Run to failure experiment C2 - digital twin informs true system

In this work remaining useful life (RUL) refers to the total flight time possible for a single mission. Hypothesis here is that the true system should never fail now. But I see that true system will select an explored trajectory if the digital twin passes it, this might be risky, we need to consider dynamic risk. This is in contract to some of our previous work where RUL referred to the entire life of the UAV across multiple missions. This time the digital twin is simulated multiple times for a distribution.

Simulation Steps

The first step is to load the models, provide an initial RUL estimate (using manufacturers information on the battery is a good starting place), and load some workspace variables. 1D polynomial fitting is used to approximate the degradation rate, and thereby predict the mean of the future degradation value distribution. These predicted values are then passed to a digital twin, which is simulated multiple times to generate a monte carlo distribution of variables tracked such as ending state of charge and voltage and mission outcome. The RUL is updated based on the result of the digital twin simulation, and then the new RUL is used by the real system for trajectory selection. The steps are as follows:

1.

Uncertainty Quantification

Trajectories

load main workspace

```
end_sim = 0;
fail_count = 0;
low_soc_count = 0;
pos_err_count = 0;

addpath(genpath(pwd));
load_db_params;
conn = database(datasource_name, user_name, password);

% load UAV airframe
uav_sern = 'X001';
octomodel = get_airframe(conn, uav_sern);

% load battery
battery_sern = 'B001';
battery = get_battery(conn, battery_sern);
```

```
batterytwin = get_battery(conn, battery_sern);

% load motors
[Motor1, Motor2, Motor3, Motor4, Motor5, Motor6, Motor7, Motor8] = get_motors(conn, octomodel.i
[Motortwin1, Motortwin2, Motortwin3, Motortwin4, Motortwin5, Motortwin6, Motortwin7, Motortwin8

% initial rul estimate, used as baseline in rul updates where the minimum
% value is taken to ensure rul_hat never exceeds this value
rul_init = 18.0;
rul_hat = rul_init;

% minimum rul
rul_threshold = 10.0;

% load base directory
load_base_workspace;
```

Initialize some variables

```
% for poly fitting
lookback = 6;

% how far into the future to look
horizon = 2;

% number of missions (can be oversized)
n_missions = 250;

% keep track of delta over time
% number of missions, 3 degradation parameters, 2 coefficients to save
% (slope & intercept)
polys = zeros(n_missions, 3, 2);

% keep track of degradation parameter values for poly fitting
q_deg = zeros(n_missions, 1);
r_deg = zeros(n_missions, 1);
m_deg = zeros(n_missions, 1);

% variance gets tighter over time, a pseudo-hack...
r_var_vals = [.001:-.00001:.0001];
q_var_vals = [.9:-.01:.2];
m_var_vals = [.02:-.00025:.0025];

% keep track of rul
ruls = zeros(n_missions, 1);
```

Main Loop

```
% load initial trajectory, catch edge case that the first trajectory
% explores rather than exploits
load_trajectory;
while trajectory.path_time > rul_init
```

```
    load_trajectory;
end

for i = 1:n_missions
    if i < 20 && i >= 11
        lookback = 8;
        horizon = 3;
    elseif i >= 21 && i < 30
        lookback = 10;
        horizon = 4;
    elseif i >= 31
        lookback = 12;
        horizon = 6;
    end

    ruls(i) = rul_hat;

    % I don't think this should ever execute now that the digital twin is
    % selecting trajectories for the true system
    if end_sim == 1
        disp("[INFO] no more valid trajectories. ending simulation.")
        break;
    end
    if trajectory.path_time > rul_hat
        fprintf("[INFO] TrueSystem selecting trajectory: <%d> with path_time: %.2f to explore c
    else
        fprintf("[INFO] TrueSystem selecting trajectory: <%d> with path_time: %.2f that meets c
    end
    sys = "TrueSystem";
    octomodel.sampletime = true_sample_rate;
    fprintf('[INFO] simulating true system on i: %d\n', i)
    %tic
    sim('truesystem.slx');
    %toc
```

update degradation parameters for saving

- assign values from the current run to the arrays for saving

```
    q_deg(i) = battery.Q;
    r_deg(i) = battery.R0;
    m_deg(i) = Motor2.Req;
```

update variance

```
    fprintf('[INFO] updating degradation parameter variance on i: %d\n', i)
    if i <= length(r_var_vals)
       r_var = r_var_vals(i);
    else
        r_var = .0001;
    end
    if i <= length(q_var_vals)
        q_var = q_var_vals(i);
```

```
    else
        q_var = .25;
    end
    if i <= length(m_var_vals)
        m_var = m_var_vals(i);
    else
        m_var = .005;
    end
```

