Comparison between Equilibrium Optimization and Systune on Aircraft Blank Angle Control

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Abstract

This paper is a direct comparison of equilibrium optimization (EO) one of the classes of meta-heuristic (MH) known for nonlinear optimization capability and Systune designed specifically for control problems for aircraft blank angle control. The control structure consisted of aileron rudder interconnection, Dutch roll damping, and proportional and integral (PI) control gain. These are set as design variables with multiple objectives and constraints including performance and robustness. The model parameter is allowed to vary up to 10% of the nominal value. The worst-case gain result was then used to evaluate the performance of the controller obtained by each approach. Overall, the EO result is superior in terms of Dutch roll damping and robustness while other aspects especially in time domain requirement is only slightly better than the result acquired from Systune.

Keywords : Meta-heuristic (MH), Aileron rudder interconnect, Multi-objective tuning of fixed-structure controllers, Aircraft lateral control

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การเปรียบเทียบประสิทธิภาพระหว่าง Equilibrium Optimization กับโปรแกรม Systune ในการออกแบบระบบควบคุมมุมเอียงของเครื่องบิน

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บทคัดย่อ

บทความวิจัยนี้เป็นการเปรียบเทียบประสิทธิภาพระหว่าง Equilibrium Optimization (EO) ซึ่งจัดอยู่ในกลุ่มของเมต้าฮิวริสติก (Meta-heuristic) กับโปรแกรม Systune สำหรับการออกแบบระบบควบคุมมุมเอียงของเครื่องบิน เมต้าฮิวริสติก (Meta-heuristic) มีความสามารถในการแก้ปัญหาแบบไม่เป็นเชิงเส้นได้ ส่วน Systune ถูกออกแบบมาเพื่อแก้ไขปัญหาทางด้านการควบคุมโดยเฉพาะ โดยรูปแบบของระบบควบคุมมีการใช้ปีกเล็กแก้เอียงผสมกับหางเสือเลี้ยว ตัวหน่วง Dutch roll และคอนโทรลเลอร์แบบพีไอ (PI) ซึ่งองค์ประกอบเหล่านี้ก่อให้เกิดตัวแปรอิสระเป็นจำนวน 4 ตัว โดยอยู่ภายใต้เป้าหมายและขอบเขตหลายประการ ทั้งในแง่ของประสิทธิภาพและความคงทนของระบบควบคุม แบบจำลองของเครื่องบินถูกนำเสนอในรูปแบบ State-space ซึ่งมีการเพิ่มความไม่แน่นอนเข้าไปในระบบโดยค่าตัวแปรในระบบสามารถแปรผันได้มากที่สุดถึง 10% จากค่าเริ่มต้น ค่าตัวแปรระบบที่ก่อให้เกิดสภาวะเลวร้ายที่สุดจะถูกใช้เป็นตัวชี้วัดสำหรับระบบควบคุมที่หาได้จากทั้งสองวิธี ในภาพรวมแล้วระบบควบคุมที่หาได้จาก EO ได้ผลลัพธ์ที่ดีกว่าระบบควบคุมของ Systune เมื่อมองในแง่ของการป้องกันมุมเอียงและความคงทนของเครื่องบิน แต่ในแง่ประสิทธิภาพนั้นมีความใกล้เคียงกัน

คำสำคัญ : เมต้าฮิวริสติก, การเชื่อมโยงปีกเล็กแก้เอียงกับหางเสือเลี้ยว, การออกแบบระบบควบคุมหลายวัตถุประสงค์, การควบคุมมุมเอียงของเครื่องบิน

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1. Introduction

Unmanned aerial vehicles (UAV) are very powerful tools due to their versatility and can operate without human interference. The use can be seen in many applications such as agriculture, military, surveillance, etc. UAVs can roughly be categorized as multi-rotor and fixed wing which in this work will focus on fixed wing. The control framework is the heart of UAV operation. It allows the mission to operate without human intervention through a feedback controller. The controller consisted of 2 loops, The outer loop calculates the waypoint to the aircraft behavior required to reach the point which often be the angle and speed of the aircraft [1]. The inner loop will follow the outer loop command as a reference and then execute the actuator to achieve the position commanded by the outer loop.

