13. Там же.
14. *Зонтова Т. В.*, *Кучер Д. Б.* Длительность механизма быстрого электрического взрыва проводников под воздействием токов спирального взрывомагнитного генератора.
15. *Зонтова Т. В.*, *Кучер Д. Б.* Использование явления вторичного пробоя при электрическом взрыве проводников для формирования мощных полиимпульсных излучений.
16. *Зонтова Т. В.*, *Кучер Д. Б.* Экспериментальные исследования паузы тока, возникающей после быстрого электрического взрыва легкоплавких проводников // Системи обробки інформації. – 2012. – Вип. 6(104), т. 2. – С. 62–65.
17. *Зонтова Т. В.*, *Кучер Д. Б.* Длительность механизма быстрого электрического взрыва проводников под воздействием токов спирального взрывомагнитного генератора.
18. *Зонтова Т. В.*, *Кучер Д. Б.* Использование явления вторичного пробоя при электрическом взрыве проводников для формирования мощных полиимпульсных излучений.
19. *Зонтова Т. В.*, *Кучер Д. Б.* Длительность механизма быстрого электрического взрыва проводников под воздействием токов спирального взрывомагнитного генератора.
20. *Зонтова Т. В.*, *Кучер Д. Б.* Использование явления вторичного пробоя при электрическом взрыве проводников для формирования мощных полиимпульсных излучений.
21. *Бурцев В. А.*, *Калинин И. В.* Указ. соч.
22. Возможные сценарии развития вторичного пробоя при электрическом взрыве проводников в вакууме и воздухе.
23. Интерпретация экспериментальных данных по электрическому взрыву тонких проволочек в воздухе / С. А. Пикуз, Д. А. Ткаченко, Д. А. Баришпольцев [и др.] // Письма в ЖТФ. – 2007. – Т. 33, вып. 15. – С. 47–55.
24. *Лебедев С. В.*, *Савватимский А. И.* Металлы в процессе быстрого нагревания электрическим током большой плотности // Успехи физических наук. – Вып. 2, т. 144. – С. 215–248.

Получено 24.11.2016

УДК 629.73(045)

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MODELING AND PREDICTIVE CONTROL OF NONLINEAR COUPLED AND UNDERACTUATED DYNAMICS OF A HEXACOPTER

Introduction

Nowadays, reducing the human factor in flights is a common topic in aerospace applications, for making the loss of human lives and economic costs as low as possible. As a consequence of this pursuit, there is an overwhelming interest in the Unmanned Aerial Vehicles (UAVs). When there are sufficient measurements the necessary states of an autonomous aerial vehicle can be estimated via the Kalman Filter (KF) [1]. Unmanned Aerial Vehicles (UAVs) fly at very low speeds and Reynolds numbers, have nonlinear coupling and tend to exhibit time-varying characteristics [1]. In order to control such vehicles it becomes necessary to design and develop robust and adaptive controllers and hence, identify the system. State and parameter estimation, which are an integral part of system identification, has been carried out on various flight data and simulations as evident from literature [2]. Some researchers, presented attitude estimation algorithms based on Kalman filter such as SAKF [3] and RAKF [4], for UAV problems when noise statistical characteristics are unknown, and time-varying vibrations are the main disturbance source, also for problems against sensor/actuator fault of the system. Others papers presented the sliding mode and high-order sliding mode respectively like an observer [5, 6] in order to estimate the unmeasured states and the effects of the external disturbances such as wind and noise. In [7], the unknown parameter of the quadrotor are identified using state estimation method with the implementation of Unscented Kalman Filter (UKF). Most researchers used estimation techniques to identify the parameters in unknown systems, while some researchers [8, 12, 14] mentioned estimation in order to predict the signals. The main objective is to estimate the altitude of the UAV, in order to use this estimated value as predictive feedback signals for UAV altitude stabilization. This value cannot be estimated using a single sensor because the fact that each sensor has its own problem [8]. The performance of the proposed KF is investigated using simulation for state estimation procedure of an Unmanned Aerial Vehicle [4, 8]. The paper proceeds as follows. In Section 2 the flight dynamics model of the UAV is given. In Section 3, UAV state estimation and predictive control are proposed. In Section 4, the simulation is carried out followed by a discussion. Section 5, gives a brief summary of the obtained results and concludes the paper.

