent the body from rotating. Directional movements can be generated by combining thruster forces induced by each rotor.

Table 1 lists the operational patterns of all directional flying movements of Flymobile. For example, Flymobile can fly up by summing the velocity of each rotor under the assumption that the characteristic of each rotor is same.

2.2. Driving operation

Using the concept of a mobile robot, three passive wheels are formed a triangle so that a driving operation can be defined as in Fig. 3. Flymobile navigates by a combined force of each rotor. The back wheel is a pin jointed and two front wheels are omni-directional so that the heading angle can be changed by rotors.

The driving operation is somewhat different from the flying operation listed in Table 1. To move forward as described in Fig. 3(a), the back force F_B is required to be smaller than the front force F_F and vice versa for the backward movement. Turning operations are different from the flying operation. To make the right turn, the left force F_L is chosen to be smaller than the right force F_R to push the body to the right as shown in Fig. 3(c) and vice versa for the left turn as in Fig. 3(d). Table 2 lists the driving operations of

Table 1
Flying motion command by rotor speed control.

	Front rotor F_F	Right rotor F_R	Back rotor F_B	Left rotor F_L
Move up	⇑	⇑	⇑	⇑
Stationary	↑	↑	↑	↑
Move down	^	^	^	^
Move forward	⇑	↑	^	↑
Move backward	^	↑	⇑	↑
Move left	↑	^	↑	⇑
Move right	↑	⇑	↑	^
Turn left	⇑	^	⇑	^
Turn right	^	⇑	^	⇑

(Relative scale: ⇑ > ↑ > ^).

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