sample the degradation parameters and update

```
    fprintf('[INFO] updating degradation parameter values via random sampling on i: %d\n', i)
    battery.R0 = max(abs(normrnd(rdeg(i), r_var)), .0001);
    battery.Q = min(abs(normrnd(qdeg(i), q_var)), 15.5);
    Motor2.Req = max(abs(normrnd(mdeg(i), m_var)), .001);
```

write telemetry data to database

```
    distance = calculatedistance([pos_actual.Data(:,1) pos_actual.Data(:,2)]);
    mission_id = table2array(select(conn, 'select id from mission_tb mt order by id desc limit
    if isempty(mission_id)
        mission_id = 1;
    else
        mission_id = mission_id + 1;
    end
    start = table2array(select(conn, 'select mt.dt_stop from mission_tb mt order by dt_stop des
    if isempty(start)
        start = datetime(now, 'ConvertFrom', 'datenum');
    end
    start = datetime(start, 'InputFormat', 'yyyy-MM-dd HH:mm:ss');
    start = dateshift(start, 'start', 'second');
    start = start + hours(1);
    stop = start + seconds(flight_time.Data(end, 1)*60);

    fprintf("[INFO] i: %d\tmission_id: %d\trul_hat: %.2f\tflight_time: %.2f\tdistance: %.2f\tR0

    write_mission_data;
    write_battery_data;
    write_flight_data;

    if any(stop_code.Data(:,1)) == 1 && ~any(stop_code.Data(:,3)) == 1
        fprintf('[WARN] true system low soc threshold exceeded on i: %d\tmission_id: %d\n', i,
        %break;
    end

    if any(stop_code.Data(:,2)) == 1
        fprintf('[WARN] true system position error threshold exceeded on i: %d\tmission_id: %d\
        %break;
    end

    if any(stop_code.Data(:,3)) == 1
        fprintf('[INFO] success on i: %d\tmission_id: %d\n', i, mission_id)
    end
```

```
    clear('trajectory', 'battery_actual', 'battery_observed', 'ctrl_err', 'current', 'current_r
```

define placeholder variables

```
    twin_ctr = 1;
    twin_count = 4;
    times = zeros(1, twin_count);
    vs = zeros(1, twin_count);
    socs = zeros(1, twin_count);
    r0s = zeros(1, twin_count);
    qs = zeros(1, twin_count);
    ms = zeros(1, twin_count);
    dist = zeros(1, twin_count);
    errs = zeros(1, twin_count);
    degs = zeros(3, twin_count);
    codes = zeros(3, twin_count);
```

Update twin degradation parameters

```
    if i > lookback
        x = double(((i - (lookback-1)):1:i)');
        r_poly = polyfit(x, smoothdata(r_deg(x), 'rlowess', 5), 1);
        q_poly = polyfit(x, smoothdata(q_deg(x), 'rlowess', 5), 1);
        m_poly = polyfit(x, smoothdata(m_deg(x), 'rlowess', 5), 1);

        polys(i, 1, :) = r_poly;
        polys(i, 2, :) = q_poly;
        polys(i, 3, :) = m_poly;

        r_mu = polyval(r_poly, i + horizon);
        q_mu = polyval(q_poly, i + horizon);
        m_mu = polyval(m_poly, i + horizon);
        fprintf('[INFO] forecasting degradation values: r_mu: %.6f\tq_mu: %.6f\tm_mu: %.6f', r_
        batterytwin.R0 = max(abs(normrnd(r_mu, r_var)), .0001);
        batterytwin.Q = min(abs(normrnd(q_mu, q_var)), 15.5);
        Motortwin2.Req = max(abs(normrnd(m_mu, m_var)), .001);
    else
        batterytwin.R0 = max(abs(normrnd(rdeg(i), r_var)), .0001);
        batterytwin.Q = min(abs(normrnd(qdeg(i), q_var)), 15.5);
        Motortwin2.Req = max(abs(normrnd(mdeg(i), m_var)), .001);
    end
    fprintf("[INFO] digital twin degradation parameters: %.4f\t%.4f\t%.4f", batterytwin.R0, bat
    write_degradation_data;
```

