Massachusetts Institute of Technology

6.1820/MAS.453 Spring 2025 **Problem Set 2** March 16, 2025

This problem set has 6 questions, each with several parts. Answer them as clearly and concisely as possible. You may discuss ideas with others in the class, but your solutions and presentation must be your own. Do not look at anyone else's solutions or copy them from anywhere.

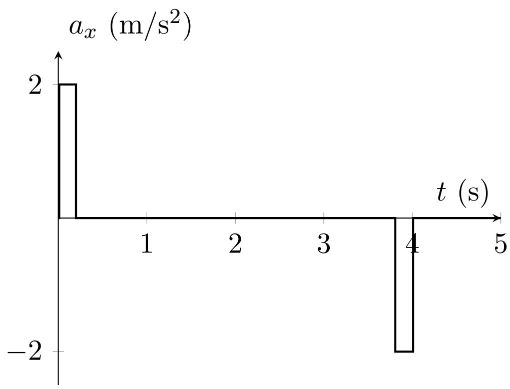
Turn in your solutions on **Thursday, April 10, 2025 before 11:59pm** by uploading it online on Gradescope.

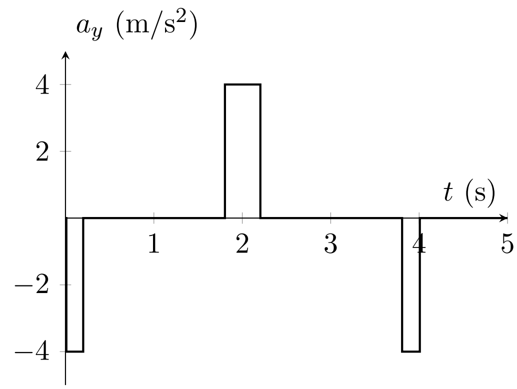
1 Inertial Sensing

1. Alice moves a device to track her movement and perform gesture recognition using accelerometer data, similar to Lab 3. Suppose that the accelerometer is free of noise and bias, there is no movement in the z direction, the orientation of the phone is constant, and the starting velocity and position are zero at $t = 0$ s. The accelerations in the x and y directions, in m/s^2, are given by

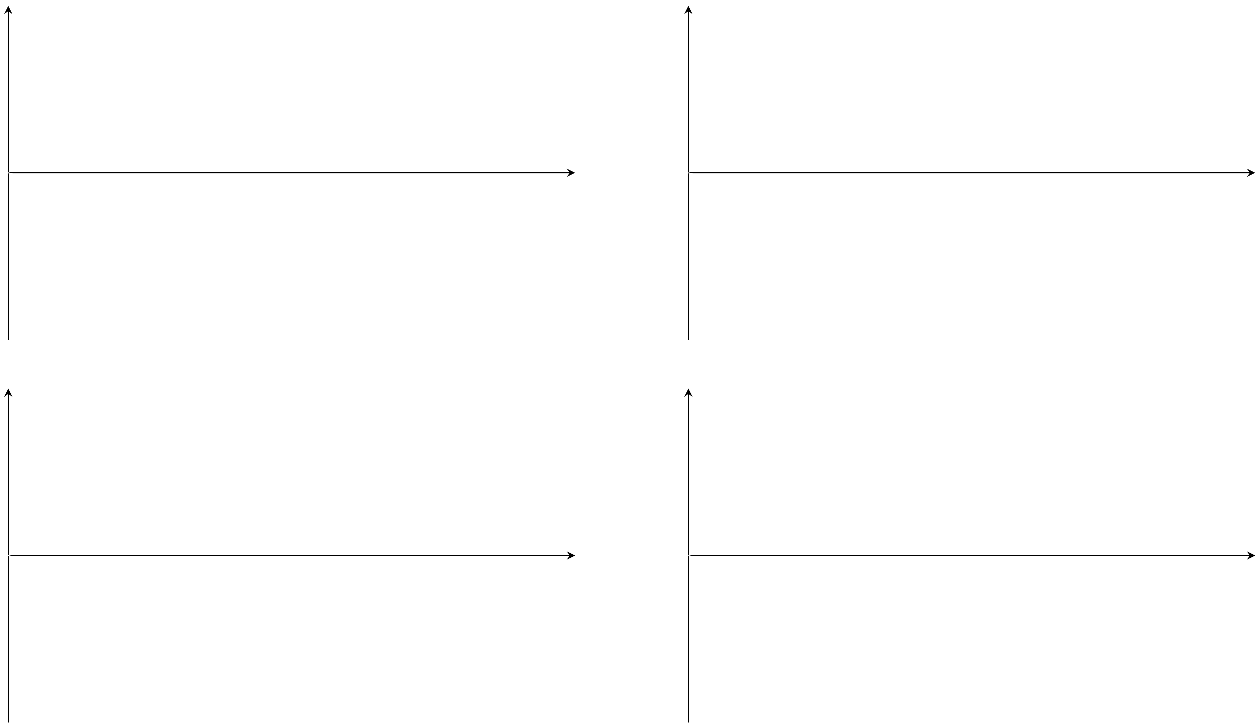
$$a_x(t) = \begin{cases} 2 & \text{if } 0 < t \leq 0.2 \\ -2 & \text{if } 3.8 < t \leq 4 \\ 0 & \text{otherwise} \end{cases} \quad \text{and} \quad a_y(t) = \begin{cases} -4 & \text{if } 0 < t \leq 0.2 \text{ or } 3.8 < t \leq 4 \\ 4 & \text{if } 1.8 < t \leq 2.2 \\ 0 & \text{otherwise} \end{cases}$$