The fixed-wing aircraft has 3 main control surfaces, aileron, rudder, and elevator for control roll, pitch, and yaw angle of the aircraft respectively. It dynamic can be separated between longitudinal and lateral dynamics for convenience as it has negligible effect on each other. Thus, it can be tuned separately. Tuning longitudinal dynamic is simpler than lateral dynamic, there is no coupling movement axis compared to lateral. In simple terms longitudinal captured altitude and speed, lateral captured directional component. So, longitudinal have to take elevator deflection with constant throttle setting to control compared to aileron and rudder in lateral motion. When an aircraft needs to change direction, it can be done by aileron not the rudder, using a rudder for directional control is not effective due to higher drag, the excessive roll movement, and furthermore rudder has less control surface area compared to the aileron. So, the rudder is used only for adjusting adverse yaw angles. In the tuning procedure, lateral motion is much more difficult compared to longitudinal due to the coupling motion of blank and sideslip angle. The aircraft lateral control system is designed to track blank angles causing unintentional side slip angles throughout the process. To address this issue, aileron rudder interconnection (ARI) can be used [2], [3]. The ARI approach was invented to adjust the rudder countering excessive side slip angle while aileron is active.

Typically, gain ARI is tuned first in order to minimize Dutch roll damping followed by feedback control design. The classical tuning method obtained gain ARI by using root locus. However, the gain ARI can post the effect on blank angle tracking later in the feedback control design. Therefore, it would be more optimal to take the gain ARI together with feedback gain as one optimization procedure.

Luckily, there are tools that can be used in the problem such as Systune [4]–[6]. Systune is a very popular algorithm in automatic tuning. It can utilize both time and frequency domain requirements with capable of handling multiple objectives and constraints for an optimal set of design variables [7]. It has an advantage over some well-known methods like linear matrix inequality (LMI), LMI can optimize only in linear problems and is not capable of large dimension systems.

Meta-heuristic (MH) is known for nonlinear optimization algorithms which are categorized as single-objective and multi-objective. As the name suggests, single objective has only one objective. The weighted sum technique is used in order to clump those objectives into one [8]. Multiple objectives on the other hand provide a set of optimal objectives through the pareto front [9]. It is also used in control framework [10] and the aviation industry suh as PID tuning [11], [12], aircraft path planning [13], aircraft engine modelng [14], aircraft system identification [15], [16], robust control tuning [17], [18], etc.. Thus, MH is suitable for lateral tuning control design problems.

Few studies are comparing MH and systune performance and usage which are rarer in lateral tunig applications. Thus, this paper aims to compare the performance in tuning blank angle tracking with ARI gain with multiple objectives and constraints. Equilibrium optimization (EO) [19] was chosen to compete with Systune for its balanced exploration and exploitation. The set of design variables, objectives, and constraints are set as close as possible for both tuning approaches. More detail can be seen in the problem setup section. The result was then compared and discussed.

2. Problem formulation

Aircraft lateral dynamic can be represented in a state-space formulation which is linearized and decoupled from the longitudinal dynamic. The dynamic of DC-8 aircraft is used to demonstrate the controller tuning technique. The flight takes place at 30,000 ft. with a velocity of 824.2 ft./sec. The state space representation can be seen in Eq. 1, these dimensional derivatives are added uncertainty components using ureal function in MATLAB which can vary up to 10% of its nominal value.

$$\begin{bmatrix} \dot{\beta} \\ \dot{\Phi} \\ \dot{p} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} Y_\beta - \frac{T^*}{mV^*} & \frac{g}{V^*} & Y_p & Y_r - 1 \\ 0 & 0 & 1 & 0 \\ L_\beta & 0 & L_p & L_r \\ N_\beta & 0 & N_p & N_r \end{bmatrix} \begin{bmatrix} \beta \\ \Phi \\ p \\ r \end{bmatrix} + \begin{bmatrix} Y_{\delta a} & Y_{\delta r} \\ 0 & 0 \\ L_{\delta a} & L_{\delta r} \\ N_{\delta a} & N_{\delta r} \end{bmatrix} \begin{bmatrix} \delta a \\ \delta r \end{bmatrix} \quad (1)$$