now simulate digital twin

```
    updated = true;
    while updated
        load_trajectory;
        if trajectory.path_time > rul_hat
            fprintf("[INFO] DigitalTwin selecting trajectory: <%d> with path_time: %.2f to expl
        else
            fprintf("[INFO] DigitalTwin selecting trajectory: <%d> with path_time: %.2f that me
        end
```

```
sys = "DigitalTwin";
octomodel.sampletime = twin_sample_rate;
for twin_ctr=1:twin_count
    fprintf('[INFO] simulating digital twin on i %d, mission_id: %d\n', i, mission_id)
    out = sim('digitaltwin1c.slx');
    %        get the output from each parallel worker
    times(twin_ctr) = flight_time.Data(end);
    vs(twin_ctr) = battery_actual.Data(end, 1);
    socs(twin_ctr) = battery_actual.Data(end, 2);
    r0s(twin_ctr) = battery_actual.Data(end, 3);
    qs(twin_ctr) = battery_actual.Data(end, 6);
    ms(twin_ctr) = motors.Data(end, 1);
    errs(twin_ctr) = mean(euclidean_pos_err);
    dist(twin_ctr) = calculatedistance([pos_actual.Data(:,1) pos_actual.Data(:,2)]);
    degs(:, twin_ctr) = [batterytwin.R0 batterytwin.Q Motortwin2.Req]';
    codes(:, twin_ctr) = [any(stop_code.Data(:,1)); any(stop_code.Data(:,2)); any(stop_
```

write digital twin parameters to db

```
    write_twin_params_data;
```

resample the degradation parameters for the next digital twin simulation

```
    if twin_count > 1 && twin_ctr < twin_count
       fprintf('[INFO] resampling for twin run # %d', twin_ctr + 1);
       if i > lookback
            batterytwin.R0 = normrnd(r_mu, r_var);
            batterytwin.Q = normrnd(q_mu, q_var);
            Motortwin2.Req = normrnd(m_mu, m_var);
        else
            batterytwin.R0 = max(abs(normrnd(rdeg(i), r_var)), .00075);
            batterytwin.Q = min(abs(normrnd(qdeg(i), q_var)), 15.5);
            Motortwin2.Req = max(abs(normrnd(mdeg(i), m_var)), .001);
        end
    end
    fprintf("[INFO] digital twin degradation parameters: %.4f\t%.4f\t%.4f", batterytwin
end

low_soc = sum(codes(1,:) == 1);
pos_err = sum(codes(2,:) == 1);
success = sum(codes(3,:) == 1);
fprintf("[INFO] DigitalTwin mean parameter values: R0 = %.5f\t Q = %.2f\t Req = %.5f\n\
```

