MODELING OF QUADROTOR DYNAMICS FOR RESEARCH AND TRAINING SIMULATOR

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Abstract

The simulator was designed and assembled for the small remotely controlled quadrotor being developed for surveillance and reconnaissance tasks. The purpose of the simulator is to train the quadrotor operators, both beginners and advanced. The quadrotor simulator architecture was based on software structure of existing reconfigurable simulator of mobile platforms. It required adequate modeling of aeromechanic properties of the rotorcraft and proper computer program structuring and coding. The model should be efficient enough to work in real time, and reflect the flying qualities of designed rotorcraft.

1. INTRODUCTION

The quadrotor seems to be the most popular type of UAV architecture, being investigated by vast amount of companies, research institutes and of course universities [1]. There are several reasons for this fact. There is a great interest in small, unmanned aircraft both in civil and military users. The rotorcraft provide unique capability of hover, vertical, forward, backward and sideward flight. The quadrotor seems to be the configuration easy to design and build. The control of quadrotor is simpler comparing to other rotorcraft configuration, the cross-couplings between the degrees of freedom are not so severe as for single rotor helicopter and are easy to cope using the simple classical control algorithms. The quadrotor is also an efficient, versatile testbed for complex control and navigation algorithms and various types of payload, see e.g. [2], [3], [4]. Quadrotors have very good handling qualities, and are easy to fly. Small unmanned quadrotors are powered by electric motors driving fixed-pitch propellers. The multirotor configuration results in a very stable flight while electric motors powering fixed-pitch propellers result in a low vibration level and an ease of control by varying the rpms of each engine.

The research reported in this paper was a part of the project devoted to development of an unmanned system based on the quadrotors. The main objective of the part reported was to develop the simulator of the quadrotor being parallely designed and built by other team of the project consortium.

2. SYSTEM REQUIREMENTS

The quadrotor was to be under 5 kg of total weight class, remotely operated for surveillance and reconnaissance missions. The main payload to be implemented in a simulator was a camera with one controlled degree of freedom and a zoom controlled by a quadrotor operator from a single console. The system should have some autonomy, such as flying between the waypoints and returning to the starting point. From simulator point of view it was important to build the reliable simulation model of rotorcraft with autopilot cooperating with the console provided by system manufacturer.

The simulator developed within the project should allow two modes of operation: a manual control of a vehicle with visual representation of the quadrotor (just as in the case of RC simulators for hobby users) and an automatic control of a vehicle using the ground control station with all the functions for defining waypoints and tasks to be performed. The latter mode should also allow to control the camera mounted on the quadrotor and to present the view from this camera on the screens of the ground control station. The simulator is composed of the COTS (commercial off the shelf) components, including PC class computers to reduce its design, manufacturing and operational costs, and to provide an option of easy upgrading its modules.

3. SIMULATOR CONFIGURATION

From the operator point of view the simulator is composed of computer station, monitors and an console used in a real system. There is also an instructor stand for supervising the quadrotor operators during their training sessions. A hardware configuration (number of computers and monitors, distribution of software modules on computers and distribution of software windows on monitor screens) is individual for each implementation and depends on several factors (eg. available room, level of mobility, etc.). Fig.1 shows sample configuration used during internal test in DAAS.

Fig. 1 The general view of the quadrotor training simulator

The simulator was built at the same time as the quadrotor system was developed, so the quadrotor layout and console from previous project were used (Fig.2), which are to be replaced with its final version at the end of this project.

Fig. 2 Quadrotor and operator console.

It was decided to use software architecture of an existing reconfigurable, research simulator as the basis for development of quadrotor simulator. This software has open, modular architecture allowing for modifications, extensions and enrichment during and after the project. The hardware architecture of the simulator consists of an operator console, a visual system with dedicated hardware and software modelling the operation of vehicle.

A visual system of the simulator allows a wide range of view, placing the operator in the middle of the action field. There is also possibility of placing operator outside of visualization screen, simulating the UAV operation from remote place with no direct scene visibility.

For quadrotor operator training the existing terrain data base was implemented. This database was developed in 3DS MAX and converted into OpenSceneGraph simulation environment. The data base contains the area of 200x200 meters (650x650 feet) size, at which many various kind of infrastructure (buildings, railway station, wagon, various surface: concrete, grass, etc.) was placed for obstacles. This virtual training area is used also for ground robot operator training.

