CS 7638 - Robotics: AI Techniques - Meteorites Project

Spring 2022 - Due Monday, February 7th, Midnight AOE

Introduction

In this project, Earth is threatened by a shower of meteorites falling in your location. It is your task to receive sensor readings of the locations of these meteorites, estimate where each of the meteorites will be one tenth of a second later using Kalman Filters (KFs), and finally, destroy each meteorite before it hits the ground by firing your laser turret at it.

This project consists of two parts:

1. Estimation—estimate meteorite locations
    a. Estimation of one meteorite's position with no noise in the observations—15% of grade
    b. Estimation of the positions of many meteorites given noisy measurements—65% of grade
2. Defense—aim and fire your laser turret at incoming meteorites before they hit the ground—20% of grade

Submitting Your Assignment

Your submission will consist of ONLY the `turret.py` file, which you will upload to Gradescope.

Academic Integrity

You must write the code for this project alone. While you may make limited usage of outside resources, keep in mind that you must cite any such resources you use in your work (for example, you should use comments to denote a snippet of code obtained from StackOverflow, lecture videos, etc). For an example of this, note how the author of this project's code cited the source for the `clamp` function in `runner.py`.

You must not use anybody else's code for this project in your work. We will use code-similarity detection software to identify suspicious code, and we will refer any potential incidents to the Office of Student Integrity for investigation. Moreover, you must not post your work on a publicly accessible repository; this could also result in an Honor Code violation [if another student turns in your code]. (Consider using the GT-provided Github server for your repository, or a git server such as Bitbucket that does not default to public sharing.)

Detailed Project Description

The motion model of the meteorites takes the form

$$x(t) = c_{pos_x} + c_{vel_x}t + S_{acc}c_{acc}\frac{t^2}{2}$$

for the meteorite's x-position, and

$$y(t) = c_{pos_y} + c_{vel_y}t + c_{acc}\frac{t^2}{2}$$

for its y-position. $S_{acc} = \frac{1}{3}$ is a constant.

Time is delimited in discrete steps (t = 0.0, 0.1, 0.2, ...). Each timestep is 0.1 seconds in duration. Each meteorite's motion can be modeled using x, y, dx, dy, a. a is acceleration; note that, due to how the acceleration term is defined, the x- and y-components of a meteorite's motion are correlated! See the "Note on Deriving the F Matrix for Meteorites" PDF on Canvas (Canvas > Files > Misc. Tutorials) for details on how to derive the state transition matrix from the above equations of motion. The KF tutorial located in the same directory is also a helpful resource for this project.

In most parts of this project, your turret's observations of the meteorites' positions are noisy, so you will leverage the uncertainty-handling properties of Kalman Filters to predict their positions more precisely.

Environment:

In this project, your world is a 2-by-2 square, with the X-range [-1, 1] and Y-range [-1, 1]; (-1, -1) is the lower left corner, and your turret is located at (0, -1), with y = -1 being the ground. This coordinate system is used throughout this project to define all entity locations. The laser turret's aim angle is 0.0 rad when the laser is pointed along the ground to the right, and π rad when the laser points along the ground to the left.

HINT: On line 21 of `turtle_display.py`, change the `DEBUG_DISPLAY` variable to `True` to show meteorite IDs and the (x, y) coordinates of the corners of the world in the GUI.

Estimation

Estimation Part a: Function `run_kf_single_meteorite`

In this function, you are predicting the location of one meteorite one timestep into the future given its current true position. That is, the measurement information passed to this function is *NOT* noisy. This part of the project is meant to help you verify that your KF works correctly in simple scenarios before applying it to more complex scenarios. We recommend that you create a function for your KF procedure that both `run_kf_single_meteorite` and Estimation Part b's function `observe_and_estimate` can call to execute a KF update.

Inputs:

The `run_kf_single_meteorite` function takes in two floats: the x-coordinate of the meteorite at time t and the y-coordinate at time t.

Outputs:

The output of the `run_kf_single_meteorite` function should be two floats–your KF's estimate of the meteorite's x- and y-coordinates at time t+1, respectively.

Goal:

To get full credit for this part of the estimation part of the project, your `run_kf_single_meteorite` function will need to provide "close enough" predictions of the meteorite's position for at least 100 timesteps out of a sliding window of the latest 125 timesteps before either the meteorite hits the ground or 500 timesteps have elapsed. Once your KF correctly predicts 100/125 timesteps, the simulation ends. The correct estimates do not need to be consecutive. For these very simple estimation cases (case0.py and case1.py) with no noise, if your KF implementation is correct, it should converge to the correct estimate quickly.

