***Bridging the gap between theory and practice*.**
A control engineering competition for the EECS-304/305 students

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1. Introduction

Control Engineering constitutes one of the core disciplines of modern Engineering [1-4]. Nevertheless, its strong mathematical background and multidisciplinary character often makes it too complex and abstract for students [5-9]. For these reasons some extra effort has to be applied to improve the students understanding.

In that context, this chapter introduces a practical controller design competition for a laboratory helicopter. It is proposed to motivate students, and to enhance their attention and comprehension of the main control engineering concepts. The design will face real-world control design problems, such as plant model uncertainty, performance specifications trade-offs, actuator constraints, sensor noise and real implementation among others.

2. Helicopter description

The system to be controlled is a bench-top helicopter manufactured by Quanser Consulting [10]. It is a laboratory scale plant with two propellers and 3 Degrees of Freedom (3DOF), pitch ϕ, elevation θ, and travel ψ angles, each one measured by an absolute encoder (Figure 1).

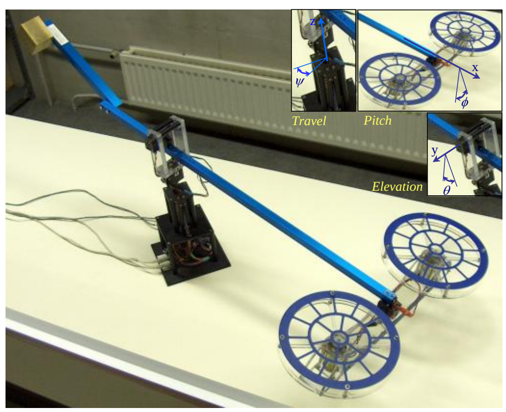

Figure 1. The Helicopter Experiment, manufactured by Quanser Consulting. It is a 3 Degrees of Freedom plant (pitch ϕ, elevation θ, and travel ψ angles), each one measured by an absolute encoder. Two propellers make the system turn around the three angles.

Although a design of the full helicopter flight control system (FCS) requires working simultaneously with the three angles, only the elevation angle θ is considered for the EECS 304/305 students competition (Figure 2). The pitch ϕ and travel ψ angles are controlled in the background by appropriate controllers. Two electrical DC motors are attached to the helicopter body, making two propellers turn. The total force F caused by aerodynamics makes the system turn around the elevation angle θ measured by an encoder. A counterweight of mass M helps the propellers lift the body of the helicopter.

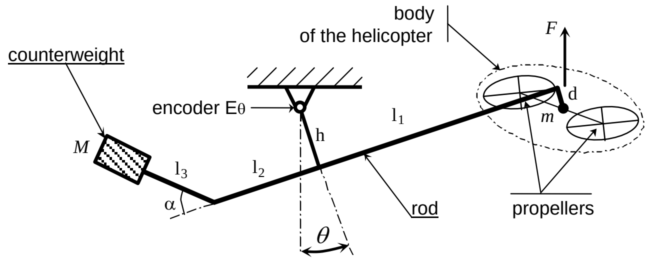

Figure 2. Mechanical diagram of the elevation angle θ to be controlled. The helicopter is suspended from the encoder E_θ and moved up and down by two propellers.

A PC by means of a data acquisition board controls the helicopter. Control structure configuration and compilation (including continuous-time control law discretization) becomes extremely easy using a Simulink application [11] and compatible libraries supplied by the manufacturer [10] to deal with sensor measures and command signals.

The plant mathematical model of the elevation dynamics is obtained applying Lagrange's equations to the mechanical scheme of Figure 2,

$$F\, l_1 - m\, g \cdot \left[(h+d)\sin\theta + l_1 \cos\theta \right] + M\, g\left(l_2 + l_3 \cos\alpha\right)\cos\theta + M\, g\left(l_3 \sin\theta - h\right)\sin\theta - b_e\, \theta' = J_e\, \theta'' \qquad (1)$$

where h, d, l_1, l_2 and l_3 are lengths; m the sum of both motors' mass; M the counterweight mass; b_e the dynamic friction coefficient; g the gravity acceleration; J_e the inertia moment of the whole system around the elevation angle θ; and α a fixed construction angle. The non-linear model –Eq. (1)- can be simplified by linearization around the operation point θ_0=0º. It yields the second order transfer function of Eq. (2) plus a set of parameters with uncertainty (Table I), estimated applying system identification techniques to real data.

$$P(s) = \frac{\theta(s)}{U(s)} = \frac{k\, \omega_n^2}{s^2 + 2\, \zeta\, \omega_n\, s + \omega_n^2} \cdot e^{-sT} \qquad (2)$$

where $\theta(s)$ is in radians and $U(s)$ in volts

Parameter	Minimum value	Maximum value	Units
k	0.1	0.15	[rad/V]
ζ	0.03	0.05	0.05
ω_n	1.0	1.5	[rad/seg]
T	0.09	0.11	[seg]

Table I: Counter Mass at 19g. Parametric uncertainty for helicopter elevation model. Original non-linear behavior of elevation angle is expressed as a linear second order transfer function with parameter uncertainty.