Fig. 3 Sample view of part of virtual training environment.a) from quadrotor camera, b) from outside the rotorcraft

The simulation software has an open, modular and hierarchical architecture (Fig.4) allowing to change software modules during the project, and also to develop components of simulator by various teams working almost independently. The requirements that modules work in a real-time should be fulfilled.

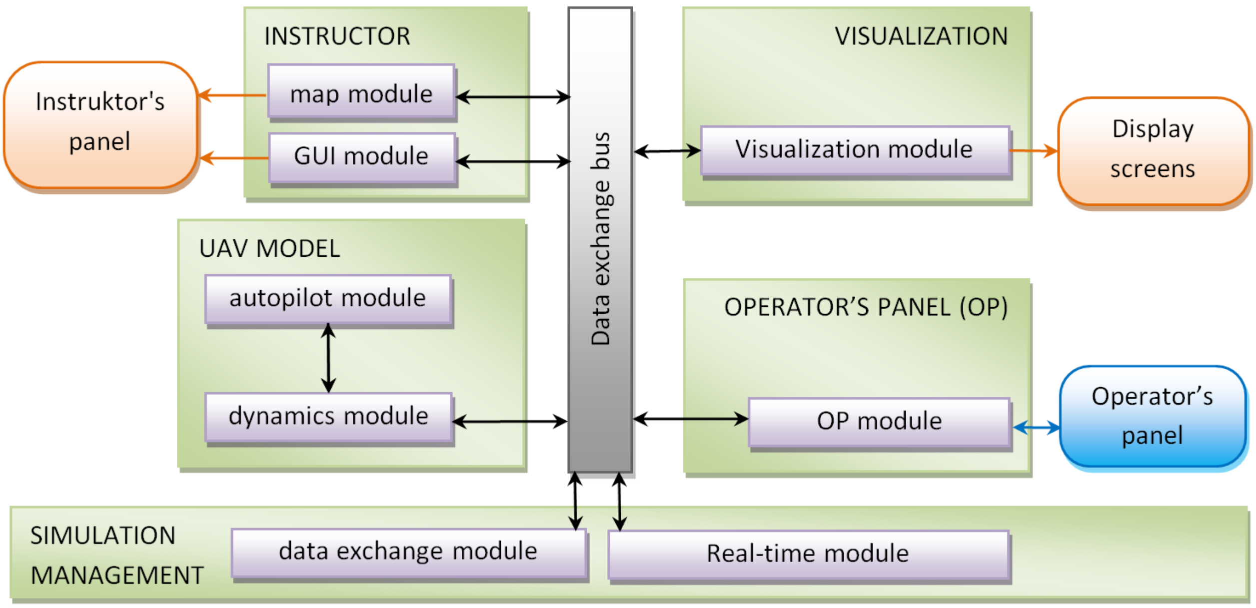

Fig. 4 Simulator software architecture

4. QUADROTOR SIMULATION MODEL

Two quadrotor simulation models were developed one for supporting design of quadrotor and the second one for implementation to simulator. The necessity to build two models stems from different requirements which models should fulfill for each of these two purposes. For supporting a design process all the crucial details of the quadrotor should be modeled to allow for sensitivity and parametric studies. The fundamental assumptions for the model development for simulator were to assure the real-time operation together with a very good correlation between the model and the real vehicle behavior, so the proper balance between the simulation computational load speed and the simulation quality was required.

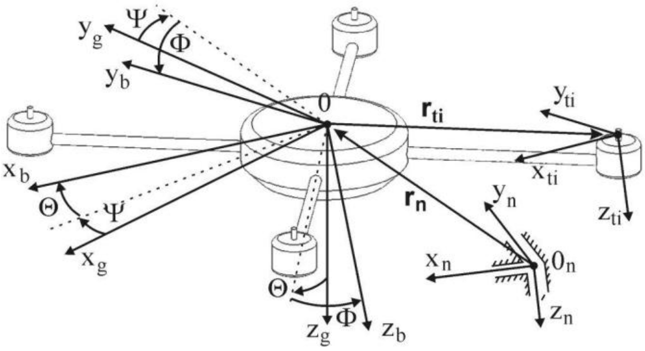

Fig. 5 Main systems of coordinates used in the quadrotor dynamic model

Both models were based on several common assumptions;

- all parts of the quadrotor are rigid,
- quadrotor is axially symmetric,
- quadrotor is controlled in "x" configuration,
- axes of the lifting rotors are parallel to the body axis of symmetry,
- mass of the vehicle is constant,
- equations of motion describe the motion of the body center of mass,
- induced velocity is modeled with the Glauert formula for forward flight.

