DEVELOPMENT OF AN UNMANNED QUADROTOR: SYSTEM AND SIMULATOR

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Abstract

In the paper the results of the project aimed at developing an unmanned system using a quadrotor rotorcraft for Intelligence, Surveillance, Target Acquisition, and Reconnaissance (ISTAR). The project was performed by a consortium composed of the private company WB Electronics and Warsaw University of Technology. The quadrotor was designed to fulfil missions in various environment including urban operations. In the paper the project results are presented focused on quadrotor simulator, applied simulation models and autopilot.

1. Introduction

In 2011 Polish National Centre for Research and Development published the call for proposal for development of a small unmanned rotorcraft. The project was granted to the consortium of the WB Electronics (private company) and Warsaw University of Technology. Initiating this project Polish Ministry of National Defence acknowledged the importance of small unmanned rotorcraft for military applications. This was a natural step for development of the systems that already had proven their operational characteristics in many areas like hobbyists, professional video recording, and research in academia and institutes.

Quadrotors unique flying qualities make them perfect platforms for use in observation system. The main advantages are stable behaviour, low vibrations, quiet flight and an easy maintenance, which is important in military day - to - day operations. The difference between the project presented and similar projects in Poland and abroad was the requirement to achieve technology readiness level TRL 9 for a small quadrotor, which means that a prospective system should prove fulfilling missions in an operational environment. This requirement was combined with short time for the project duration, which forced Consortium to focus mainly on practical application aspects not on a pure research.

2. SYSTEM REQUIREMENTS

The main requirements for the system published with the call for the proposals in 2011 were:

1. *max take-off weight – 5 kg*
2. *operational radius with the maximum take-off weight – not less than 2 km (including urban operation),*
3. *max ceiling – not less than 3000 m a.s.l. (not less than 250 m above the take-off point)*
4. *operational ceiling 5-100m*
5. *flight endurance – min 30 minutes*

6. *max horizontal speed – not less than 40 kph*
7. *continuous transmission of the digital video data in real time*
8. *automatic flight using predefined route waypoints*
9. *ability to modify the waypoints in a real time during mission*
10. *ability to work in highly dusty conditions*
11. *payload equipment should allow for day and night observation with aim to recognize and identify various objects.*
12. ***system should include training device based on the real operator console.***

3. SYSTEM DEVELOPMENT

The architecture of the developed unmanned quadrotor system is typical for these classes of systems and consists of: Ground Control Station (GCS), radio link, unmanned rotorcraft, electro-optical payload. Also a training simulator had to be developed to support pilot training. All quadrotor system components were developed and build by the WB Electronics. The simulator was developed at Warsaw University, in Department of Automation and Aeronautical Systems.

During the project several ideas for the main airframe were tested, among others was the airframe in shape of an H letter (Fig. 1)

Fig. 1 One on quadrotor airframe designs investigated during project

After several iterations the designers decided to use the cross-shape of the airframe (Fig. 2).

Fig. 2 Final shape of the quadrotor airframe

The quadrotor was design in the „x" configuration. The central body contains all electronic equipment including autopilot system with sensors, radio-links for data and video transmission, electro-optical payload, and batteries.

Total weight of the platform with batteries for 35 minutes of flight and electro-optical payload was around 3 kg. The payload included a day-night video camera (Fig. 3) or a photo camera with laser range finder (Fig. 4)

Fig. 3 Day/night video stabilised camera

Fig. 4 Stabilised photo camera with laser range finder

The Ground Control Station (GCS) was build using a Getac E 110 ruggedized tablet (Fig. 5).

Fig. 5 Getac E110 tablet used for quadrotor ground station

The GCS allows presentation of all the information about platform and mission status including digital map of the terrain and window for presenting video data from the payload. The GCS also allows controlling the vehicle in a semi-autonomous mode using virtual joysticks.