The uncertainty of each parameter shown in Eq. 1 is as follows:

```
Y_b1=ureal('Y_b1',-0.0868,'Percentage',10)
T1=ureal('T1',T1,'Percentage',10)
mV1=ureal('mV1',mV1,'Percentage',10)
```

```
L_b1=ureal('L_b1',L_b1,'Percentage',10)
L_p1=ureal('L_p1',L_p1,'Percentage',10)
L_r1=ureal('L_r1',L_r1,'Percentage',10)
N_b1=ureal('N_b1',N_b1,'Percentage',10)
N_p1=ureal('N_p1',N_p1,'Percentage',10)
N_r1=ureal('N_r1',N_r1,'Percentage',10)
Y_dr1=ureal('Y_dr1',Y_dr1,'Percentage',10)
L_da1=ureal('L_da1',L_da1,'Percentage',10)
N_da1=ureal('N_da1',N_da1,'Percentage',10)
N_dr1=ureal('N_dr1',N_dr1,'Percentage',10)
```

The aircraft controller is as in Figure 1 which has 4 tunable characteristics comprised of yaw or sideslip damper (Kr), aileron rudder interconnection (Kari), proportional gain, and integral gain for the control blank angle of the aircraft. The set of design variables are expressed in Eq. 2-4 with lower and upper bound as in Table 1. Ideally, the sideslip angle is required to be zero as it interferes with blank angle control but in lateral dynamic, the sideslip is coupled with blank angle control. Thus, the sideslip angle can be reduced using ARI and sideslip damper. The aircraft normally tunes the sideslip damper and aileron rudder interconnection first then proceeds to the blank angle feedback controller. It may not be the optimal way of tuning because this gain can affect the controller's performance. The controller is designed to track the blank angle command using aileron as the main actuator, rudder on the other hand used as a secondary actuator assisting the movement of the aircraft.

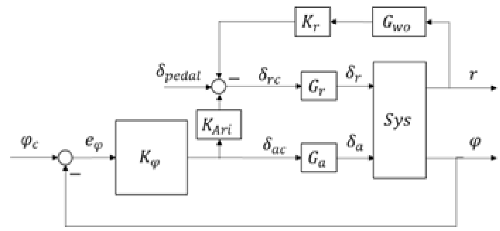

Figure 1 *Interconnection of aircraft controller*

$$K_r = x(1) \quad (2)$$

$$K_{ari} = x(2) \quad (3)$$

$$K_\varphi = \frac{x(3)s + x(4)}{s} \quad (4)$$

Table 1 *Lower and upper bound of design variables*

Design variables	Lower	Upper
x(1)	-5	5
x(2)	-10	10
x(3)	0	10
x(4)	0	10

The objective of the controller is not only tracking the blank angle reference signal but also guaranteeing robust and stability of the aircraft for this flight condition. The first objective is set to search for maximum robust and stability so it is divided by 1, how large the gain will cause the system to be unstable. Second is control effort, for this objective seeking the controller to be as efficient as possible. Third is settling time, which is the classical component considering how fast the controller handles the reference signal.

Fourth is the root mean square (RMS) of the side slip, minimizing the side slip angle that occurs while the aileron is active. Fifth and sixth are the norm of the transfer function and sensitivity function, the norm is used for noised and disturbance rejection. In summary, there are a total of 6 objectives to be considered which are combined into one objective using the weighted sum technique with weighting each objective of 2, 2, 1, 10, 1, and 1 respectively.

$$f1 = \frac{1}{\max(lower, upper\ limit)} \quad robust\ stability(\text{robstab command}) \tag{5}$$

$$f2 = RMS\ of\ control\ effort \tag{6}$$

$$f3 = settling\ time \tag{7}$$

$$f4 = RMS\ of\ beta\ (side\ slip\ when\ used\ aileron) \tag{8}$$

$$f5 = norm\ inf\ of\ \frac{GK}{1+GK} \tag{9}$$

$$f6 = norm\ inf\ of\ \frac{1}{1+GK} \tag{10}$$

$$f = 2*f1 + 2*f2 + f3 + 10*f4 + f5 + f6 \tag{11}$$

The problem is also subjected to constraints consisting of overshoot, aileron deflection, rate limit, roll rate limit, rise time, and Dutch roll damping as in Eq 12-17. These constraints are handled with a penalty function in Eq. 18.

