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INVERSE KINEMATICS IN ULTRALIGHT UAV CONTROL PROBLEM WITH ADDITIONAL ON-BOARD MICROCOMPUTER

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Abstract

The architecture of the autopilot control unit for the UAV is given. The possibility of using additional on-board microcomputer for collaboration with the autopilot to increase functionality of UAV is considered. The microcomputer TRIK is used. The dynamic and kinematic of flight process are described. Several coordinate systems for describe the dynamic behaviors of UAV are given. The method of partly implement the autopilot systems control modules to microcomputer is proposed. Simulation results of motion’s model in Simulink are described. Testing the proposed module on the real UAV is planned.

Key words

Inverse kinematics, ultralight UAV, control problem, on-board microcomputer.

1 Introduction

Unmanned aerial vehicles (UAV) successfully used to solve many civilian tasks, covering a wide range of possibilities, such as the work of emergency services (warning of natural disasters, fire safety control), border patrols (patrolling zones), monitoring of agricultural crops forestry and fishing control, also mapping (geodesy, geology and geography), monitoring of green areas (reserves), monitoring of oil and gas facilities, construction companies and works in the field of mass media (aerial photography and videography), and many others.

There are a lot of different UAVs in the world, differing in their specifications and set of characteristics (purpose, weight, size, flight duration and flight altitude, launch and landing system, autopilot and navigation systems, aerial and video format, etc.).

For the successful implementation of the tasks above it is necessary to choose the right components for the inner and outer stuffing of the UAV, leaving without due attention to the software. Thus, it is necessary to maximize the UAV’s own capabilities, which includes both the selection of high-quality hardware solutions designed for possible extreme conditions and increased loads, and the software that provides stable uninterrupted control of the UAV in conditions of noisy and delays from the sensors. The control module should also be optimized in terms of power consumption, since the UAVs have a limited supply of energy due to the weight of the batteries, which affects the flight performance [Amelin, 2010].

The subject of this paper is the description and development of the UAV control chain from receiving data from sensors to setting a signal for control mechanisms in conditions of noise and delay. It also requires the selection of hardware and the practical implementation of such control.

The problem is that for the UAV control unit to make decision based on the sensor readings, a large number of transformations and calculations must be performed, and in order for the control unit to work effectively in real time, these calculations must be carried out in an optimal way.

In the design of UAV flight physics, a number of problems arise. First, the UAV model can and must be viewed in different coordinate systems, which makes it necessary to constantly use spatial mathematical transformations. This is due, for example, to the fact that the classical equations of motion are considered in inertial frames of reference, that is, in the earth’s reporting system, but the movement itself is easier to describe with respect to the position of the drones, that is, in the constantly changing body-axes reference frame. Secondly, the various forces and moments that act on the drone are also described in the UAV system. However, the sensors available to the UAV only partially give evidence to this system. For example, the GLONASS/GPS (Global Navigation Satellite System/Global Positioning System) sensors give indications in the Earth's coordinate system. In order to be able to process the readings of all sensors, it is necessary to enter all possible necessary reference frames and be able to pass from one to the other by means of mathematical transformations. Thirdly, a non-trivial task is to describe the kinematics and dynamics of the flight process. To describe the motion of a UAV with six degrees of freedom, it will take 12 different variables describing the coordinates, velocity, angles and angular moments of the UAV in the framework of non-linear differential equations describing the physics of UAV flight.

It is also necessary to consider all the forces and moments that act on the UAV at the time of movement. It should be noted that this includes the wind, which plays a very important role in the case of unmanned aerial vehicles. At what comes here as a constant wind, available in some place for a while, and some gusts of wind that need to be taken into account. It is also worth noting that the forces and moments of the forces acting on the UAV are highly dependent on the characteristics of the UAV itself, which must also be taken into account. This is both the surface area and shape of the wing, as well as the fact of the presence or absence of the UAV plumage.

For the efficiency of the control module, the linearization of the differential some equations are performed. Thus, all the forces and moments acting on the UAV will be considered as longitudinal and lateral, which greatly simplifies the understanding of the flight process, as well as interaction with it with the help of an autopilot.

As the final part, you need to prepare the hardware component, which was chosen as a microcontroller TRIK together with the autopilot ArduPilot, but before you begin implementation on a real microcontroller, the system must be tested. For this purpose, the Simulink simulation environment is used in the Matlab application package.

