Massachusetts Institute of Technology

6.1820/MAS.453 Spring 2025 **Problem Set 2 - Solution** 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.

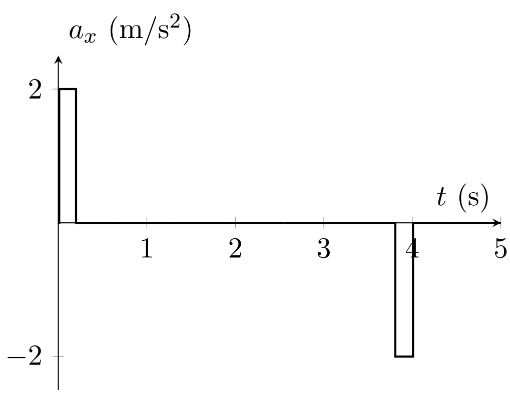
Turn in your solutions on **Thursday, April 10, 2025 before 11:59pm** by uploading it online on Gradescope.

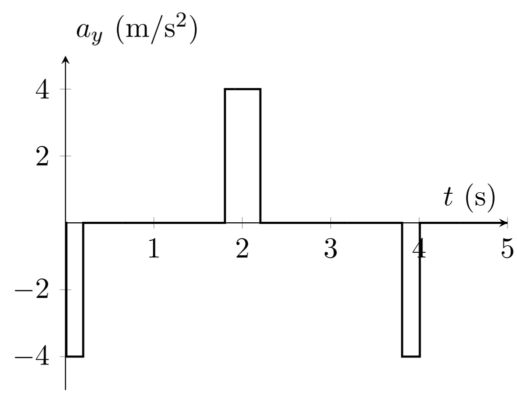
1 Inertial Sensing

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

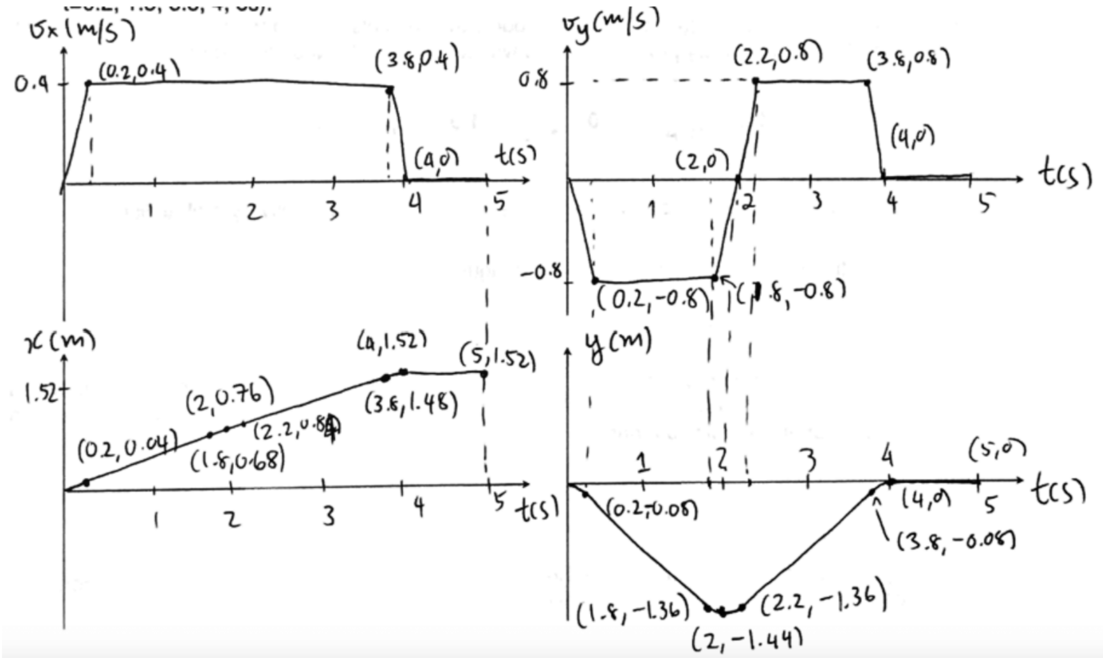
$$a_x(t) = \begin{cases} 2 & \text{if } 0 < t \leq 0.2 \\ -2 & \text{if } 3.8 < t \leq 4 \\ 0 & \text{otherwise} \end{cases} \quad \text{and} \quad a_y(t) = \begin{cases} -4 & \text{if } 0 < t \leq 0.2 \text{ or } 3.8 < t \leq 4 \\ 4 & \text{if } 1.8 < t \leq 2.2 \\ 0 & \text{otherwise} \end{cases}$$