The UAV dynamics

Newton-Euler equations were used. In order to make the modeling, some assumptions have been made, taking into consideration that the hexacopter is a rigid body and has a symmetrical structure. The motion can be decomposed into translational and rotational components. Therefore, the equations with respect to the body frame are as derived in [9] and [10]:

$$\begin{cases} \dot{u} = -\dfrac{k_t}{m}u + g.\sin\theta - \left(qw - vr\right) + \dfrac{F_{d1}}{m} \\ \dot{v} = -\dfrac{k_t}{m}v - g.\sin\text{ø}\cdot\cos\theta - \left(ru - pw\right) + \dfrac{F_{d2}}{m} \\ \dot{w} = \sum_{i=1}^{6}\left|T_i\right| - \dfrac{k_t}{m}w - g.\cos\text{ø}.\cos\theta - \left(pv - qu\right) + \dfrac{F_{d3}}{m} \end{cases} \quad (1)$$

$$\begin{cases} \dot{p} = -\dfrac{\sqrt{3}}{2J_x} l\left(|T_3| - |T_4| - |T_5| + |T_6|\right) - \\ -\dfrac{k_r}{J_x} p - qr\dfrac{\left(J_z - J_y\right)}{J_x} + \dfrac{M_{d1}}{J_x} \\ \dot{q} = -\dfrac{1}{2J_y} l\left(|T_3| - |T_4| + |T_5| - |T_6| + 2|T_1| - 2|T_2|\right) - \\ -\dfrac{k_r}{J_y} q - pr\dfrac{\left(J_x - J_z\right)}{J_y} + \dfrac{M_{d2}}{J_y} \\ \dot{r} = -\dfrac{\rho C_Q A R^3}{J_z} l\left(\omega_1^2 + \omega_4^2 + \omega_6^2 - \omega_2^2 - \omega_3^2 - \omega_5^2\right) - \\ -\dfrac{k_r}{J_z} r - pq\dfrac{\left(J_y - J_x\right)}{J_z} + \dfrac{M_{d3}}{J_z} \end{cases} \quad (2)$$

where m is the hexacopter's total mass, k_t is the constant of aerodynamic force, g is the gravity constant, $F_{dist} = \left[F_{d1} \quad F_{d2} \quad F_{d3}\right]^{\mathrm{T}}$ is the disturbance force along the axis, T_i and ω_i (where i = 0…6) are the thrust and angular moments of the motors, J_x, J_y and J_z are inertial moments of the rigid body along axes, k_r is the constant of aerodynamic moment, l is the distance from CG to the center motors, C_Q is the motor's torque coefficient, ρ is the air density, A is the disc area, R is the disc radius, and $M_{dist} = \left[M_{d1} \quad M_{d2} \quad M_{d3}\right]^{\mathrm{T}}$ is the disturbance moment along the axis. The equations of motion that govern the translational and rotational motion for the hexacopter with respect to the inertial (Earth) frame are [9, 10]:

$$\ddot{\xi} = \left[\ddot{x} \quad \ddot{y} \quad \ddot{z}\right]_E^{\mathrm{T}} = C_b^n \cdot \left[\dot{u} \quad \dot{v} \quad \dot{w}\right]_B^{\mathrm{T}} \quad (3)$$

$$\ddot{\sigma} = \left[\ddot{\varphi} \quad \ddot{\theta} \quad \ddot{\psi}\right]_E^{\mathrm{T}} = S \cdot \left[\dot{p} \quad \dot{q} \quad \dot{r}\right]_B^{\mathrm{T}} \quad (4)$$