2 Kinematics and Dynamics

The movement of an unmanned aerial vehicle in a space having 6 degrees of freedom is described using the twelve variables shown in the table[Beard and McLain, 2012]:

Name	Description
p$_n$	The UAV's coordinate axis to north in F^i
p$_e$	The UAV's coordinate axis to east in F^i
p$_d$	Axis directed to the center of the Earth in F^i
u	Speed along the axis i$^b inF^b$
v	Speed along the axis j$^b inF^b$
w	Speed along the axis k$^b inF^b$
ϕ	The heeling angle given in F^{v2}
θ	The pitch angle given in F^{v1}
ψ	The yaw angle given in F^v
p	Angular roll speed
q	Angular velocity of pitch
r	Angular speed of yaw

The formulas for the recalculation of these variables for a flying UAV can be found in the following books on mechanics [Goldstein, 1951], spatial dynamics [Wiesel, 1997], flight dynamics[Shuster, 1993], robotics [Spong and Vidyasagar, 1989]. (In formulas $s(\alpha)$ means $sin(\alpha)$ and $c(\alpha)$ means $cos(\alpha)$).

$$\begin{pmatrix}\dot{p}_n\\ \dot{p}_e\\ \dot{p}_d\end{pmatrix} =$$

$$\begin{pmatrix} c(\theta)c(\psi) & s(\phi)s(\theta)c(\psi)-s(\phi)s(\psi) & c(\phi)s(\theta)c(\psi)+s(\phi)s(\psi)\\ c(\theta)s(\psi) & s(\phi)s(\theta)s(\psi)+c(\phi)c(\psi) & c(\phi)s(\theta)s(\psi)-s(\phi)c(\psi)\\ -s(\theta) & s(\phi)c(\theta) & c(\phi)c(\theta)\end{pmatrix} \times$$

$$\times \begin{pmatrix}u\\ v\\ w\end{pmatrix} \tag{1}$$

$$\begin{pmatrix}\dot{u}_n\\ \dot{v}_e\\ \dot{w}_d\end{pmatrix} = \begin{pmatrix}rv-qw\\ pw-ru\\ qu-pv\end{pmatrix} + \frac{1}{m}\begin{pmatrix}f_x\\ f_y\\ f_z\end{pmatrix} \tag{2}$$

$$\begin{pmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{pmatrix} = \begin{pmatrix}1 & s(\phi)tan(\theta) & c(\phi)tan(\theta)\\ 0 & c(\phi) & -s(\phi)\\ 0 & \frac{s(\phi)}{c(\theta)} & \frac{c(\phi)}{c(\theta)}\end{pmatrix}\begin{pmatrix}p\\ q\\ r\end{pmatrix} \tag{3}$$

$$\begin{pmatrix}\dot{p}\\ \dot{q}\\ \dot{r}\end{pmatrix} = \begin{pmatrix}\Gamma_1 pq-\Gamma_2 qr\\ \Gamma_5 pr-\Gamma_6(p^2-r^2)\\ \Gamma_7 pq-\Gamma_1 qr\end{pmatrix} + \begin{pmatrix}\Gamma_3 l+\Gamma_4 n\\ \frac{1}{J_y}m\\ \Gamma_4 l+\Gamma_8 n\end{pmatrix} \tag{4}$$

3 Forces and Moments

At the time of flight, the UAV undergoes a non-trivial action of various forces and moments of different natures, namely gravitational (f_g), aerodynamic(f_a, m_a) and movement control (f_p, m_p). Then the total action of forces and moments on UAV can be described by formulas [Beard and McLain, 2012]:

$$f = f_g + f_a + f_p, \tag{5}$$

$$m = m_a + m_p. \tag{6}$$

The gravitational force in an inertial coordinate system is described by a simple vector:

$$f_g^v = \begin{pmatrix} 0 \\ 0 \\ mg \end{pmatrix} \tag{7}$$

In the UAV body coordinates system:

$$f_b^v = \begin{pmatrix} -mg \cdot sin(\theta) \\ mg \cdot cos(\theta) sin(\phi) \\ mg \cdot cos(\theta) cos(\phi) \end{pmatrix} \tag{8}$$

When an airplane is flying through the air, it generates its own wings with a lift force and a breaking force, as shown in Fig. 1. The force and pressure distribution acting on the aircraft depends on the speed at which it travels through the air, the air density, the shape and position of the aircraft in the air. Thus, the dynamic pressure is described by formula $\frac{1}{2}V_a^2$, where - density of air, and V_a is the airspeed relative to air.