The system present two classical non-linearities: a saturation limit of ±10 V in the motors and a quantization effect of 0.0015 rad on the sensors (Figure 3). They could produce limit cycles.

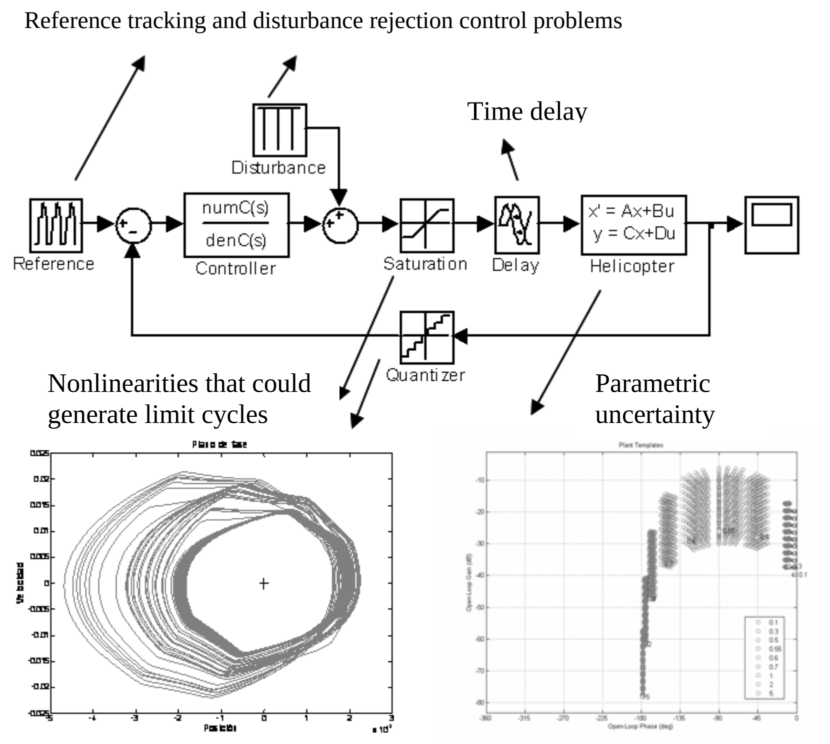

Figure 3. Control diagram.

3. Arrangement of the competition

Some of the main aspects to be considered in the controller design are summarized in the following points:

- increase system stability,
- reduce the tracking error as soon as possible,
- reduce or remove reference tracking errors at steady state,
- reject disturbances as soon as possible,
- reduce overshoot and increase damping,
- reject the effect of high frequency noise introduced at sensors,
- consider actuator saturation,
- consider quantization effects in the sensors,
- consider model uncertainty,
- deal with a very low damped system,
- reduce the control signal (fuel consumption).

Practical issues.

Two files to help the controller design and validation can be found in Blackboard:

- cf.m (Cost function)
- helicopter.mdl (Simulation)

Each student will write a brief report (four pages maximum) with the designed controller as a Laplace transfer function in the form of two polynomials numerator/denominator in the first page.

Deadline for the report: April 23rd, 2012, 9.00 am.

The competition with the helicopter at the lab (Olin 606) will take place on April 25th, 2012, 9.00 am.

Students can use any existing controller design methodology in the literature. The objective of the controller (performance control specifications) is to achieve the best reference tracking and disturbance rejection behavior with the minimum fuel consumption (control effort). This will be stated by minimizing the cost function *J* described in Eq. (3), as a measurement that balances the tracking error and the control effort.

$$J = \frac{1}{J_0} \sum_{i=1}^{6} J_i \tag{3}$$

where:

$$J_i = \beta_i \cdot \int_{t_i}^{t_{i+1}} |e(t)| \cdot t \cdot dt \;\; ; \;\; i = 1, 2, 3, 4$$

$$J_5 = \beta_5 \cdot \int_{t_1}^{t_5} |v(t)| \cdot dt$$

$$J_6 = \beta_6 \cdot \int_{t_1}^{t_5} \left| \frac{dv(t)}{dt} \right| \cdot dt$$

and where $e(t)=\theta_{ref}(t)-\theta(t)$ is the elevation angle tracking error (in radians), $v(t)$ the control signal (in volts) applied to the motors, J_0 a number to normalize the results (corresponding to the result of the trial when applying a typical PID controller), and $t_1 = 15$; $t_2 = 65$; $t_3 = 80$; $t_4 = 95$; $t_5 = 120$; $\beta_1 = 0.0579$; $\beta_2 = 2.8648$; $\beta_3 = 0.6366$; $\beta_4 = 0.2727$; $\beta_5 = 0.00072$; $\beta_6 = 0.000017$. The reference set point is shown in Figure 4 a. Note that at $t_3 = 65$ seconds a disturbance is introduced (Figure 4 b), stopping the motors of the helicopter for two seconds.