The angular position of the body frame with respect to the inertial one is defined by Euler angles: roll φ, pitch θ and yaw ψ. These together form the vector: $\sigma = \left[\varphi \quad \theta \quad \psi\right]^{\mathrm{T}}$ where φ and $\theta \in \left]-\frac{\pi}{2}, \frac{\pi}{2}\right[$; $\psi \in \left]-\pi, \pi\right[$. The inertial frame position of the vehicle is given by vector $\xi = \left[x \quad y \quad z\right]^{\mathrm{T}}$ [9, 7, 10]. While, the angular velocity is defined by the vector $\Omega = \left[p \quad q \quad r\right]^{\mathrm{T}}$, and the linear velocity is defined by the vector $V = \left[u \quad v \quad w\right]^{\mathrm{T}}$ in the body frame. The transformation from the body frame to the inertial frame is realized by using the well-known rotation matrix C_b^n defined in [1, 9, 10], which is orthogonal and $C_b^{n\mathrm{T}} = C_b^{n^{-1}} = C_n^b$. In addition, the transformation matrix for angular velocities from the body frame to the inertial one is S as mentioned in [9, 10, 11]. The block diagram in Figure (1) shows the variables of the mathematical model of a hexacopter aircraft.

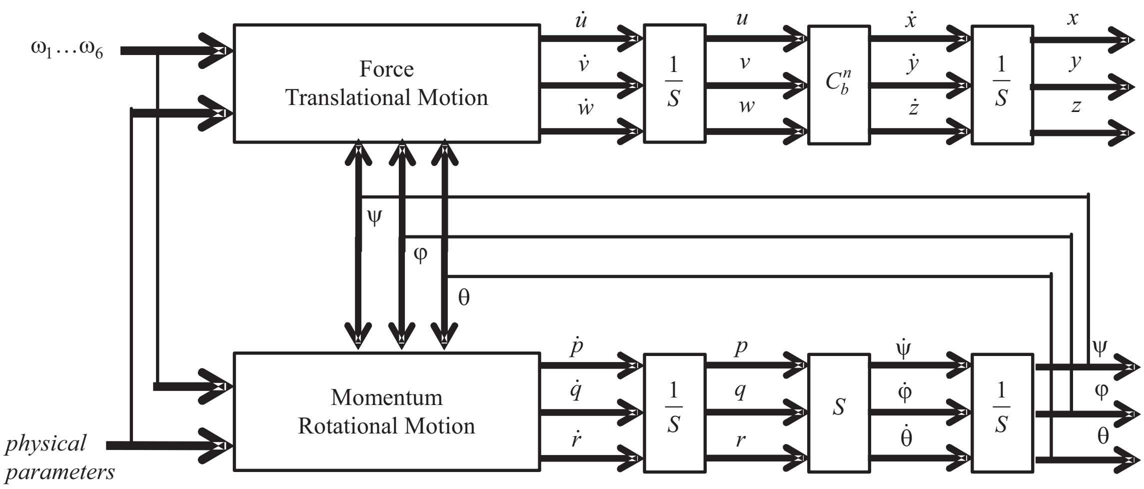


Figure 1. A mathematical model of Hexacopter

UAV State Estimation and Predictive Control

Large modeling errors may often appear when aircraft maneuvers. In order to decrease modeling errors [11], Subspace identification method via principle component analysis was used to identify a precise nonlinear model based on Kalman filter to estimate and predict the hexacopter's altitude from flight data [8, 14]. The estimated system is then used to cancel and minimize disturbances on the aircraft, as shown in figure (2) where the left side clarify the simple model without predictive method while the right side shows how we used estimated model as feedback to enhance the response of the aircraft altitude by canceling the disturbances. The $Y(t)$ is the altitude of the aircraft, $Y'(t)$ is the disturbed altitude, X is the state space, $u(t)$ is the control signal, $e(t)$ is the error signal and $r(t)$ is the altitude set-point. The effectiveness of the proposed method is evaluated comparing the simulation results with flight test data [12, 13].