The system contains also radio links, spare batteries, batteries charger, maintenance tools and transport backpack. The total weight of all the system components is around 14 kg.

The presented system was proven to fulfil all the requirements stated in the call for project by the Polish National Centre for Research and Development.

4. SIMULATOR DEVELOPMENT

The system was supplemented with the simulator, used as training device developed in Department of Automation and Aeronautical Systems, Faculty of Power and Aeronautical Engineering. The simulator can be used to train operators in accordance with the appropriate operator training program, developed during this project.

4.1. Simulator Architecture

The architecture of the simulator contains two layers: hardware and software.

From the hardware point the simulator is built from commercially available components. As quadrotor control station, an actual Ground Control Station was used (Fig. 6). In the software layer there can be distinguished program modules and software backbone that integrates software modules and allows for communication between them. The integral simulator modules are: computer model of the quadrotor and a model of its autopilot system.

Fig. 6 Training simulator of the unmanned system

In the simulator a non-linear model of a quadrotor was implemented with an automatic flight control system. Architecture of the simulated autopilot was similar to actual concept developed by WB Electronics and it is prepared to cooperate with a dedicated GCS. The differences between real and simulator autopilots stem from the need to adjust the autopilot to the simulation environment and to the structure of dynamics model.

4.2. Quadrotor Dynamics Modelling

The fundamental requirement for the quadrotor model developed for simulator was to assure the real-time operation together with a very good correlation between a model and the real vehicle behaviour, so a proper balance between the simulation computational speed and the simulation quality was required. Details of the developed model were presented in [3].

The model was 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 centre of mass,
- induced velocity is modelled with the Glauert formula for forward flight,
- propellers loads were calculated using wind-tunnel validated numerical model.

To fulfil requirement of a real-time operation it was decided to use the maps of pre-calculated loads of each propeller. The maps were obtained using the validated model of the propeller. All six elements of propeller aerodynamic loads were calculated for various inflow angles and speeds. Such a map of loads is used during simulation, and forces and moments of each propeller are interpolated separately. Such an approach allows for quick operation of the aircraft model and still maintains good correlation with the modelled object performance.

4.3. Autopilot model development

The flight control system of a quadrotor consists of Ground Control Station and on-board Autopilot, Fig. 7. The GCS generates and sends demanded values of controls to on-board autopilot via wireless communication. The autopilot generates control signals to quadrotor rotors depending on the demanded and measured values of flight parameters. The control signal is organized as a vector $\mathbf{\Omega}$, which components are the required values of rotors angular velocities.

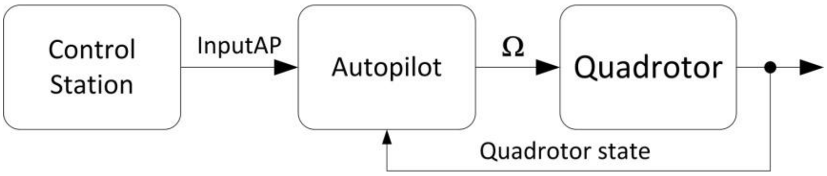

Fig. 7 Quadrotor flight control system structure

The control system may operate in semiautonomous and autonomous modes. In a semiautonomous mode an operator of a quadrotor sets demanded values of quadrotor linear velocities and azimuth via GCS. In fully autonomous mode an operator controls the flight level and the waypoints on route of the vehicle. The signals are transmitted to the autopilot, which controls the quadrotor attitude and lift to assure demanded flight conditions. The longitudinal and lateral velocities are controlled using values of pitch and roll angles. The control of flight level is obtained by the vertical speed variation. If the demanded value of vertical speed is equal zero the altitude controller holds actual flight level.