$$g1 = Overshoot < 5\% \tag{12}$$

$$g2 = Aileron\ deflection\ limit < 20\ deg \tag{13}$$

$$g3 = roll\ rate\ limit < 30 \tag{14}$$

$$g4 = Aileron\ deflection\ rate\ limit < 100\ deg/sec \tag{15}$$

$$g5 = Rise\ Time < 4\ sec \tag{16}$$

$$g6 = Dutch\ roll\ damping > 0.2 \tag{17}$$

Penalty function

$$fp = f + 10000 * \max(g > 0) \tag{18}$$

2.1 MH set up

Equilibrium optimizer is chosen for this problem, the detail of the algorithm is shown in the original algorithm paper [19]. The population sizes are set as 100, the max iteration is set to be 50, in total of 5,000 function evaluation. The equilibrium pools are chosen as 4 pools for balancing between convergent rates and searching radius. The best result out of 5 individual runs is captured for comparison.

2.2 Systune setup

The Systune requirement is not straightforward to directly compare with MH thus, the problem is set to have as good as result with satisfied the requirement of MH. The step tracking requirement dictated the performance and constraint violation of the controller so, this value needs to be adjusted several times to get the best result for comparison. Other requirement are straight forward requirements like control effort limit, overshoot, roll rate limit, etc.. The setup is adjusted as follows.

```
overshoot=0;
tou=0.75;
Req0 = TuningGoal.StepTracking('phic','phi',
          tou,overshoot);
Req1 = TuningGoal.Gain('phic','phi',1);
Req2 = TuningGoal.Overshoot('phic','phi',5);
Req3 = TuningGoal.Gain('phic','beta',0.15);
Req4 = TuningGoal.Gain('phic','p',1.5);
Req5 = TuningGoal.Gain('phic','da',1);
Req6 = TuningGoal.Gain('phic','da_rate',20);
```

3. Result and discussion

Starting from robustness and stability, MH reaches 5.9737 over 4.7574 of Systune meaning MH is more robust. Furthermore, MH has less control effort, settling time, and side slip error when excites the system while the transfer function and sensitivity function norm are nearly identical for both approaches. Step response in Figure 2 shows the comparison of 2 different tuning techniques blank angle, both perform very well to the command. The major difference is in sideslip damping, MH approach surpasses Systune for handling unintentional sideslip as it has larger Dutch roll damping compared to Systune. Dutch roll damping effect can also be seen in Figure 3. The system is exited with duplet aileron deflection again MH is clearly rejected sideslip far better than Systune. The difference between both tuning techniques is around 1 degree. The result comparison of Systune and MH tuning approach appeared in Table 2 indicating that the MH approach performs better in every aspect. Both methods managed to pass all 6 constraints as seen in Table 3. and have an overshoot of around 2%, and aileron constraints and roll rate limits are very small compared to the setup limit. The worst-case gain from the uncertainty content can then be identified using the wcgain command which finds the worst uncertainty combination that maximizes the output gain of the system from the aileron command to roll. The uncertainty then substitutes back to the nominal system leading to a worst-case gain system which alters the performance of the design system significantly. There is only a robust stability objective that uses the uncertainty content in calculation the others are computed from the nominal value. So, the objective f1 is not present in the worst-case gain result. The worst-case gain system objectives and constraints are presented in Tables 2 and 3. Both approaches have exceeded the overshoot limit by around twice the value of 5%. Settling time is increased for MH but interestingly decreased for Systune. The others are slightly different than the nominal value. The optimal gain can be seen in Table 4, Gain ARI and integral gain obtained from MH is really small compared to Systune.