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

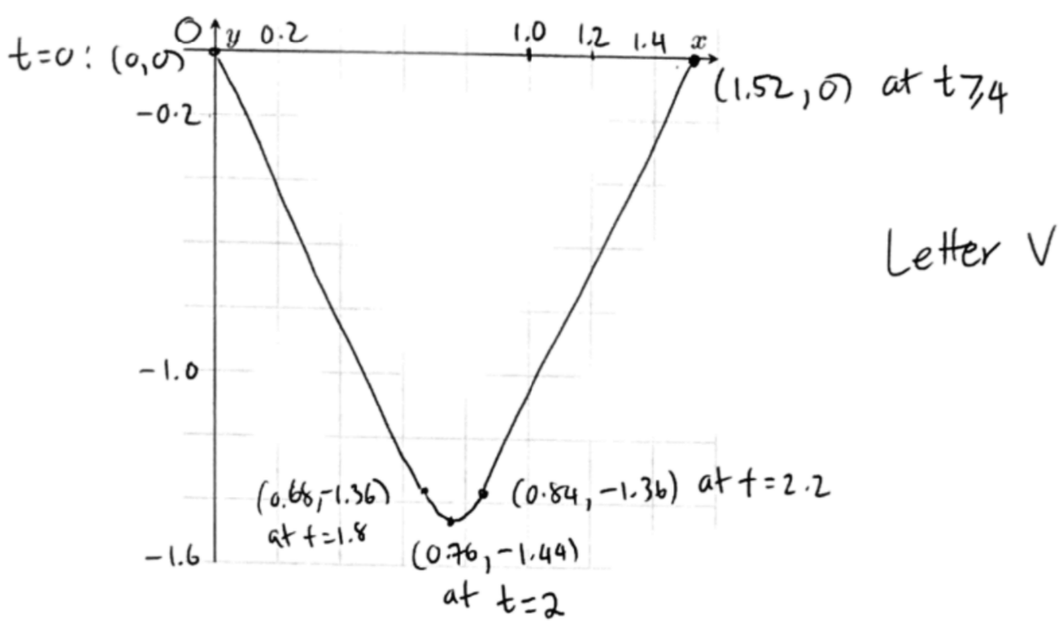




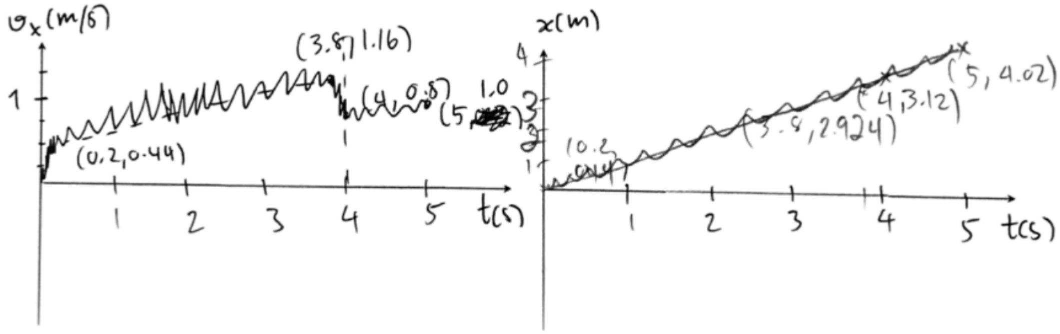
Sketch the **velocity** and **position** in the x and y directions from $t = 0$ s to $t = 5$ s. Label the **axes** with units and indicate the values at each of the **peaks**, **valleys**, and transition points in your plots (e.g., at t=0.2, 1.8, 3.8, 4, 5s). *Feel free to sketch on a separate paper 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 $+0.2\,\text{m/s}^2$ 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.