The plots of accelerations in the x and y directions, a_x and a_y, are shown below.

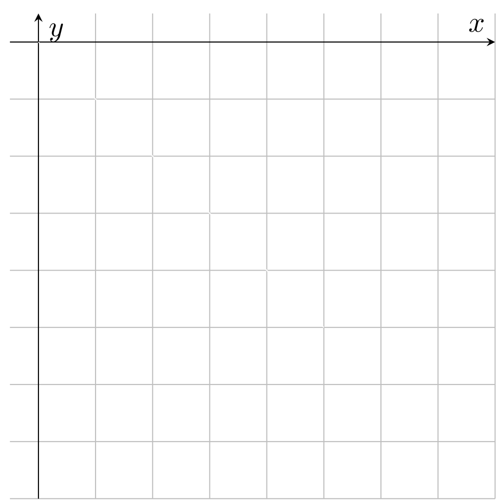




Sketch the **velocity** and **position** in the x and y directions from $t = 0$ s to $t = 5$ s. Label the **axes** with units and indicate the values at each of the **peaks**, **valleys**, and transition points in your plots (e.g., at t=0.2, 1.8, 3.8, 4, 5s). *Feel free to sketch on a separate paper if easier.*



2. Sketch the trajectory of the device in the xy-plane. What letter does the device trace?



3. Bob performs the exact same movement. However, the x-axis accelerometer suffers from a constant bias of $+0.2\,\mathrm{m/s^2}$ and a small zero-mean Gaussian noise. Sketch the **velocity** and **position** in the x direction from $t = 0$ s to $t = 5$ s. Label the **axes** with units and indicate the values at each of the **peaks**, **valleys**, and transition points in your plots (e.g., at t=0.2, 3.8, 4, 5s). *Feel free to sketch on a separate paper if easier.*

4. List two ways to stabilize the noisy trajectory tracking.

2 Pothole Patrol

The pothole patrol system uses different thresholds and filters to eliminate unwanted events. In one or two sentences, briefly answer the following questions and explain your reasoning.

1. How does it discard scenarios when the car is accelerating, braking, or making turns? Specifically, does it use a high-pass filter or a low-pass filter on the accelerometer data and why?

2. How does it discard expansion joints and rail crossing (i.e., distinguish them from potholes)?

3. Why does it cluster the pothole events?

4. The Pothole Patrol project used two types of training data, loosely-labeled and hand-labeled. What is the difference between the two? Why did the authors need to use two different types of training data?

5. Assume the trained pothole patrol system had the following performance:

- 60 potholes in total were detected.
- Out of those 60, only 40 were correct potholes while the rest were other (non-pothole) road deformities.
- 15 real potholes were missed.

