UNIVERSITY OF MORATUWA
Faculty of Engineering
Department of Electronic and Telecommunication Engineering
B. Sc. Engineering
Semester 8 Examination

EN4593 AUTONOMOUS SYSTEMS

Time allowed: *Two (2)* hours — July 2023

INSTRUCTIONS TO CANDIDATES:

- This paper contains **4** questions on **5** pages.
- Answer **ALL** questions.
- All questions carry equal marks.
- This is an **open**-book examination.
- This examination accounts for **60**% of the module assessment. The total maximum mark attainable is **100**. The marks assigned for each question and sections are indicated in square brackets.
- Electronic/communication devices are not permitted. Only equipment allowed is a calculator approved and labeled by the Faculty of Engineering.
- Derivations are not required if they are not explicitly requested for in the question.
- Assume reasonable values for any data not given in or with the examination paper. Clearly state such assumptions.
- If you have any doubt as to the interpretation of the wording of a question, make your own decision, and clearly state it.

ADDITIONAL MATERIAL:

- No additional material is provided.

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Question 1.

(a) Explain why a probabilistic approach is needed in the design and implementation of autonomous systems. [5 marks]

(b) An autonomous robot system is utilized to clean the windows of an office environment. The windows have two conditions (states x_t): clean and unclean. There are no workers in the office to manually clean the windows, and the job is totally done using the above cleaning robot. When the robot approaches a particular window it has no prior knowledge about the condition of it. However, the robot has been programmed to believe that any window is in a clean state with only a prior probability of 0.37 when it is approached.

The windows are cleaned by a cleaning tool, which is not 100% reliable, attached at the end of the robotic arm. Note that the cleaning tool may also introduce dirt to the window due to the tool not being properly cleaned after each cleaning. The following probabilities for the cleaning action (u_t) are provided:

$$\mathrm{P}(x_t = \text{is\_clean} | x_{t-1} = \text{is\_clean}, u_t = \text{clean}) = 0.92$$
$$\mathrm{P}(x_t = \text{is\_clean} | x_{t-1} = \text{is\_unclean}, u_t = \text{clean}) = 0.81$$

The robot uses its camera sensor to identify the condition of the window, and the following probabilities regarding the camera observations (z_t) are provided:

$$\mathrm{P}(z_t = \text{sense\_clean} | x_t = \text{is\_clean}) = 0.68$$
$$\mathrm{P}(z_t = \text{sense\_clean} | x_t = \text{is\_unclean}) = 0.23$$

i. Is the camera sensing system more capable of sensing a clean window or an unclean window? Justify your answer. [4 marks]

ii. Suppose at time instance T the robot performs cleaning of the approached window, takes a camera observation and senses an unclean window. Bel and $\overline{Bel}$ have their usual meanings.

α) Find $\overline{Bel}(x_T = \text{is\_clean})$. [4 marks]

β) Find $Bel(x_T = \text{is\_clean})$ after incorporating the observation. [8 marks]

γ) Will the robot perform cleaning again on the window based on the above state estimation? Justify your answer. [4 marks]

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Question 2.

Human gait analysis is the study of human locomotion, in which human walking patterns and arm motions are analyzed (Fig. Q2). Low-cost depth sensors can be utilized in gait analysis, and manufacturers usually provide software that outputs the position coordinates of joints (e.g., 25 joints) of the human body. However, these position measurements can suffer from limited accuracy.

You have been asked to design an autonomous human gait analysis system using a depth sensor. Answer the following questions regarding your proposed system.

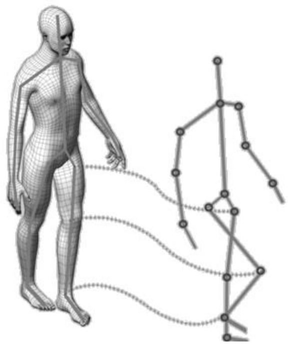

Figure Q2: Human gait analysis

(a) What requirements should be satisfied to employ Kalman filter for the above problem. [5 marks]

(b) To simplify the design process, it is suggested to use multiple Kalman filters, i.e., one for each joint, for the implementation. Discuss the theoretical validity of the usage of multiple Kalman filters, and give pros and cons. [5 marks]

(c) Give the state vector by identifying suitable state variables. [5 marks]

(d) Construct a suitable state transition model, while stating any assumptions you have made. The time step between state transition can be taken as Δt. The process noise vector is given by ϵ_t and its covariance matrix by R_t. [5 marks]

(e) Assuming that the observations of each joint positions are available from the manufacturer software, formulate the measurement model for the depth sensor. The measurement noise vector is given by δ_t and its covariance matrix by Q_t. State any assumptions you have made. [5 marks]