Based on these assumptions, a nonlinear equations of quadrotor dynamics were obtained in a general form [5], [6]:

(1) $$\mathbf{I_p}\dot{\mathbf{x}} + \mathbf{\Omega}(\mathbf{x})\mathbf{I_p}\mathbf{x} = \mathbf{f} \ ,$$

(2) $$\dot{\mathbf{y}} = \mathbf{T}\mathbf{x}$$

where:

$\mathbf{x} = [U \quad V \quad W \quad P \quad Q \quad R]^T$ is the state vector composed of linear velocities and angular rates, $\mathbf{y} = [x_g \quad y_g \quad z_g \quad \Phi \quad \Theta \quad \Psi]^T$ is the vector describing position and attitude of the vehicle, $\mathbf{I_p}$ is the inertia matrix, $\mathbf{\Omega}(\mathbf{x})$ is the matrix of linear velocities and angular rates [6], $\mathbf{f}$ is the vector of total loads acting on the quadrotor expressed in the body system of coordinates and $\mathbf{T}$ is the transform matrix resulting from the kinematic equations [5], [6].

The left hand sides of the equations of motion (1) are standard descriptions of rigid body with six degrees of freedom.

The right hand sides of the equations contain gravity $\mathbf{f_{GK}}(\mathbf{y})$ and aerodynamic loads calculated as two components: the aerodynamic loads of the fuselage $\mathbf{f_{AK}}(\mathbf{x},\mathbf{y})$ and the aerodynamic loads generated by the rotors $\mathbf{f_{AW}}(\mathbf{x},\boldsymbol{\delta})$, so eq.(1) takes the form

(3) $$\mathbf{A}\dot{\mathbf{x}} + \mathbf{\Omega}(\mathbf{x})\mathbf{I_p}\mathbf{x} = \mathbf{f_{GK}}(\mathbf{y}) + \mathbf{f_{AK}}(\mathbf{x},\mathbf{y}) + \mathbf{f_{AW}}(\mathbf{x},\delta_i) \ ,$$

where δ_i is the i-th engine control signal.

In both simulation models the gravity and fuselage aerodynamic loads were calculated in the same way. Gravity loads were calculated in a standard way for the 6 DoF platform. For aerodynamic loads it was assumed that the fuselage generates only drag and the drag coefficients were calculated using simple geometrical model of the fuselage [6]. The vector of rotor loads $\mathbf{f_{AW}}$ is the sum of the loads of each rotor transferred to the body system of coordinates.

$$\mathbf{f_{AW}}(\mathbf{x},\delta_i) = \sum_{i=1}^{4} \mathbf{f_{AWi}}(\mathbf{x},\delta_i) \ .$$

The difference between both simulation model was mainly in the way of calculating the aerodynamic loads of the rotors. Both methods will be described in the following chapters.

Research simulation model

The main purpose for developing the research simulation model was to support the design of the quadrotor as well as the necessity for having a baseline model for verification of the other - simplified model. As the requirement for real-time operation was not important in the case of the research model, typical approach of the blade element theory was applied in calculating the aerodynamic loads of the rotors.

In the first step, geometry of a fixed-pitch 15 inch propeller, chosen by the partners responsible for quadrotor design and manufacturing was checked using laser scanning method. Results of this work was the distribution of chord, twist and airfoils. The airfoils were compared with the standard airfoils database and best matching airfoils' characteristics were used in calculations. The induced velocity was calculated using Glauert formulas for axial and forward flight.

In the next step of the research the selected propeller was tested in the wind tunnel and its thrust and torque were measured for a set of inflow angles and wind speeds. Then the results of the wind-tunnel tests and the calculations were compared. Sample results for hover are presented in Fig. 6.

