YAW AND PITCH CONTROL TUNING USING MULTIOBJECTIVE OPTIMISATION TECHNIQUES

Matheus Eduardo Garbelini*, Victor Henrique Alves Ribeiro†, Gilberto Reynoso-Meza*, Leandro dos Santos Coelho*

*Polytechnic School, Pontifical Catholic University of Parana (PUCPR), Imaculada Conceição, 1155, Zip code 80215-901, Curitiba, PR, Brazil
†Industrial and Systems Engineering Graduate Program (PPGEPS), Pontifical Catholic University of Parana (PUCPR), Imaculada Conceição, 1155, Zip code 80215-901, Curitiba, PR, Brazil

Emails: matheus.garbelini@pucpr.br, victor.henrique@pucpr.edu.br, g.reynosomeza@pucpr.br, leandro.coelho@pucpr.br

Abstract—Yaw and pitch control tuning are usual task (and requirement) for the autonomous flight control device in Unmanned Aerial Systems (UAS), in order to get a desired performance and stability. Multiobjective optimisation techniques can be integrated into the tuning procedure of different processes. They are useful due to its capabilities to depict trade-off between conflicting objectives. In this work, we use such optimisation techniques, in order to appreciate the trade-off between performance and reliability in UAS. For such purpose, different PID controllers are tuned for a two degree of freedom helicopter model, in order to validate its usability.

Keywords—Unmanned Aerial Systems, Evolutionary multiobjective optimisation, PID control

1 Introduction

Nowadays, Unmanned Aerial Systems (UAS) are emerging and strategic research topic (Wargo et al., 2014); researches and technologists have found a field with great potential in commercial and civil applications. Such applications range from monitoring (pipes, crop fields, forest, weather), sensing and recording (pollution, vigilance) to delivery of goods (Fregene, 2012).

UAS’ are comprised by (at least) a Ground Control Station (GCS) and an Unmanned Aerial Vehicle (UAV). In such UAV, one of the most important devices is the Flight Control System (FCS), which provides the desired level of autonomy to the vehicle.

The FCS comprises sensors, positioning systems, control actuators and on board CPU, which are integrated in the UAV (flight platform). It is important to remember that most of the times such UAVs are unmanned but not unpioloted: they are remotely supervised. Even when flying pre-programmed routes and missions, real-time remote-pilot intervention is always available from the GCS. The GCS is usually in charge of monitoring and interpreting data collected and sent by the UAV, and defining or reconfiguring the flight mission on-line according to the requirements of the ground-based personal.

Several alternatives for control algorithms have been used in the FCS of UAVs, in order to provide the autonomy level required to accomplish their tasks. For example, proportional-integral-derivative (PID) controllers (Pounds et al., 2012), linear quadratic regulators (LQR) (Zarei et al., 2007), fuzzy logic techniques (Kadmiry and Driankov, 2004), artificial neural networks (Song et al., 2009), adaptive control (Wang et al., 2010) and predictive control (Du et al., 2008) have been extensively used for such purpose. Nevertheless, new control techniques and procedures are still required in order to improve the performance of an UAS (CSS, 2012).

Recently Evolutionary Multi-objective Optimisation (EMO) techniques have shown to be a valuable tool for controller tuning applications (Reynoso-Meza et al., 2014). They enable the designer or decision maker (DM) having a close embedment into the tuning process since it is possible to take into account each design objective individually; they also enable comparing design alternatives (i.e. different controllers), in order to select a tuning fulfilling the expected trade-off among conflicting objectives.

It could be argued that the basic control requirement for a FCS is to stabilize the UAV, which usually means tracking the desired pitch, yaw and roll angles. In order to test control algorithms for such angles, it is usual employing less complex models and systems, before going to systems with greater complexity. An usual example is provided by two degrees of freedom (2-DOF) helicopters, which emulate the behaviour of an helicopter, where pitch and yaw angle should be controlled. It is a helpful platform in order to test control techniques in a laboratory environment (García-Sanz et al., 2006; García-Sanz and Elso, 2007a; García-Sanz and Elso, 2007b).