The meteorite in case0.py will not hit the ground within 500 timesteps, as it is not subject to acceleration. case0 is a good opportunity to ensure that the fundamentals of your KF setup are correct. case1.py is nearly identical to case0.py, but is subject to acceleration, and thus may hit the ground before 500 timesteps elapse if your KF does not converge quickly. Focus first on getting your KF to pass case0.py, and once your turret.py passes case0.py, move on to case1.py.

Note that you may still need to tune your KF somewhat for the remaining parts of the project even if your turret passes this part of the project, but passing this part of the project should be a good indication that the fundamentals of your KF implementation are correct.

How To Test Your Part a Estimation Code

To test your code on an estimation case and see a visualization of the simulation, run the following in your Python environment (the `case` argument may be 0 or 1; the command to run case 0 is shown here):

```
python test_one.py --case 0 --display turtle kf_nonoise
```

This will run a simulation with a a visualization similar to that shown in "How To Test Your Part b Estimation Code," just with one meteorite instead of many.

A similar command lets you run the test with only text output (no visualization). This text-only mode is what `test_all.py` uses. (see "Testing Everything" below)

```
python test_one.py --case 0 --display text kf_nonoise
```

As before, the `case` argument may be 0 or 1.

Estimation Part b: Function `observe_and_estimate`

In this function, you will be estimating the location of each meteorite visible on the screen one timestep in the future given *noisy* measurements of meteorite locations you have for the current timestep (`noisy_meteorite_observations`).

Inputs:

The `observe_and_estimate` function takes in a tuple of tuples of meteorite ID numbers, x-coordinate observations, and y-coordinate observations; that is, the `noisy_meteorite_observations` argument has the form

```
((0, -0.83, 0.46),
(1, 0.44,  0.8),
(3, -0.72, -0.3),
...
(1003, 0.34, 0.1))
```

Note that the meteorites in `noisy_meteorite_observations` are not guaranteed to be sorted in any sort of order, so do not expect the ID numbers to be sequential.

Outputs:

The output of the `observe_and_estimate` function should be a tuple of tuples of estimated meteorite locations one timestep into the future.

Goal:

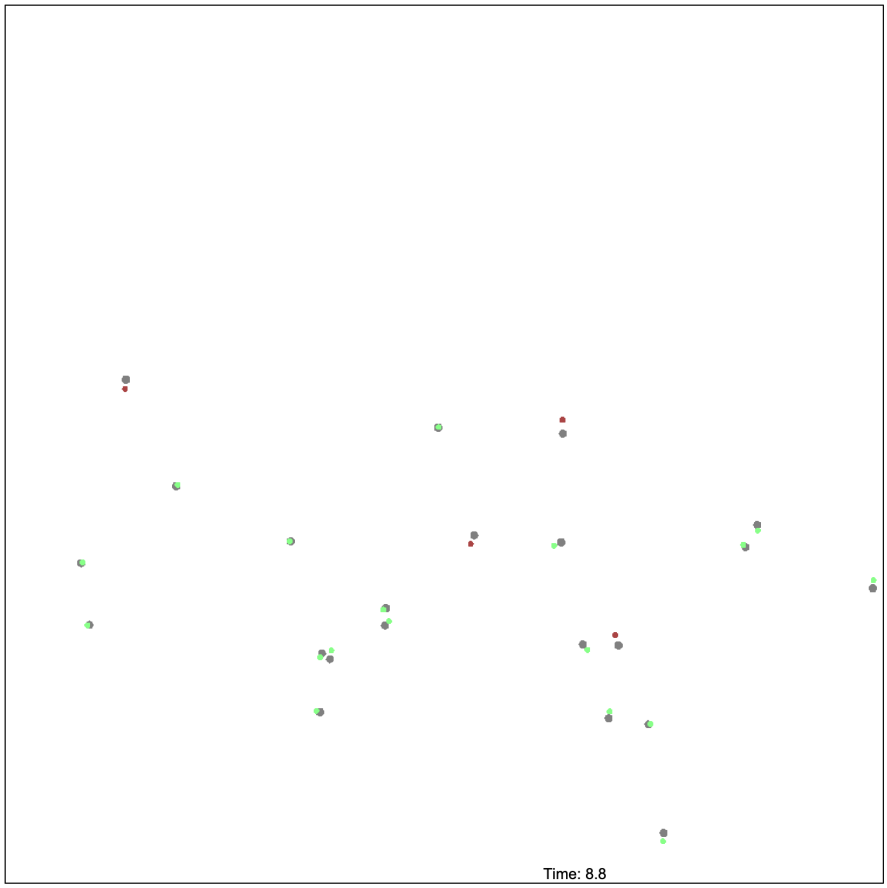
To get full credit for this part of the project, your `observe_and_estimate` function will need to provide "close enough" estimates of all meteorites within the 2-by-2 box within 500 timesteps (50 seconds) (and on Gradescope or when using `test_all.py`, 10 real-world "wall-time" seconds) for at least five (5) consecutive timesteps. A meteorite location estimate is close enough when the Euclidean distance between the estimate and the actual location is less than 0.02 units. If 90% of your meteorite estimates for a case are close enough for five consecutive timesteps within 500 timesteps or (when using `test_all.py`) ten wall-time seconds—whichever is shorter—you'll get full credit for that case's estimation portion. Passing back predictions for non-existent meteorites (e.g. meteorites that have hit the ground and have an ID of -1) will not affect your score.