Considering the final course grade normalized between 0 and 10 (obtained from the project qualification), the controllers will be evaluated by adding an extra score between 0.5 and 1.5 points obeying Eq. (4),

$$extra\, score = 0.5 + \left(\frac{N - n + 1}{N} \right)^{2.5} \tag{4}$$

where N is the total number of controllers (students) in the competition, and n is the position achieved by everyone minimizing the function J of equation (3).

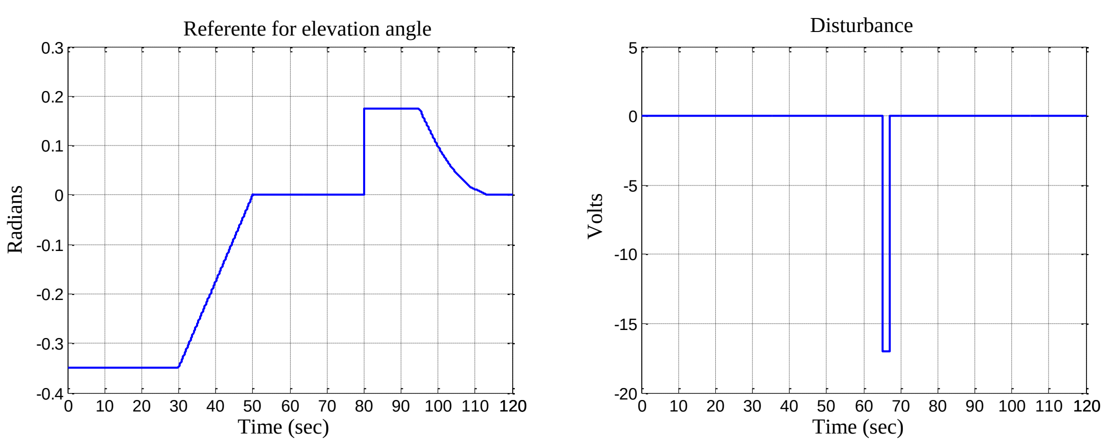

Figure 4. a) Reference for elevation angle; b) Disturbance.

Some experimental results achieved by a well-classified control algorithm in past competitions are shown in Figure 5. It is possible to appreciate an excellent reference tracking, with a short rise time, good damping and small overshoot. In addition, magnitudes of the control signal are basically comprised within the specified range of the actuator, that is ± 10 V.

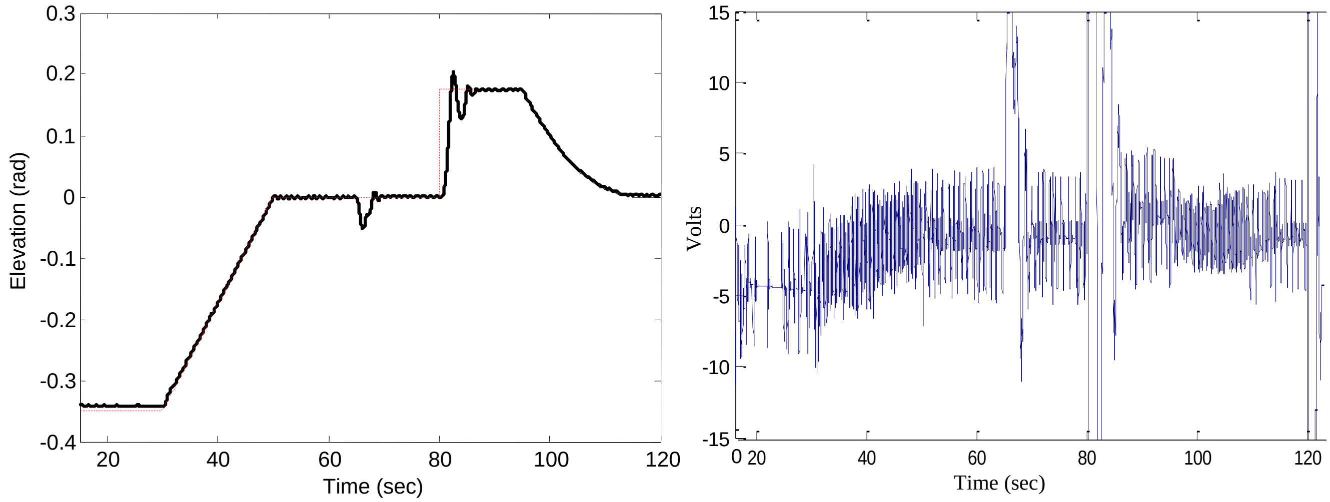

Figure 5. Experimental results of the elevation angle control with a well-classified controller.
a) Actual elevation angle (black-solid) and reference (red-dashed); b) Control signal.

4. References

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