NTNU – Trondheim
Norwegian University of
Science and Technology

Department of Engineering Cybernetics

Examination paper for TTK4190 Guidance and Control of Vehicles

Academic contact during examination: Professor Thor I. Fossen

Phone: 918 97 361

Examination date: Friday May 31, 2013

Examination time (from-to): 09:00 – 13:00

Permitted examination support material: All printed and handwritten materials are allowed. All type of calculators is approved*.

* For *all type of calculators* the following applies:
  - Calculators must not communicate with other electronic units/computers.
  - The calculator must not be attached to the power outlet.
  - The calculator must not make noise.
  - The unit's display must be the only printing device.
  - The calculator must only be one unit.
  - The calculator must be in pocket size.

Language: English

Number of pages: 4

Number of pages enclosed: 5

Checked by:

Date Signature

Problem 1: Constant Bearing Guidance System (25 %)

The two-dimensional position of a ship is propagating according to:

$$\mathbf{p}_t^n = \begin{bmatrix} 10t \\ 5t \end{bmatrix}$$

where t is the time in seconds, the position is given in meters and the heading angle is kept constant at 30 degrees.

A. (2 %) Compute the North-East velocities v^{N} and v^{E}.

B. (2 %) Compute the body-fixed velocities u, v and r.

C. (3 %) Compute the sideslip angle.

D. (1 %) What is the speed of the ship?

E. (5 %) The surge dynamics of a second ship is given by:

$$(m - X_{\dot{u}})\dot{u} - X_{|u|u}|u|u = (1-t)T$$

where all parameters are known. Show that the nonlinear controller:

$$T = \frac{1}{1-t}\Big((m - X_{\dot{u}})\dot{u}_d - X_{|u|u}|u|u_d - K_d(u-u_d)\Big)$$

gives a globally asymptotically stable equilibrium point of the error dynamics. The desired surge velocity u_d is bounded and smooth.

F. (12 %) The second ship is approaching the first ship on the port side in order to do off-loading, see Figure 1. The position (x, y) of the approaching ship is measured at each time instance.

Figure 1. Rendezvous operation at seas.

Design a constant bearing guidance control system. The control objective is that the approaching ship should converge to a position 15 m to the port side of the first ship. Write down the necessary equations needed to implement the constant bearing guidance system and control law. Include a block diagram with equations showing the ship, guidance system and control law as three blocks.

Problem 2: Line-of-Sight Guidance System (25 %)

The desired course angle is given as:

$$\chi_r = \arctan\left(-\frac{e}{\Delta}\right)$$

where $\Delta > 0$ is the look-ahead distance and e is the cross-track error. Assume that the desired path is parametrized as:

$$x_d(t) = x_0 + 2t$$
$$y_d(t) = y_0 + t$$

where t is the time and (x_0, y_0) is constant. The x-axis points in the North direction and y points in the East direction.

A. (6 %) Compute the path-tangential angle α_k and find a formula for the cross-track error e. The cross-track error should be a function of the position (x, y) of the ship and the path variables.

B. (4 %) The ship is exposed to wind, waves and ocean currents. This forces the ship to sideslip during path following. Explain what we mean with sideslipping?

C. (5 %) Will a ship sideslip if the environmental forces are zero (explain why/why not)? Include equations to support your answer.

D. (10 %) Explain how a path-following controller can be designed when the sideslip angle is unknown. Write down the necessary equations to implement the controller and included a block diagram with equations showing the ship, guidance system and path-following controller.

Problem 3: Navigation Systems (20 %)

A. (4 %) Assume that you have a magnetometer located in your office, which can be used to measure the BODY-fixed magnetic field $\mathbf{m}^b$ of a moving rigid body. How will you proceed to measure the magnetic field (reference vector) $\mathbf{m}^n$ in the NED reference frame for a given fixed location?

B. (4 %) Consider a strapdown IMU. If you integrate the accelerometer measurements once to obtain the BODY-fixed velocity vector of an aircraft moving at constant velocity what will happen? If you repeat the experiment for a body at rest will the result be different or the same (explain why/why not)?