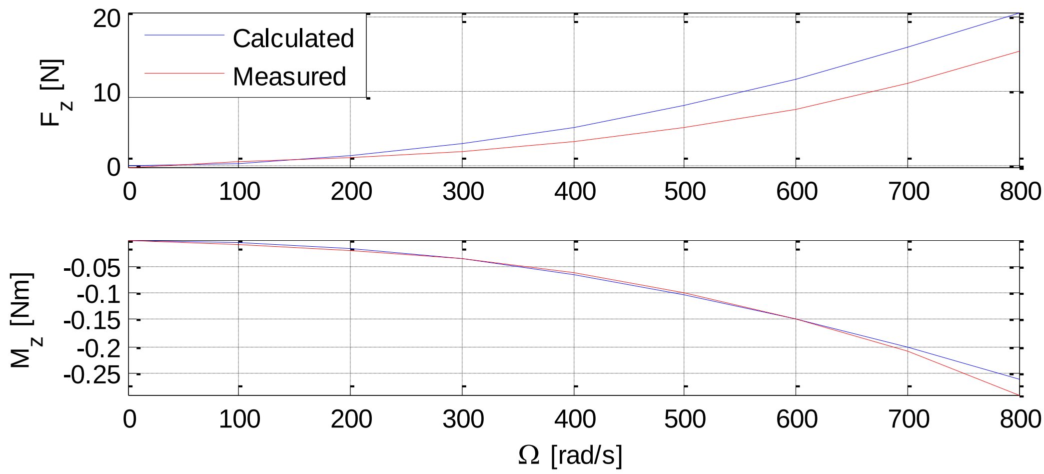

Fig. 6 Comparison of measured and calculated propeller thrust and torque

As may be noticed form the presented results the calculated thrust (F_z) is overestimated while the torque is approximated quite well. During a validation process such comparisons were performed for the whole set of wind speeds and inflow angles, and the correction factors for lift and drag coefficients of the airfoils were calculated. The result of characteristics for the hover case with corrected lift and drag coefficients is presented in Fig. 7.

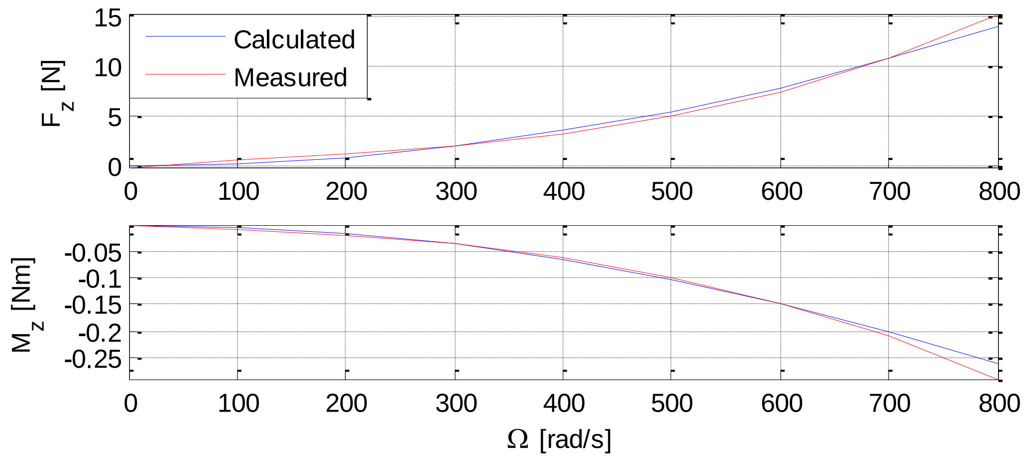

Fig. 7 Propeller thrust and torque after validation of the model

The validated propeller model is used in the research simulations and also was the basis for development of the simplified, real-time model.

Real-time simulation model

The real-time simulation model was developed to be used in the unmanned system flight simulator. Because of the real-time operation requirement some simplifications in comparison to the research simulator were introduced. It was decided to replace the calculated aerodynamic loads with the map of pre-calculated loads of a specific propeller. Using the validated model of the propeller presented earlier the database of propeller loads was prepared. All six elements of propeller aerodynamic loads were calculated for various inflow angles and speeds. Such a map of loads is loaded during simulation and loads of each propeller are interpolated separately. Such an approach allows for quick operation of the aircraft model and still maintains good correlation with the modeled object performance.

For simulator tests an autopilot system was developed. The functionality of the autopilot allows vehicle speed, altitude and azimuth control. The autopilot is based on the classical approach using mainly PID controllers. In the final version of the simulator a new autopilot model will be implemented based on the real hardware configuration developed for the quadrotor by other partners of the project.

5. QUADROTOR MODELS VALIDATION

Currently the hardware for models validation is in being assembled and tested in the laboratory. The measurement system consists of IMU sensor, GPS receiver, magnetic compass, pressure sensors and recorders of the control inputs. After completion of the laboratory tests, the flight tests will be performed and models validation will be done using time domain identification methods.

6. CONCLUSIONS

The quadrotor simulator for research and training application was built in Warsaw University of Technology. Two simulation models of the quadrotor were developed for research and simulator purposes. The supporting research of rotor characteristics confirmed the methods of calculation of rotor aerodynamic loads.
The flight test of the quadrotor (scheduled end of September this year) will be used to validate and tuning the simulation model.

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