Table 2 *Objective comparison of Systune VS MH*

Objective	Nominal		Worst-case gain	
	Systune	MH	Systune	MH
f1 = Robust stability (norm)	4.7574	5.9737	-	-
f2 = Control effort (RMS)	0.5779	0.5205	0.5566	0.5008
f3 = Settling Time (second)	6.5758	2.7255	4.7169	4.7478
f4 = beta error (RMS)	0.0765	0.0575	0.0671	0.0509
f5 = inf norm Transfer function (norm)	1.0005	1	1.0005	1.0000
f6 = inf norm Sensitivity function (norm)	1.3968	1.381	1.3968	1.3810

Table 3 *Constraints comparison of Systune VS MH*

Constraints	Nominal		Worst-case gain		Limit
	Systune	MH	Systune	MH	
g1 = Overshoot	2.1716%	1.9992%	11.4646	10.8484	<5%
g2 = aileron defection limit	2.99	2.5914	2.9853	2.5876	<20 deg
g3 = roll rate limit	2.9265	2.658	3.3572	3.041	<20 deg/ sec
g4 = aileron defection rate limit	5.3623	4.6443	5.3604	4.6427	<100 deg/ sec
g5 = rise time	1.6644	1.8081	1.3572	1.496	<4 sec
g6 = Dutch roll damping	0.3568	0.4122	0.3568	0.4122	>0.2

Table 4 *Design variables comparison*

Design variables	Systune	MH
x(1)	-0.72293	-0.85563
x(2)	0.05846	1.6772e-05
x(3)	0.61153	0.52925
x(4)	0.0028251	0.00012331

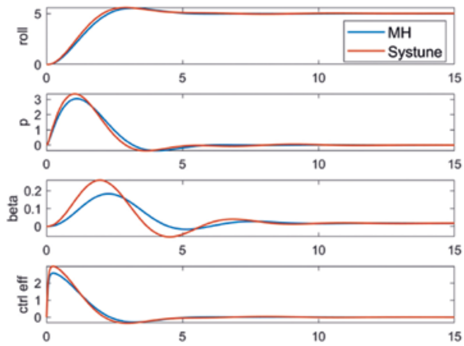

Figure 2 *Step responses of plant with controller*

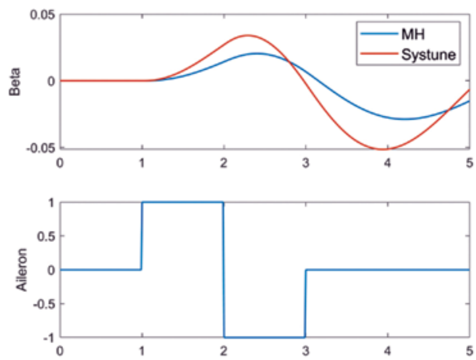

Figure 3 *Doublet responses from aileron to beta*

The bode plot of an open loop plant with a controller structure with 100 sampling uncertainty is captured in figure 4. The classical gain and phase margin of the system are decent on both Systune and MH approaches which indicates the robustness of both systems. The minimum gain and phase margin on both approaches are 25 db and 70 degrees.

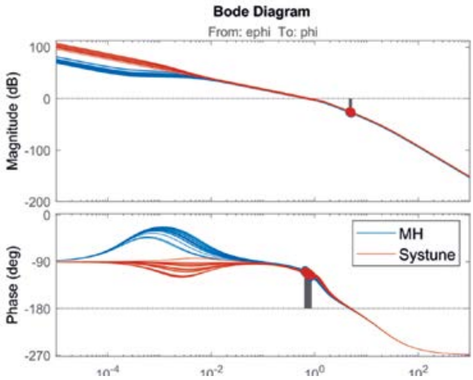

Figure 4 Bode plot of open loop roll angle

4. Conclusion

This numerical experiment compares these Systune and MH performances on tuning control structures are not simple. The problem cannot be identical due to the different processes of optimization. So, Systune is tuned as similarly as possible to meet the same requirements as MH. Tuning Sytune requires the knowledge of the toolbox to adequately tune the controller to be as designed. MH, on the other hand is straightforward and more flexible. It can list the set of objectives and constraints and fulfill all the constraints while Systune usually treats constraints as soft constraints. In terms of consistency, Systune is superior to MH as it requires a couple of repetitions to guarantee the best performance. Overall MH technique is superior to Systune in robustness, error tracking, and side slip minimization. The problem can be set as accurate to the real-world system which is much more complex than this simple example.

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