How To Test Your Part b Estimation Code

To test your code on an estimation case and see a visualization of the simulation, run the following in your Python environment (the `case` argument may be 2-9; the command to run case 2 is shown here):

```
python test_one.py --case 2 --display turtle estimate
```

When you run a case with the `turtle` visualization option, you should see something like what is shown in the image below. The gray circles represent the actual locations of meteorites. A red dot indicates a prediction that is too far from the meteorite's actual location to count as correct, and a green dot indicates an estimate close enough to be counted as correct.



A similar command lets you run the test with only text output (no visualization). This text-only mode is what `test_all.py` uses. (see "Testing Everything" below)

```
python test_one.py --case 2 --display text estimate
```

As before, the `case` argument may be 2-9.

Defense: Function `get_laser_action`

For the defense part of the project, you will be devising a simple algorithm to aim and fire your laser turret at falling meteorites. The defense part of the project makes use of the predictions of the meteorite locations computed by

`observe_and_estimate` in the Estimation Part a portion of the project. *(HINT: Don't over-think your strategy here; perhaps simply aiming at the lowest meteorite above some minimum threshold is sufficient!)* A meteorite is destroyed with probability 0.75 if the laser line comes within a small distance (the value denoted as `min_dist` in the relevant case file) of it. When the laser fires at time t, the shot hits the meteorite at time t+1. The laser line itself is 1.1 units of length long, measured from the turret. The laser can only fire a limited number of shots before it runs out of power; the number of shots remaining are displayed in the GUI or command line output.

Each meteorite's ID number is unique as long as the meteorite has not been destroyed. When a meteorite is destroyed, its ID number is set to -1. This ID number change is handled by the simulation. Keep in mind that you may want your Turret to check that it does not try to aim at a meteorite with an ID of -1!

Inputs:

This function takes in a float corresponding to the laser turret's current aim angle, in radians.

Outputs:

The output of this function is either a float or a string:

- Float: The change in aim angle (in radians) you want the laser to move; if the magnitude of this value is greater than `max_angle_change` (0.0873 rad; approximately 5 degrees), it will be lowered to `max_angle_change` rad, but with the sign of the angle you outputted.
- String: Outputting the string `'fire'` will cause the laser turret to fire.

The laser cannot move and fire at the same time. Note that trying to move the laser's aim outside of the [0, π] range will result in its aim being clamped to 0 or π, respectively. The laser's aim angle does NOT wrap around—if you output an angle change that would set the laser's current aim to, say, 3.3 rad, the laser's aim will stay π rad until you change the laser's aim back to within the [0, π] range.

Goal:

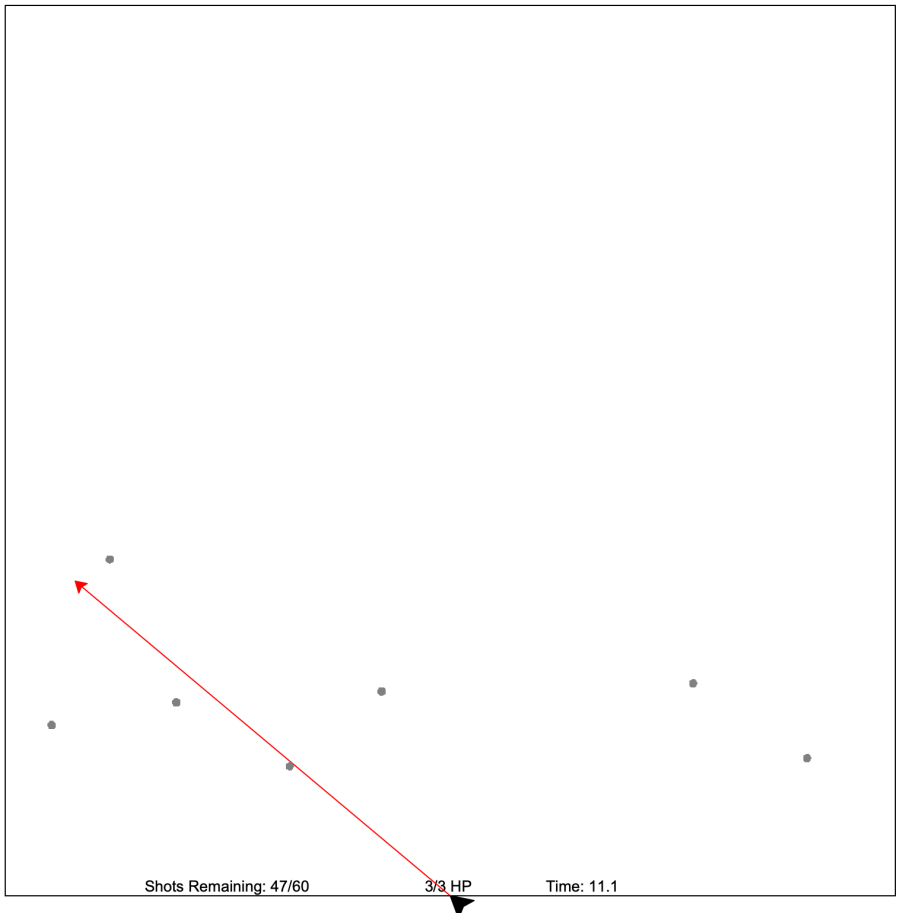
Your goal in the defense part of the project is to make sure your laser turret survives for 500 timesteps. Your laser turret starts with a specific number of health points (HP), which are shown below the turret in `turtle` simulation mode and printed to the command line in `text` mode. Each time a meteorite hits the turret or the ground (y = -1), the turret loses one HP. Credit is given for a case if the turret's HP is 1 or greater by the end of the 500-second bout (on Gradescope and in `test_all.py`, there is also a 45-second wall-time time limit); no credit is given if the turret's HP drops to 0 within that time limit.

How To Test Your Defense Code

To test your code on a defense case and see a visualization of the simulation, run the following in your Python environment (the `case` argument may be 2-9):

```
python test_one.py --case 2 --display turtle defense
```

When you run the above command, you should see something like the image below.



A similar command lets you run the test with only text output (no visualization); this is the mode that `test_all.py` uses to run all test cases. (See "Testing Everything" below) As before, the `case` argument may be 2-9.

```
python test_one.py --case 2 --display text defense
```

Testing Everything

To test all of the local estimate and defense cases using the `text` display option, use the command

```
python test_all.py
```

This is the testing mode used by Gradescope.

Generating New Test Cases

The cases used for grading on Gradescope are not the same as those provided to you, though they are very similar. If you wish to generate additional test cases to more rigorously test your code, you can use `generate_test_case.py` to generate new test cases. For reference, here is the guidance that is printed to the console when running the `--help` argument with `generate_test_case.py`:

```
python generate_test_case.py --help

usage: Generate parameters for a test case and write them to file.

[-h] [--turret_x TURRET_X] [--turret_hp TURRET_HP]
[--num_laser_shots NUM_LASER_SHOTS] [--t_past T_PAST] [--t_future T_FUTURE]
[--t_step T_STEP] [--noise_sigma_x NOISE_SIGMA_X]
[--noise_sigma_y NOISE_SIGMA_Y] [--min_y_init MIN_Y_INIT]
[--max_y_init MAX_Y_INIT] [--nsteps NSTEPS] [--dt DT]
[--meteorite_c_pos_max METEORITE_C_POS_MAX]
[--meteorite_c_vel_max METEORITE_C_VEL_MAX]
[--meteorite_c_accel_max METEORITE_C_ACCEL_MAX]
[--min_dist MIN_DIST] [--max_angle_change MAX_ANGLE_CHANGE]
[--seed SEED] outfile

positional arguments:
  outfile               name of file to write

optional arguments:
  -h, --help            show this help message and exit
  --turret_x TURRET_X   X-location of turret (should be in the range
                        (-1.0, 1.0))
  --turret_hp TURRET_HP
                        Turret's initial health point count
  --num_laser_shots NUM_LASER_SHOTS
                        Initial number of laser shots turret can fire
  --t_past T_PAST       time in past (negative integer) from which to
                        start generating meteorites
  --t_future T_FUTURE   time into future (positive integer) at which
                        to stop generating meteorites
  --t_step T_STEP       add a meteorite every N-th time step
  --noise_sigma_x NOISE_SIGMA_X
                        sigma of Gaussian noise applied to the
                        x-component of
                        meteorite measurements
```

```
  --noise_sigma_y NOISE_SIGMA_Y
                        sigma of Gaussian noise applied to the
                        y-component of
                        meteorite measurements
  --min_y_init MIN_Y_INIT
                        Lowest initial meteorite y-coordinate
  --max_y_init MAX_Y_INIT
                        Maximum initial meteorite y-coordinate
  --nsteps NSTEPS       Number of timesteps to simulate
  --dt DT               Duration of a single timestep
  --meteorite_c_pos_max METEORITE_C_POS_MAX
                        maximum magnitude for meteorite position term
                        coefficient
  --meteorite_c_vel_max METEORITE_C_VEL_MAX
                        maximum magnitude for meteorite velocity term
                        coefficient
  --meteorite_c_accel_max METEORITE_C_ACCEL_MAX
                        maximum magnitude for meteorite acceleration
                        term coefficient
  --min_dist MIN_DIST   minimum distance estimate must be from
                        meteorite
                        location to be considered correct; also, if a
                        laser
                        comes within this distance of a meteorite, the
                        meteorite is destroyed with p=0.75.
  --max_angle_change MAX_ANGLE_CHANGE
                        maximum increment of the laser's angle, in
                        radians
  --seed SEED           random seed to use when generating meteorites
```