update rul

```
if low_soc > 1
    fprintf('[WARN] DigitalTwin low soc threshold exceeded on i: %d\tmission_id: %d\n',
    temp = mean(times(:)) - 1;
    res = max(temp, rul_hat - 2);
    fprintf('[INFO] updating RUL from %.2f to %.2f', rul_hat, res)
    rul_hat = mean(times(:)) - 1; % rul is now 1 minute less than the digital twin flig
    updated = true;
end
```

```
        if pos_err > 1
            fprintf('[WARN] DigitalTwin position error threshold exceeded on i: %d\tmission_id:
            temp = mean(times(:)) - 1;
            res = max(temp, rul_hat - 2);
            fprintf('[INFO] updating RUL from %.2f to %.2f', rul_hat, res)
            rul_hat = mean(times(:)) - 1; % rul is now 1 minute less than the digital twin flig
            updated = true;
        end

        if success >= 3 && pos_err < 2 && low_soc < 2
            fprintf('[INFO] digital twin mission success on i: %d\tmission_id: %d\n   trajector
            updated = false;
            if mean(times(:)) - 1 > rul_hat
                fprintf('[INFO] new RUL update is available, %.2f replaces %.2f\n', mean(times(
                rul_hat = mean(times(:)) - 1;
            end
        end
        if updated
            fprintf('[INFO] selecting new trajectory to repeat DigitalTwin simulation')
        end

        % otherwise, end of life was never reached so the current rul estimate
        % is the best estimate

        if rul_hat <= rul_threshold
            fail_count = fail_count + 1;
            fprintf('[INFO] digital twin rul_hat: %.2f does not meet the threshold: %.2f on i,m
            if fail_count == 10
                fprintf('[INFO] fail_count reached limit. Stopping simulation.')
                end_sim = 1;
                break;
            end
        end
        clear('battery_actual', 'battery_observed', 'ctrl_err', 'current', 'current_rs', 'eucli
    end
end
```

```
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 18.00
[INFO] simulating true system on i: 1
[INFO] updating degradation parameter variance on i: 1
[INFO] updating degradation parameter values via random sampling on i: 1
[INFO] i: 1 mission_id: 764 rul_hat: 18.00 flight_time: 14.83 distance: 1083.24 R0: 0.00041 Q: 13.49 Req: 0.25288
[INFO] success on i: 1 mission_id: 764
[INFO] digital twin degradation parameters: 0.0004 15.5000 0.2113
[INFO] DigitalTwin selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 18.00
[INFO] simulating digital twin on i 1, mission_id: 764
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0016 15.4209 0.2409
[INFO] simulating digital twin on i 1, mission_id: 764
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0009 14.4787 0.2467
[INFO] simulating digital twin on i 1, mission_id: 764
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0008 15.3795 0.2589
[INFO] simulating digital twin on i 1, mission_id: 764
[INFO] digital twin degradation parameters: 0.0008 15.3795 0.2589
[INFO] DigitalTwin mean parameter values: R0 = 0.00093  Q = 15.19  Req = 0.23944
  stop code counts: low_soc: 0 pos_err: 0  success: 4
```

```
[INFO] digital twin mission success on i: 1 mission_id: 764
   trajectory <11> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 18.00
[INFO] simulating true system on i: 2
[INFO] updating degradation parameter variance on i: 2
[INFO] updating degradation parameter values via random sampling on i: 2
[INFO] i: 2 mission_id: 765 rul_hat: 18.00 flight_time: 16.36 distance: 1218.75 R0: 0.00112 Q: 15.50 Req: 0.22509
[INFO] success on i: 2 mission_id: 765
[INFO] digital twin degradation parameters: 0.0024 15.5000 0.2086
[INFO] DigitalTwin selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 18.00
[INFO] simulating digital twin on i 2, mission_id: 765
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0009 15.4218 0.2441
[INFO] simulating digital twin on i 2, mission_id: 765
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0024 15.5000 0.2189
[INFO] simulating digital twin on i 2, mission_id: 765
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0008 15.2945 0.2364
[INFO] simulating digital twin on i 2, mission_id: 765
[INFO] digital twin degradation parameters: 0.0008 15.2945 0.2364
[INFO] DigitalTwin mean parameter values: R0 = 0.00161  Q = 15.43  Req = 0.22699
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 2 mission_id: 765
   trajectory <14> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 18.00
[INFO] simulating true system on i: 3
[INFO] updating degradation parameter variance on i: 3
[INFO] updating degradation parameter values via random sampling on i: 3
[INFO] i: 3 mission_id: 766 rul_hat: 18.00 flight_time: 14.83 distance: 1083.20 R0: 0.00360 Q: 15.36 Req: 0.24658
[INFO] success on i: 3 mission_id: 766
[INFO] digital twin degradation parameters: 0.0003 13.8268 0.2535
[INFO] DigitalTwin selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 18.00
[INFO] simulating digital twin on i 3, mission_id: 766
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0008 15.5000 0.2027
[INFO] simulating digital twin on i 3, mission_id: 766
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0027 15.5000 0.2402
[INFO] simulating digital twin on i 3, mission_id: 766
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0008 14.6276 0.2430
[INFO] simulating digital twin on i 3, mission_id: 766
[INFO] digital twin degradation parameters: 0.0008 14.6276 0.2430
[INFO] DigitalTwin mean parameter values: R0 = 0.00111  Q = 14.86  Req = 0.23486
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 3 mission_id: 766
   trajectory <14> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 18.00
[INFO] simulating true system on i: 4