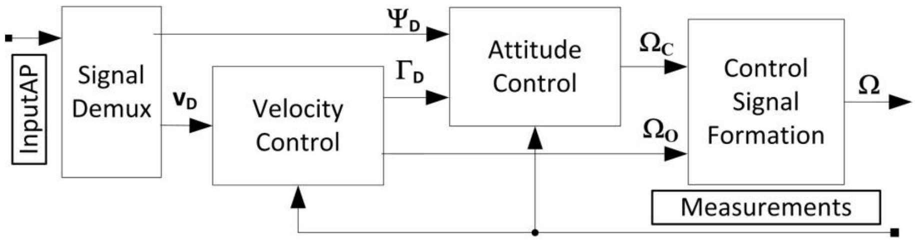

Fig. 8 Autopilot structure

The overall autopilot structure is shown in Fig. 8. It consists of three main blocks: Velocity Control, Attitude Control and Control Signal Formation. The control signal is a vector of demanded rotors angular rates:

$$\mathbf{\Omega} = \Omega_H \begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix}^T + \mathbf{\Omega_D}. \tag{1}$$

The control signal $\mathbf{\Omega}$ is calculated as an increment of rotors angular rates $\mathbf{\Omega_D}$ relative to hovering condition Ω_H. The inherent feature of quadrotor is that lift and control loads are produced only by changing angular velocities of rotors. The rotor thrust, expressed as function of the rotor angular rate, is divided into lift and attitude parts. The lift part provides the altitude control whereas the attitude part guarantees manoeuvrability.

The demanded values of rotors angular velocities are calculated in CSF block as:

$$\mathbf{\Omega_D} = w_\Omega \cdot \mathbf{\Omega_O} + (1 - w_\Omega) \cdot \mathbf{\Omega_C}, \tag{2}$$

where $\mathbf{\Omega_O}$ is a collective control signal used for altitude control, $\mathbf{\Omega_C}$ is a cycling control signal comes from attitude controllers, and a weighting coefficient w_Ω expresses the portion of rotor thrust that is allocated for lift control.

The Attitude Control block contain three independent controllers for pitch, roll and yaw angles. The yaw angle controller is based on PID control law. The pitch and roll controllers have identical PD control laws but the output signals are distributed to the rotors in a different way. The output signals vector of AC block, named cycling control signal, is a sum of output signals of all controllers distributed according to the selected quadrotor configuration:

$$\mathbf{\Omega_C} = u_\Phi \begin{bmatrix} -0.33 \\ -0.33 \\ 0.33 \\ 0.33 \end{bmatrix} + u_\Theta \begin{bmatrix} 0.33 \\ -0.33 \\ -0.33 \\ 0.33 \end{bmatrix} + u_\Psi \begin{bmatrix} -0.34 \\ 0.34 \\ -0.34 \\ 0.34 \end{bmatrix}, \tag{3}$$

where u_Φ, u_Θ, u_Ψ are output signals from roll, pitch and yaw controllers.

The Velocity Control block contains controllers for horizontal (longitudinal and lateral) velocities and flight level. The longitudinal and lateral controllers are based on PID control laws with adaptive integral coefficients, and provide demanded values for pitch and roll control signals, which are sent to the Attitude Control block as a $\mathbf{\Gamma_D}$ vector. The flight level controller contains altitude and vertical speed control laws. The classical P altitude control law produces demanded value for PID vertical speed control law. The demanded value of vertical speed can also come from an operator, when it is not zero. The vertical speed controller provides the collective control vector $\mathbf{\Omega_O}$:

(4) $$\mathbf{\Omega_O} = u_W \begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix}^T .$$

5. CONCLUSIONS

The new unmanned system using a small quadrotor vehicle was developed by WB Electronics in cooperation with Warsaw University of Technology. The system requirements were set by the Polish Ministry of National Defence. A complete system was developed for everyday usage. An important part of the system, developed at the Warsaw University of Technology, is a training simulator allowing for training of the operators using the real control stations of the system. For the purpose of the simulator a dynamic model of the quadrotor and the dedicated autopilot model were developed.

All the system elements were tested and proven to fulfill the requirements stated in the project call.

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