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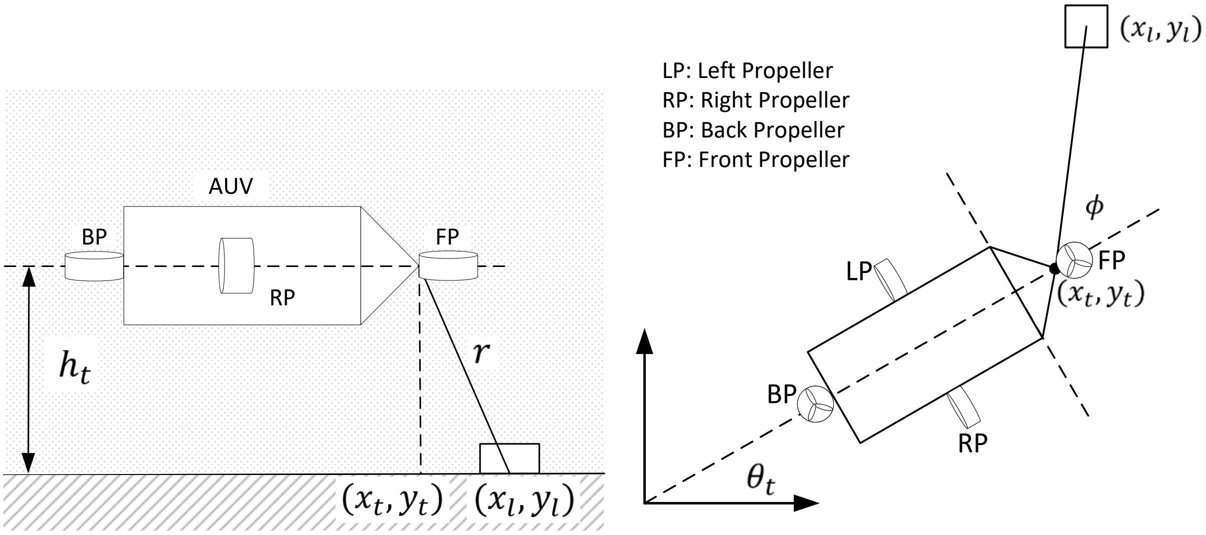
Question 3.

Autonomous underwater vehicles (AUVs) are becoming increasingly popular for deep-sea exploration. AUVs can operate in dangerous and remote environments without putting human lives at risk, especially where conditions can be harsh and unpredictable.



(a) side view (b) top-down view

Figure Q3: Autonomous underwater SLAM system

An AUV as depicted in Fig. Q3 is to be utilized for the exploration of a certain shipwreck. The AUV achieves autonomous navigation using a semi 3D-SLAM system with a feature-based map. The state of the AUV is given by its 3D position (x_t, y_t, h_t) and its 2D orientation θ_t. Distinct rocks on flat seabed are considered to be landmarks in the map. The state of a landmark is given by its 2D coordinates (x_l, y_l). Consider the following conditions for the motion model of the AUV:

- AUV receives a control input $u_t = [v_t \quad \omega_t \quad \gamma_t]^T$ at each time step. v_t is the horizontal translational velocity, ω_t is the horizontal rotational velocity, and γ_t is the vertical velocity.
- During each time step (Δt), the overall effect of u_t is such that the AUV, first, adjusts its height using γ_t for Δt_γ, and then rotates on the spot using ω_t for Δt_ω, and finally moves in a straight line using v_t for Δt_v $(\Delta t = \Delta t_\gamma + \Delta t_\omega + \Delta t_v)$.

The perception system returns sonar range-bearing measurements (r, ϕ) as illustrated in Fig. Q3.

(a) Explain how the AUV achieves different types of motion using its propellers (LP, RP, BP, and FP). [6 marks]

(b) Construct the motion model as a function of control input u_t and the AUV's previous state. [4 marks]

(c) Augment the motion model to the full SLAM state transition model for a single landmark situation. [3 marks]

(d) Derive the Jacobian matrix of the augmented state transition model with respect to the state variables of the augmented state. [4 marks]

(e) Formulate the measurement model of the system. [4 marks]

(f) Derive the Jacobian matrix of the measurement model with respect to the state variables of the augmented state. [4 marks]

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Question 4.

An unmanned aerial vehicle (UAV) undergoes a flight maneuver of the following sequence $R_{z,60^0} \rightarrow R_{y,-20^0} \rightarrow R_{x,10^0}$ about its body coordinate frame.

(a) Determine the corresponding rotation matrix R_B^E for UAV orientation after the maneuver (E: Earth, B: Body). [5 marks]

(b) After the maneuver, the onboard gyro of the UAV reads the following angular velocities:
$\omega_x = 15^0/s, \qquad \omega_y = -20^0/s, \qquad \omega_z = 30^0/s.$

Estimate the rotation matrix R_B^E after 50 ms. You may assume that the gyro readings do not change within this time period, and the first order approximation for rotation matrix update is still valid. [5 marks]

(c) Calculate the orthogonality error of the estimated rotation matrix in (b) using its first two columns. [5 marks]

(d) Re-orthogonalize the estimated rotation matrix in (b). [5 marks]

(e) Normalize the rotation matrix obtained in (d) using a suitable method. [5 marks]

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