EMO techniques have been employed with success for such systems (Reynoso-Meza et al., 2013; Carrillo-Ahumada et al., 2015). Nevertheless, defining adequate and meaningful design objectives to measure controller performance is still a challenge. Such design objectives statement is a fundamental task given that the most meaningful the design objectives, the easier the DM’s task of
selecting a preferable controller fulfilling her/his expected performance.

In this paper, a simple multiobjective problem statement is defined, using a reference case controller in order to improve pertinency of solutions in the approximated Pareto front. The remainder of this works is as follows: firstly in Section 2 it is presented a brief background on UAS’s and PID control tuning process. Secondly, an EMO procedure for pitch and yaw control is presented in Section 3 and it is validated in Section 4. Finally, a conclusive view of this work and its future researches are commented.

2 Background

In order to describe the tuning approach of this paper, some preliminaries in control of aerodynamic process, multivariable proportional-integral-derivative (PID) controllers and EMO are required. They are provided below.

2.1 Control of aerodynamic process

In Figure 1 a UAS is depicted. As commented before, the UAS is comprised by (at least) a GCS and an UAV. In such UAV, one of the most important devices is the Flight Control System (FCS), which provides the desired level of autonomy to the vehicle. Perhaps the most basic task of the FCS is to stabilise the aircraft by tracking the desired angles, usually denoted as yaw, pitch and roll (See Figure 2). Yaw angle is usually associated with course while pitch angle with pitching of the aircraft.

One of the basic control structures for stabilization of the UAV is by means of PID controllers, which are commented next.

2.2 Background on PID controller tuning

A basic control loop is depicted in Figure 3. It comprises transfer functions $P(s)$ and $C(s)$ of a process and a controller respectively. The objective of this control loop is to keep the desired output $Y(s)$ of the process $P(s)$ in the desired reference $R(s)$.

Equation (1) shows the transfer function of the selected structure of the PID controller:

\[
C(s) = k_p \left( 1 + \frac{1}{T_i \cdot s} + T_d \cdot s \right)
\]

subject to:

A maximisation problem can be converted to a minimisation problem. For each of the objectives that have to be maximised, the transformation: \( \max J_i(\theta) = \min (-J_i(\theta)) \) could be applied.

Figure 2: Yaw, pitch and roll angles in an aircraft.

Figure 3: Basic control loop.
\[ K(\theta) \leq 0 \quad (3) \]
\[ L(\theta) = 0 \quad (4) \]
\[ \theta_i \leq \theta_i \leq \theta_i^{\ast}, i = [1, \ldots, n] \quad (5) \]

where \( \theta = [\theta_1, \theta_2, \ldots, \theta_n] \) is defined as the decision vector with \( \dim(\theta) = n \); \( J(\theta) \) as the objective vector and \( K(\theta), L(\theta) \) as the inequality and equality constraint vectors respectively; \( \theta_i, \theta_i^{\ast} \) are the lower and the upper bounds in the decision space.

It has been noticed that there is not a single solution in MOPs, because there is not generally a better solution in all the objectives. Therefore, a set of solutions, the Pareto set, is defined. Each solution in the Pareto set defines an objective vector in the Pareto front. All the solutions in the Pareto front are a set of Pareto optimal and non-dominated solutions:

- Pareto optimality (Miettinen, 1998): An objective vector \( J(\theta^1) \) is Pareto optimal if there is not another objective vector \( J(\theta^2) \) such that \( J_i(\theta^1) \leq J_i(\theta^1) \) for all \( i \in [1,2,\ldots,m] \) and \( J_j(\theta^2) < J_j(\theta^1) \) for at least one \( j, j \in [1,2,\ldots,m] \).
- Dominance (Coello and Lamont, 2004): An objective vector \( J(\theta^1) \) is dominated by another objective vector \( J(\theta^2) \) iff \( J_i(\theta^1) \leq J_i(\theta^2) \) for all \( i \in [1,2,\ldots,m] \) and \( J_j(\theta^2) < J_j(\theta^1) \) for at least one \( j, j \in [1,2,\ldots,m] \). This is denoted as \( J(\theta^2) \leq J(\theta^1) \).