To create a new case, run as follows:

```
python generate_test_case.py my_case.py [additional arguments here]
```

To use this new test case, pass the filename to `test_one.py` using the `--case` argument:

```
python test_one.py --case my_case.py --display turtle defense
```

Note: New case files must have the `.py` extension to be imported correctly by the `test_one.py` code, and are not included in the cases executed by `test_all.py`.

FAQ

How do Kalman Filters apply in this project?

As we know the structure of the motion model that governs the motion of the meteorites, we can use Kalman filters to track their locations. Each meteorite has different coefficients in their equations of motion, but for an individual

meteorite, those coefficients are constant; thus, we need to estimate as many models as there are meteorites. That is a good indicator that we can initialize one Kalman filter for each meteorite—we will have (# meteorites) KFs—and use our noisy measurments over time to improve our estimates of where each individual meteorite will be one timestep from now. You'll want to create and update separate $\bar{x}$s and Ps for each meteorite, using the Kalman filter equations. The state transition matrix (aka motion model matrix, F), measurement model matrix (H), and uncertainty matrices should all be constant and the same for all meteorites. Take a look at the Kalman Filter tutorial and the "Note on Deriving the F Matrix for Meteorites" PDFs on Canvas under Files > Misc. Tutorials for thorough explanations.

How do I share data between `run_kf_single_meteorite`, `observe_and_estimate`, `get_laser_action`, and other functions in my Turret class?

In your implementation of `Turret`, you can refer to the current turret instance using `self` and attach additional data to it. Here is an example of creating a `value` variable in a `Counter` class that can be used in other functions in the `Counter` class:

```
class Counter(object):

    def __init__(self):
        self.value = 0

    def increment(self):
        self.value += 1

    def show(self):
        print(self.value)

ctr = Counter()
ctr.increment()
ctr.increment()
ctr.show()        # should display '2'
```

If Estimation Part a of this project does not use noisy measurements, why should I bother implementing a Kalman Filter for that part of the project?

Estimation Part a of this project has been designed specifically to allow you to test your Kalman Filter against very simple test cases to ensure that it works before moving on to the remaining parts of the project. Part a is designed to let you make sure your KF works in very simple cases before running it in the more complex cases in the rest of the project.

Why do I get less credit on Gradescope than I do on my local machine?

Keep in mind that (1) Gradescope uses different case files than what you have access to (though they are similar to the case files you have), and (2) your local computer is likely faster than the virtual machine Gradescope is using to run your code. If you are getting timeouts on Gradescope, think about whether there is a way you can make your code a little more efficient. Also, when running `test_one.py` for an `estimate` or `kf_nonoise` case, there is no wall-time time limit applied—just a limit to the maximum timesteps your solution may take to converge its estimates. When running `test_all.py`, which is what Gradescope uses, each `estimate` and `kf_nonoise` case is limited to 10 wall-time seconds, and each defense case is limited to 45 wall-time seconds; execution time greater than those limits for a case results in an `execution_time_exceeded` result.

My question is not answered in this FAQ.

If you have additional questions, first, please check the course FAQ document, syllabus, policy guidelines, and code review guide, which can be found on Canvas > Files. If none of those documents answer your question, please feel free to ask on EdDiscussion in accordance with the guidance in the code review document. (Remember: if you are posting code in your EdDiscussion post, your post must be *private*!)