C. (4 %) Explain how you compute the roll and pitch angles from a 3-axes accelerometer for a body at rest. What happens if you try to do this for a vehicle during a hard turn?

D. (4 %) Consider a strapdown IMU. If you integrate the 3-axes gyro measurements will you obtain an estimate of the Euler rates, angular velocity or none of previous mentioned? Explain why.

E. (4 %) Consider a navigation system based on IMU, GNSS and velocity measurements. The navigation system does not have a model of the vehicle. The measurements are used to update a Kalman filter, which estimates position, velocity and attitude. What happens with the position and velocity estimates if you loose the position measurements?

Problem 4: Unmanned Aerial Vehicle (UAV) (30 %)

Consider the Recce D6 fixed-wing UAV in Figure 2.

Figure 2. The Recce D6 fixed-wing UAV.

The drag and lift coefficients are given by:

$$C_L(\alpha) = 0.2\alpha - 0.0067\alpha^2$$
$$C_D(\alpha) = 0.0035\alpha^2$$

where α is the angle of attack in degrees. The *longitudinal* equations of motion are:

$$\dot{U} = VR - WQ - g\sin(\Theta) + \frac{T}{m} + \frac{\bar{q}S}{m} C_X(\alpha)$$
$$\dot{W} = UQ - VP + g\cos(\Theta)\cos(\Phi) + \frac{\bar{q}S}{m} C_Z(\alpha) + b_1\delta_E$$
$$\dot{Q} = \frac{I_x - I_z}{I_y} PR + \frac{\bar{q}S\bar{c}}{I_y} C_m(\alpha) + b_2\delta_E$$
$$\dot{\Theta} = Q$$

A. (4 %) Linearize the lift and drag coefficients in the interval 0-15 degrees and plot them together with their nonlinear counterparts as a function of angle of attack.

B. (1 %) Compute the *stall angle*.

C. (4 %) Derive the formulae for the aerodynamic coefficients $C_X(\alpha)$ and $C_Z(\alpha)$ in the expressions:

$$X = \bar{q} S C_X(\alpha)$$
$$Z = \bar{q} S C_Z(\alpha)$$

where S is the total wing area and

$$\bar{q} = \frac{1}{2} \rho_a V_T^2$$

is the dynamic pressure, V_T is speed, and ρ_a is the denisty of air (numerical expressions are required for C_X and C_Z). What are the physical interpretations of X and Z?

D. (5 %) Design a feedback linearizing speed controller for tracking of desired speed $U_d(t)$ using the propeller RPM n as input. The propeller thrust is given by:

$$T = K_t \rho_a D^4 n^2$$

where the propeller coefficient K_t and diameter D are known parameters.

E. (3 %) Attitude is controlled using the elevator δ_e. The pilot has a joystick system, which generates the desired flight path angle γ_d as shown in Figure 3. Show how the feedback signal γ is computed from the aircraft states. Moreover, you are supposed to write down the equation in Block (1) in Figure 3.

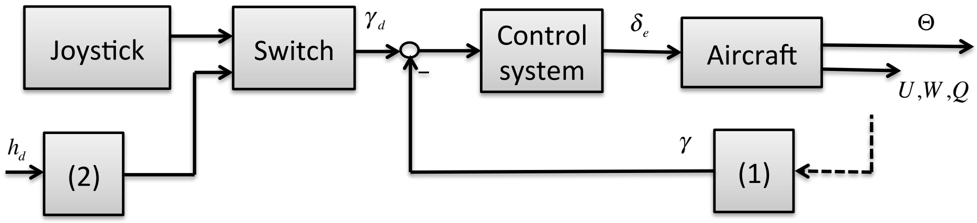

Figure 3. Attitude control system.

F. (8 %) Design an asymptotically stable flight-path control law using elevator δ_e as control input and such that the flight path γ converges asymptotically to the desired flight path γ_d. All states and the angle of attack α are measured so no observer is needed.

G. (5 %) Assume that the desired attitude $h_d(t)$ and its derivatives are specified by the pilot. Propose a line-of-sight (LOS) formula for generation of the desired flight path γ_d specified by Block (2) in Figure 3. The switch is used to bypass the joystick signal.