- Exponential Damping
- Non linear damping
- Rest Recognition
- Calibration to remove non-zero bias

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?

High-pass filter, because slow changes in acceleration are not characteristic of potholes.

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

a_x/a_z <threshold

3. Why does it cluster the pothole events?

Clustering improves robustness as the pothole detection may not occur in exactly the same GPS location each time; this also helps eliminate noise

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?

In Pothole Patrol, hand-labeled data provided precise annotations of road anomalies, while loosely-labeled data offered larger-scale data with general labels but no exact positions. The authors used both to combine the accuracy of hand-labeled data with the scalability of loosely-labeled data, improving model robustness and generalization.

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.

- Total detected potholes = 60
- True positives (TP) = 40
- False positives (FP) = 20
- False negatives (FN) = 15

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}} = \frac{40}{40 + 20} = \frac{2}{3}$$

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}} = \frac{40}{40 + 15} = \frac{8}{11}$$

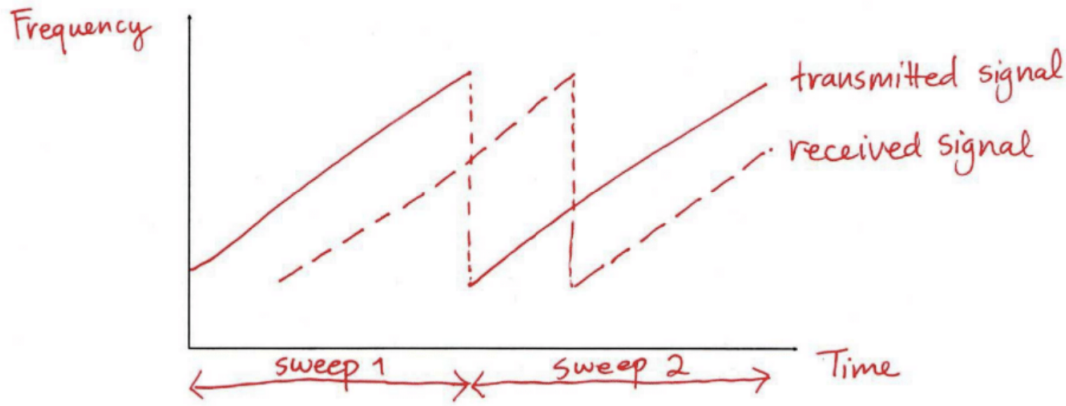
$$\text{F1} = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} = \frac{16}{23}$$

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.

There is no phase ambiguity if $\Delta\phi < 2\pi$
$\Delta\phi = \frac{2\pi}{\lambda}\Delta x = \frac{2\pi f}{c}\Delta x < 2\pi$
$\Delta x < \frac{c}{f} \implies D = \frac{\Delta x_{max}}{2} = \frac{c}{2f}$

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.

Resolution $= \frac{c}{2B} = \frac{3\times10^8}{2\times75\times10^6} = 2\ m$

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?

  2 antennas

- 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.

  See lecture 4 slide 21

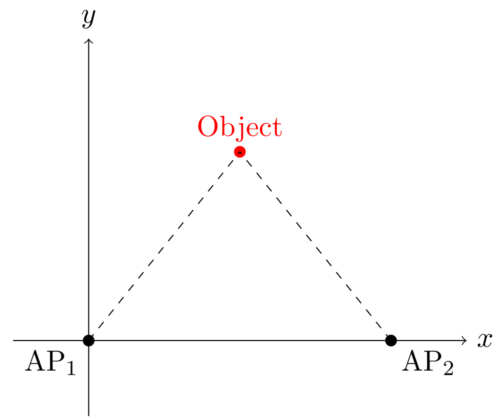
5. Ben realizes FMCW hardware is expensive and he goes back to the idea of using a single frequency. He wants to use an access point that has 1 transmit antenna and multiple (omnidirectional) receive antennas to obtain the *angle* to an object instead of the distance.