From figure (2) it is clear that in the simple method, PID control loops were implemented to control the altitude and velocity of a UAV rotorcraft. The PID gains can be selected precisely before the flight. No accurate model existed at first research stages. Tuning gains on a flying platform can be difficult because poor gains yield poor stability characteristics [13], which can lead to potentially destructive crashes. Once a set of acceptable gains has been found, it is not less difficult to ensure that they are optimal.

Simulation and Discussion

A LabVIEW simulation was conducted by using Runge-Kutta 2 method with a fixed step of 0.05 sec. As shown in figure (3), it is clear that there is a long response time in addition to chattering and a big overshoot. These problems are results of the nonlinearity nature of hexacopter as well as coupling characteristic, which requires nonlinear methods to enhance the response. Predictive control technique was used in order to reduce the hexacopter problems, and the results were compared with those results taken from the simple method without inserting disturbances as shown in figure (2). Table shows the stability response of proposed controllers.

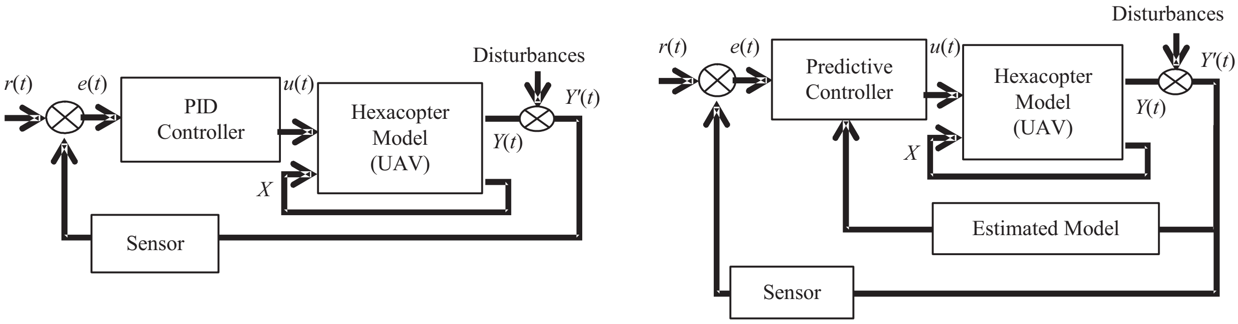
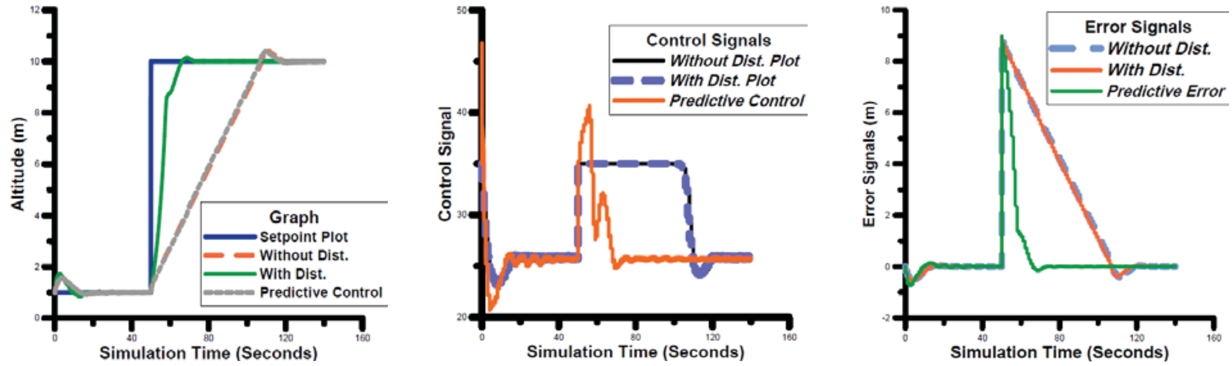


Figure 2. The proposed model of predictive control



Altitude Signals of Hexacopter
Control Signals
Altitude Error Signals

Figure 3

Stability Response of Simple and Predictive Control

Controller	Response Time (S)	Steady-State Error
PID controller	68	-0.0.44 (m)
Predictive Controller	23	0.0097 (m)

Conclusion

A real and complex dynamic model was considered, which addresses the nonlinearity, time variance, underactuation, and disturbance. The controller's parameters were tuned using Ziegler-Nichols algorithm to get the best performance and avoid the occurrence of vibrations in the output variables of the flying object as possible. In this paper, simple method and predictive method were used in altitude control, the predictive technique guarantees stability in presence of disturbances for nonlinear, coupled and underactuated systems compared with the simple method.