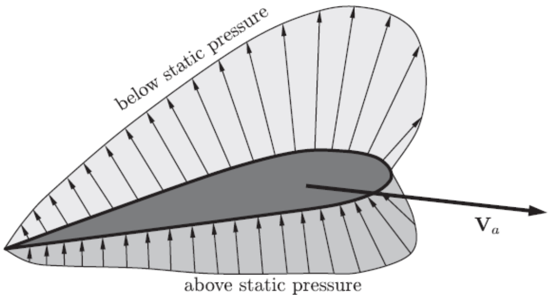

Figure 1. Distribution of air density around the wing during flight.

The force of inhibition, the force of lifting, and the moment of forces are usually described by the following formulas: [Wiesel, 1997]

$$F_{lift} = \frac{1}{2}V_a^2 S C_L \tag{9}$$

$$F_{drag} = \frac{1}{2}V_a^2 S C_D \tag{10}$$

$$m = \frac{1}{2}V_a^2 S c C_m, \tag{11}$$

where C_L, C_D, C_m — dimensionless quantities characterizing the aerodynamic coefficients, S - sing surface area, c — value equal to half of the wing.

4 Control Module

The control module operates according to the principle depicted in Fig. 2. The Path Planner module specifies the points through which the UAV is scheduled to fly. The Path Manager module converts the sequence of these points into a sequence of lines and arcs (arcs of Dubin), as part of the trajectory over which the UAV is scheduled to fly. Next in the path following, the autopilot itself tracks the passage of the UAV along this path, making adjustments along the route and transferring commands to all means available for route maintenance such as engine, ailerons, rudders, etc.

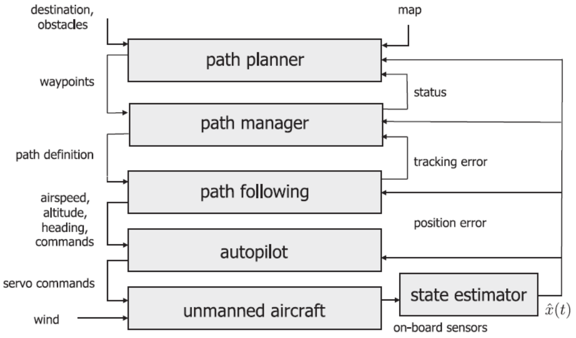

Figure 2. System architecture of the UAV control module.

There are two classes of problems for planning a path. The first is point-to-point algorithms, the purpose of which is to force the UAV to fly through all given points, bypassing obstacles. The second class of problems are the algorithms for covering a given region using a UAV. For example, for aerial photography. We will focus only on the first class, considering point-to-point algorithms.

Since the control module must take into account the errors and mistakes that come with the sensor readings, there is a State estimator module for this purpose, which estimates these errors and makes corresponding corrections.

5 Testing and Analysis

Before implementing the proposed architecture on the UAV, the UAV flight simulator was simulated in the Simulink environment of the Matlab application package. Matlab / Simulink is a graphical simulation environment that allows you to build dynamic models, including discrete, continuous and hybrid, non-linear and discontinuous systems, using block diagrams in the form of directed graphs.

The environment is very convenient because it allows you to program differential equations using the built-in S-functions [Matlab-site]. Draws the position of the UAV in real time, as shown in Fig. 3. During the course of the UAV to its Simulink route, it displays all the parameters of all the given physical quantities at any time, which is very convenient, and clearly allows you to check the correctness of the work, as well as analyze the physics of the UAV movement. This is shown in Fig. 4. Allows you to specify a complex interaction structure for modules.