- 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)?

  2 antennas

- 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.

  at least 2 access points to measure angle from different locations. The intersection of two angle lines (from different known access point locations) provides a unique point in 2D space. Place the two access points at known, separate positions. Each access point measures the angle to the object. The lines along these measured angles will intersect at a unique point, giving the object's 2D location.



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

Camera - Cameras are better for reading road signs due to their high resolution and ability to capture visual text and symbols.

(b) Locating pedestrians in clear weather and daylight

Camera - In clear weather and daylight, cameras provide detailed visual data, making them ideal for identifying pedestrians.

(c) Locating cars in the opposite lane in fog

mmWave - Radar performs better in poor visibility conditions like fog, reliably detecting vehicles through low-visibility environments.

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

mmWave - Radar can penetrate foliage and detect motion behind obstructions like bushes, making it suitable for spotting hidden moving objects.

(e) Detecting traffic light color

Camera - Traffic light color detection requires interpreting visible light, which cameras are designed to handle.

(f) Driving at night

mmWave - Radar operates independently of ambient light, making it more reliable for detecting objects while driving at night.

6 Acoustic Sensing

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

At least two, each at a different ultrasonic frequency.

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?

The frequencies of the three tones exceed the range that a microphone can record, e.g. < 24 kHz, because they are filtered by the microphone's low-pass filter

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

Nonlinearity creates $f_1 + f_2, f_1 - f_2, 2f_1, 2f_2$ from f_1 and f_2. The frequencies that fall within the recordable range are 2 kHz, 10 kHz, and 12 kHz.

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?

Passive RFIDs harvest energy from the reader's signal (using inductive coupling or radiative power).

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

By switching between different reflective states. Or by modulating their (antenna/matching/electrical) impedance.

3. Why can't RFIDs work underwater?

Because they rely on RF signals, which do not work well in water or die exponentially fast in water

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?

Underwater backscatter uses piezoelectric material. Its key property is to convert mechanical energy to electrical energy.

9. *(6 points)* In each of the scenarios below, we use radars to image the surface of the objects. The objects' surfaces are very smooth. In each scenario, there is one or more Tx and one or more Rx. For each scenario:

1 • Add an "x" to the point(s) of the surface that will reflect the transmitted signal back to each of the Rx receivers.

1 • Draw the rays of the transmitted and the received signal(s)

1 • Explain your reasoning

- diagnormal / ∠ incidence = ∠ reflection
or
Specular

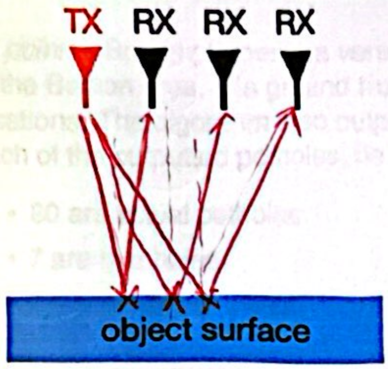


Figure 1: Scenario A

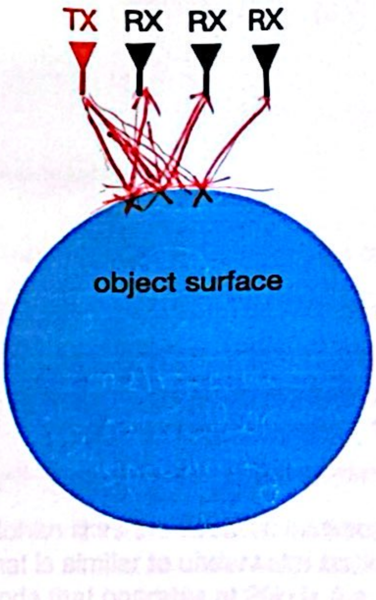


Figure 2: Scenario B

Scanned with CamScanner