References

1. *GrzonkaS.*, *Grisetti G.*, *Burgard W.* Towards a navigation system for autonomous indoor flying // Robotics and Automation, 2009. ICRA'09. IEEE International Conference on 2009 May 12. – Pp. 2878–2883.

2. *Baranek R.*, *Solc F.* Hexacopter Pitch Estimator for a Pitch Stabilizer // IFAC Proceedings Volumes. 2013 Dec 31; 46(28). – Pp. 326–329.

3. Attitude Estimation of the Multi-rotor UAV Based on Simplified Adaptive Kalman Filter Algorithm / X. Zhang, Y. Bai, Z. Xu, R. Wang // Proceedings of the 2015 Chinese Intelligent Automation Conference, Springer Berlin Heidelberg, 2015. – Pp. 219–227.

4. *Hajiyev C.*, *Soken H. E.* Robust adaptive Kalman filter for estimation of UAV dynamics in the presence of sensor / actuator faults // Aerospace Science and Technology. 2013 Jul 31; 28(1). – Pp. 376–383.

5. *Mokhtari A.*, *Benallegue A.*, *Belaidi A.* Polynomial linear quadratic gaussian and sliding mode observer for a quadrotor unmanned aerial vehicle // Journal of Robotics and Mechatronics. – 2005. – 17(4). – P. 483.

6. Feedback linearization and linear observer for a quadrotor unmanned aerial vehicle / A. Mokhtari, N. K. M'Sirdi, K. Meghriche, A. Belaidi // Advanced Robotics. – 2006 Jan 1; 20(1). – Pp. 71–91.

7. *Abas N.*, *Legowo A.*, *Akmeliawati R.* Parameter identification of an autonomous quadrotor // Mechatronics (ICOM), 2011 4th International Conference On 2011 May 17. – Pp. 1–8.

8. *Wang J.*, *Qin S. J.* A new deterministic-stochastic subspace identification method using principal component analysis // Automatica, submitted for publication. – 2004.

9. *Ibrahim N. I.*, *Oumran B.* A Coupled and Underactuated Dynamic Model of Microcopter Using LabVIEW // IV Всерос. науч.-техн. конф. аспирантов, магистрантов и молодых ученых с междунар. участием (Ижевск 20-21 апреля 2016). – С. 981–990.

10. *Ibrahim N. I.* Attitude and Altitude Stabilization of Microcopter using PID Controllers with Disturbances in LabVIEW // IV Всерос. науч.-техн. конф. аспирантов, магистрантов и молодых ученых с междунар. участием (Ижевск 20-21 апреля 2016). – С. 989–996.

11. *Zhong-ke S.* On-line state estimation and parameter identification for flight // Decision and Control, 1990. Proceedings of the 29th IEEE Conference on 1990 Dec 5. – Pp. 1559–1560.

12. *Chamberlain C. H.* System Identification, State Estimation, and Control of Unmanned Aerial Robots // All Theses and Dissertations. – 2011. – Paper 2605. – URL: http://scholarsarchive.byu.edu/etd/2605

13. *Sahawneh L. R.* Airborne Collision Detection and Avoidance for Small UAS Sense and Avoid Systems // All Theses and Dissertations. – 2016. – Paper 5840. – URL: http://scholarsarchive.byu.edu/etd/5840

14. *Van O. P.*, *De Moor B.* N4SID: Subspace algorithms for the identification of combined deterministic-stochastic systems // Automatica. – 1994 Jan 31; 30(1). – Pp. 75–93.

Получено 20.10.2016