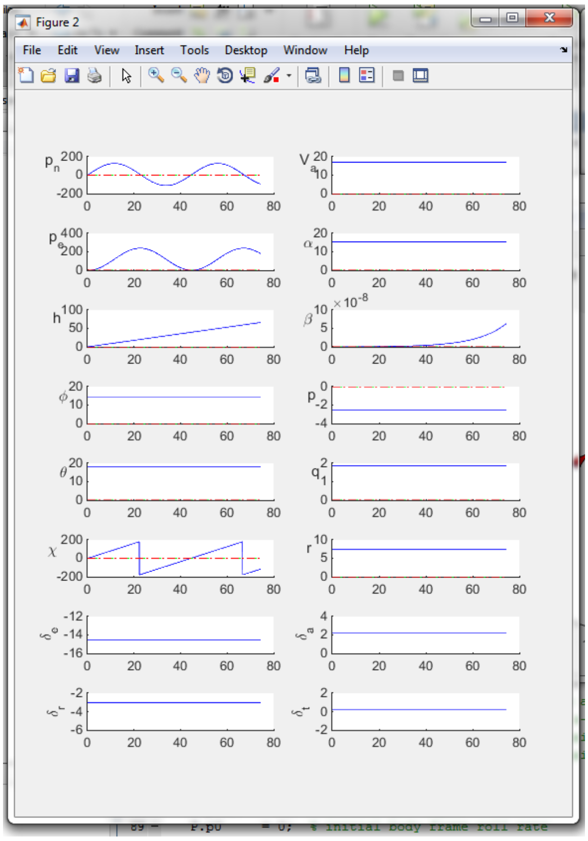

Figure 4. Matlab / Simulink shows all the specified traffic parameters in real time.

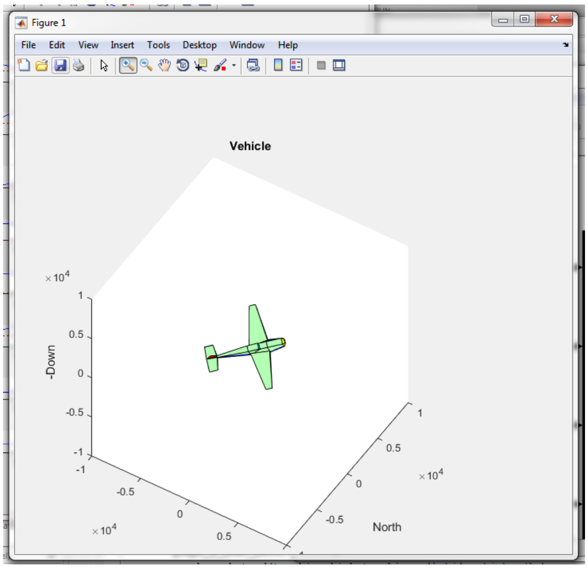

Figure 3. Displays the UAV model in real time.

6 Conclusion

The architecture of the autopilot control unit for the UAV was created. It is studied and realized with the help of graphical simulation environment of the physics of the UAV motion process. This includes the basic set of mathematical transformations, which allows you consider the movement of UAVs in different coordinate systems, as well as formulas and accompanying explanations of the dynamics and kinematics of the flight process. The formulas of the forces and the moments operating on the UAV were studied and realized.

The resulting model of motion in the Simulink environment is a good representation of the movement of a real UAV, since it takes into account almost the entire set of forces and moments that affect the UAV, including both constant wind and gusts of wind, presented as white noise.

Further development of the work consists in porting the resulting module to a real UAV, adding an apparatus for estimating the noise of instrument measurements.

Also the received system is a good platform for testing any ideas and hypotheses for UAV, modeling of mathematical processes.

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References

Beard, R.W. and McLain, T.W. (2012). Small unmanned aircraft: Theory and practice.

Roskam, J. (1998). Flight Dynamics and Automatic Flight Controls, Parts I II. Lawrence, KS: DARcorporation

Nelson, R.C. (1998). Flight Stability and Automatic Control. Boston, MA: McGrawHill, 2nd ed.

Amelin, K. (2010). The method of orienting an ultralight UAV with a rare update of its location.

Texas Instruments. Section of the site of the company "Texas Instruments", dedicated to the processor OMAP L138. url: http://www.ti.com/product/omap-l138.

TRIK. The site of the company "TRIK" url: http://www.trikset.com/.

Matlab. S-Function documentation. url: http://www.mathworks.com/help/simulink/matlab-s-functions-1.html.

Goldstein, H. (1951). Classical Mechanics.

Wiesel, W. E. (1997). Spaceflight Dynamics.

Shuster, M.D. (1993). A survey of attitude representations, *The Journal of the Astronautical Sciences*, **41**, pp. 439–517, October–December.

Spong, M.W. and Vidyasagar, M. (1989). Robot Dynamics and Control.