What is the precision, recall, and F-measure of this system? Explain your answer in detail for each of these 3 measures.

3 RF localization and WiTrack

1. Ben Bitdiddle has an idea to estimate the distance from an RF transmitter to an object when there is no noise and no multipath using only one transmit and one receive antenna co-located on the same device. He transmits a sinusoidal waveform at frequency f Hz and then computes the **phase** of the reflected signal. The radio signal travels at c meters per second. He finds that he can make this approach work as long as the distance to the object is less than some value, D meters. What is D in terms of the parameters provided? Explain your answer.

2. Now consider the WiTrack system discussed in class, which uses a frequency-modulated continuous wave (FMCW). There is no multipath and no noise and a single reflector. Sketch the frequency of the ideal FMCW transmitted signal as a function of time. On the same graph, also sketch the received signal as a function of time. Label the axes.

3. Suppose that the bandwidth allowed for the WiTrack FMCW frequency sweep is 75 MHz. What is the distance resolution, i.e., the minimum distance between two objects so that they may be located separably? Assume that the transmit and receive antennas are co-located. The speed of the radio signal is 3×10^8 m/s.

4. Ben now wants to localize the person's reflection in 2D, rather than just computing distance. Ben wants to use one transmitter and multiple receivers to do that. For the sake of this problem and the next you, you can assume that all the antennas he uses are directional (specifically, they only receive a signal from what is in front of them and the object of interest is in front of them).

- What is the minimum number of receive antennas that Ben needs?
- Draw how using 1 transmit antenna and the number of receiver antennas you highlighted above (each antenna is separate), Ben can localize a person in 2D. Briefly explain your reasoning.

5. Ben realizes FMCW hardware is expensive and he goes back to the idea of using a single frequency. He wants to use an access point that has 1 transmit antenna and multiple (omnidirectional) receive antennas to obtain the *angle* to an object instead of the distance.

- What is the minimum number of receive antennas that Ben needs for each access point location to get a unique angle (in a 2D plane)?
- How many access points does he need (with the number of antennas mentioned above) to obtain a unique 2D location? Draw the setup (location of access points), and briefly explain your reasoning.

4 mmWave Sensing for Self-Driving Cars

1. In the self-driving car lecture, we talked about cameras and millimeter-wave (mmWave) radars being used for imaging and perception. For each of the cases listed below, would it be better to use a camera *or* a mmWave radar? Briefly explain your choice (1 sentence).

(a) Reading road signs

(b) Locating pedestrians in clear weather and daylight

(c) Locating cars in the opposite lane in fog

(d) Locating a child walking toward the road behind bushes.

(e) Detecting traffic light color

(f) Driving at night

5 Health Sensing

1. Name three factors that cause inaccuracy in PPG sensors of an iWatch.

2. In hearable devices,

(a) What is passive sensing? Articulate in one sentence.

(b) What is active sensing? Articulate in one sentence.

(c) Why does passive sensing have limited accuracy in detecting heartbeats? Explain two reasons, with 1-2 sentences per reason.

6 Acoustic Sensing

1. How many ultrasonic speakers does the BackDoor system use to make microphones hear inaudible sounds?

2. Consider the Backdoor acoustic system. An ultrasonic speaker sends three tones at 40 kHz, 50 kHz, and 52 kHz. Alice uses her smartphone's microphone to record the signal.

a) Alice uses a spectrogram app to detect what frequencies she recorded. She does not see any of the three tones on her spectrogram. Why?

b) Instead, Alice notices some other frequency tones in her spectrogram. What are these frequencies?

c) According to the paper, which of these can be a reason for the frequency tones observed in part (b): (Select all that apply)

- Non-linearities in the microphone's amplifier.
- Non-linearities in the speaker's amplifier.
- Non-linearities in the microphone's receive chain *after* the filter.

7 Backscatter in Air and Water

1. How do passive RFIDs power up?

2. In 1 sentence, explain how RFIDs transmit bits of zeros and ones.

3. Why can't RFIDs work underwater?

4. What type of material does underwater backscatter use? Briefly explain what is the key property/properties of the material that makes it usable for backscatter?