Such definitions are depicted in Figure 4.

![Figure 4: Pareto optimality and dominance concepts.](image)

3 MOOD procedure for yaw and pitch control

As commented before, a usual system to test control techniques for UAVs is the 2-DOF helicopter. Here will be used the linear and non-linear models from (Reynoso-Meza et al., 2013; Carrillo-Ahumada et al., 2015) which are based on a Twin Rotor MIMO system (TRMS) of Feedback instruments (see Figure 5). It is a TITO (two inputs, two outputs) system, where two direct current (DC) motors have control over the vertical angle (main angle, pitch) and horizontal angle (tail angle, yaw) respectively. Both inputs are limited in the normalized range \([-1,1]\), the main angle being in the range \([-0.5,0.5]\) rad, and the tail angle in the range \([-3.0,3.0]\) rad.

![Figure 5: Twin Rotor MIMO System (TRMS) setup.](image)

The TRMS linear (TRMS-l) model will be used for controller tuning in the optimisation stage, while the TRMS non-linear (TRMS-nl) model will be used as real tuning in order to validate the robustness of the calculated and selected controllers. Now the MOP definition, MOO process and the MCDM stage will be stated accordingly.

3.1 Multiobjective problem definition

Given that the TRMS is a TITO system, coupling effects between yaw and pitch angles are expected. In this case, \( P(s) \) is composed of four sub-processes \( P_{ij} \) with \( i, j \in \{1,2\} \) and it has the following structure:

\[
P(s) = \begin{bmatrix}
P_{11}(s) & P_{12}(s) \\
P_{21}(s) & P_{22}(s)
\end{bmatrix}
\]

The complexity of a process like this is mainly due to its coupling effects between inputs and outputs. There are several alternatives to control a TITO system, and the selection of one technique over another depends on the desired balance between complexity and trade-off between design specifications. PID controllers are simple but successful solutions, and their performance can be improved with complementary techniques (Aström...
and Häglund, 2005); because of this, they are used in this work. The decoupled PID controller $C(s)$ proposed has two SISO (single-input, single-output) PID controllers:

$$C(s) = \begin{bmatrix} C_1(s) & 0 \\ 0 & C_2(s) \end{bmatrix}$$  \hspace{1cm} (7)

Within this context, the decision variables for the optimisation statement are $\theta = [k_{p1}, T_{I1}, T_{D1}, k_{p2}, T_{I2}, T_{D2}]$. The following reference case controller $C_{ref}(s)$ is stated: $\theta_R = [1, 10, 10, 1, 2, 10]$. Using a reference controller is a useful practice in control systems, to evaluate improvements of the controllers.

It will be defined two design objectives for the optimisation stage: one related to performance on yaw and pitch tracking, and one for robustness. In the first case, the integral of the absolute value of total variation (TV) of the control action for main and tail rotor will be used.

$$J_{IAE}(\theta) = \int_{t=t_0}^{t_f} |r(t) - y(t)| dt \hspace{1cm} (8)$$

$$J_{TV}(\theta) = \int_{t=t_0}^{t_f} \left| \frac{du}{dt} \right| dt \hspace{1cm} (9)$$

Where $r(t)$ is the desired reference, $y(t)$ the measured value and $u(t)$ the control action. In order to approximate such index via numerical integration, a time simulation with a predefined trajectory will be implemented. Given that the TRMS is a TITO system, an IAE for yaw and another for pitch will be required; in the same way, one TV for main rotor and one for the tail rotor. In order to avoid the number of design objectives, it will be used the reference case controller in order to build an aggregate objective function for IAE and one for TV. With this in mind, and with the aim of getting meaningful design objectives, the following optimisation statement is defined:

$$\min_{\theta} J(\theta) = [J_1(\theta), J_2(\theta)] \hspace{1cm} (10)$$

where

$$J_1(\theta) = \frac{100}{2} \left( \frac{J_{IAE_{yaw}}(\theta)}{J_{IAE_{yaw}}(\theta_R)} + \frac{J_{IAE_{pitch}}(\theta)}{J_{IAE_{pitch}}(\theta_R)} \right) \hspace{1cm} (11)$$

$$J_2(\theta) = \frac{100}{2} \left( \frac{J_{TV_{yaw}}(\theta)}{J_{TV_{yaw}}(\theta_R)} + \frac{J_{TV_{pitch}}(\theta)}{J_{TV_{pitch}}(\theta_R)} \right) \hspace{1cm} (12)$$

subject to:

$$k_{p1}, k_{p2} \in [0, 10]$$

$$T_{I1}, T_{I2} \in [0, 100]$$

$$T_{D1}, T_{D2} \in [0, 100] \hspace{1cm} (13)$$

3.2 Multiobjective optimisation process

For the optimisation stage, the sp-MODE algorithm (Reynoso-Meza et al., 2010) will be used. It is an algorithm based on the differential evolution algorithms (Storn and Price, 1997), (Das and Suganthan, 2010) which uses a spherical grid in order to prune the approximated set of solutions, and thus promoting diversity along the Pareto front approximation. It includes also a mechanism to improve pertinency (described in (Reynoso-Meza et al., 2012)). In this case, the objective vector $J(\theta_R)$ is used. Therefore, the algorithm will seek actively for a Pareto front approximation which dominates such reference controller, for the design objectives stated. Default evolutionary parameters are used in this work.

3.3 Multi-criteria decision making stage

Given that for this case, two design objectives are stated, no further tools are required in order to visualise and analyse trade-off between design alternatives in the approximated Pareto front. Interested readers may refer to (Tušar and Filipič, In press) for a review on visualisation tools and techniques.

4 Proposal validation

With the aim of compensating the stochasticity added by the optimization algorithm (an evolutionary algorithm), a total of 51 runs were carried out. This will be done in order to show the expected performance of this approach. Simulations and Pareto front approximations were performed in a standard personal computer with Intel Core i5-4210U, 1.7GHz, 4GB RAM. The Hypervolume measure is an usual choice to evaluate the performance of a given Pareto front approximation (Zitzler et al., 2003). In figure $\text{B}$ the attained surface at 50% (Knowles, 2005) is shown (which is a graphical visualization of the expected covering) and also the Pareto front approximation with the median value of the Hypervolume measure.

The Pareto front approximation for analysis is also depicted in figure $\text{B}$ the controller structure which will be selected is according to the following criteria:

A MOP with 4 or more design objective is named a many-objectives problem, which is out of the scope of this work.
Those controllers with a $J_{TV}(\theta) > 16$ are filtered and excluded from the analyses as they present a control effort that could compromises the stability in the TRMS-nl system.

Those controllers with $J_{IAE}(\theta) > 80$ are discarded, since their performance is outside of the DM’s preferences.

According to this, a total of 3 possible solutions are chosen to be evaluated in TRMS-nl. After evaluating the possible solutions using the same reference as in the TRMS-l, just one solution has a desirable performance for the DM. Such solution is represented in Figure 6 with 25.74% and 80.64% of IAE and TV optimization augment respectively when compared with the reference signal. Its performance in the TRMS-nl is depicted in Figure 7.

5 Conclusions and future work

Yaw and pitch control are important for any aerial system that needs an autonomous FCS. Effectiveness of such devices depend on the quality of the time response when tracking a desired path reference. MOOD techniques have shown to be valuable for this purpose due to their usefulness in controller tuning applications. They enable the possibility to appreciate the trade-off between performance and stability. The MCDM stage allowed more flexibility and easiness to chose a final tuning that matches the problem requirements. The behaviour of the chosen controller in TRMS-nl model validates such affirmation.

Future works will be oriented on the one hand, to parallelize the computational processing of the optimisation stage in order to speed up the tuning process; on the other hand in restructuring design objectives in order to reflect adequately designers preferences.

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References


Figure 7: Simulation time response.