[INFO] updating degradation parameter variance on i: 4
[INFO] updating degradation parameter values via random sampling on i: 4
[INFO] i: 4 mission_id: 767 rul_hat: 18.00 flight_time: 14.83 distance: 1083.51 R0: 0.00230 Q: 14.07 Req: 0.26346
[INFO] success on i: 4 mission_id: 767
[INFO] digital twin degradation parameters: 0.0038 14.5349 0.2476
[INFO] DigitalTwin selecting trajectory: <3> with path_time: 17.83 that meets constraint: path_time < 18.00
[INFO] simulating digital twin on i 4, mission_id: 767
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0026 15.5000 0.2287
[INFO] simulating digital twin on i 4, mission_id: 767
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0012 14.7659 0.2104
[INFO] simulating digital twin on i 4, mission_id: 767
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0017 14.9246 0.2296
```

```
[INFO] simulating digital twin on i 4, mission_id: 767
[INFO] digital twin degradation parameters: 0.0017 14.9246 0.2296
[INFO] DigitalTwin mean parameter values: R0 = 0.00232  Q = 14.93  Req = 0.22907
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 4 mission_id: 767
   trajectory <3> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <3> with path_time: 17.83 that meets constraint: path_time < 18.00
[INFO] simulating true system on i: 5
[INFO] updating degradation parameter variance on i: 5
[INFO] updating degradation parameter values via random sampling on i: 5
[INFO] i: 5 mission_id: 768 rul_hat: 18.00 flight_time: 17.84 distance: 1302.10 R0: 0.00058 Q: 14.23 Req: 0.20449
[INFO] success on i: 5 mission_id: 768
[INFO] digital twin degradation parameters: 0.0006 15.0931 0.2188
[INFO] DigitalTwin selecting trajectory: <15> with path_time: 17.63 that meets constraint: path_time < 18.00
[INFO] simulating digital twin on i 5, mission_id: 768
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0010 13.7253 0.2245
[INFO] simulating digital twin on i 5, mission_id: 768
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0015 14.2750 0.2421
[INFO] simulating digital twin on i 5, mission_id: 768
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0030 15.5000 0.2587
[INFO] simulating digital twin on i 5, mission_id: 768
[INFO] digital twin degradation parameters: 0.0030 15.5000 0.2587
[INFO] DigitalTwin mean parameter values: R0 = 0.00156  Q = 14.65  Req = 0.23604
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 5 mission_id: 768
   trajectory <15> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <15> with path_time: 17.63 that meets constraint: path_time < 18.00
[INFO] simulating true system on i: 6
[INFO] updating degradation parameter variance on i: 6
[INFO] updating degradation parameter values via random sampling on i: 6
[INFO] i: 6 mission_id: 769 rul_hat: 18.00 flight_time: 17.63 distance: 1283.62 R0: 0.00339 Q: 15.50 Req: 0.24696
[INFO] success on i: 6 mission_id: 769
[INFO] digital twin degradation parameters: 0.0030 14.1732 0.2267
[INFO] DigitalTwin selecting trajectory: <20> with path_time: 19.65 to explore constraint boundary < 18.00
[INFO] simulating digital twin on i 6, mission_id: 769
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0011 15.3316 0.2345
[INFO] simulating digital twin on i 6, mission_id: 769
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0009 14.6134 0.2291
[INFO] simulating digital twin on i 6, mission_id: 769
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0008 14.8913 0.2287
[INFO] simulating digital twin on i 6, mission_id: 769
[INFO] digital twin degradation parameters: 0.0008 14.8913 0.2287
[INFO] DigitalTwin mean parameter values: R0 = 0.00143  Q = 14.75  Req = 0.22978
  stop code counts: low_soc: 1 pos_err: 0  success: 3
[INFO] digital twin mission success on i: 6 mission_id: 769
   trajectory <20> selected for TrueSystem
[INFO] new RUL update is available, 18.48 replaces 18.00
[INFO] TrueSystem selecting trajectory: <20> with path_time: 19.65 to explore constraint boundary < 18.48
[INFO] simulating true system on i: 7
[INFO] updating degradation parameter variance on i: 7
[INFO] updating degradation parameter values via random sampling on i: 7
[INFO] i: 7 mission_id: 770 rul_hat: 18.48 flight_time: 19.63 distance: 1448.97 R0: 0.00251 Q: 15.13 Req: 0.25889
[INFO] success on i: 7 mission_id: 770
[INFO] forecasting degradation values: r_mu: 0.004603 q_mu: 15.357487 m_mu: 0.233794
[INFO] digital twin degradation parameters: 0.0045 15.2890 0.2571
[INFO] DigitalTwin selecting trajectory: <20> with path_time: 19.65 to explore constraint boundary < 18.48
[INFO] simulating digital twin on i 7, mission_id: 770
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0062 15.7571 0.2406
```

```
[INFO] simulating digital twin on i 7, mission_id: 770
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0067 16.6475 0.2506
[INFO] simulating digital twin on i 7, mission_id: 770
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0050 14.9052 0.2317
[INFO] simulating digital twin on i 7, mission_id: 770
[INFO] digital twin degradation parameters: 0.0050 14.9052 0.2317
[INFO] DigitalTwin mean parameter values: R0 = 0.00558  Q = 15.65  Req = 0.24498
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 7 mission_id: 770
   trajectory <20> selected for TrueSystem
[INFO] new RUL update is available, 18.64 replaces 18.48
[INFO] TrueSystem selecting trajectory: <20> with path_time: 19.65 to explore constraint boundary < 18.64
[INFO] simulating true system on i: 8
[INFO] updating degradation parameter variance on i: 8
[INFO] updating degradation parameter values via random sampling on i: 8
[INFO] i: 8 mission_id: 771 rul_hat: 18.64 flight_time: 19.63 distance: 1449.06 R0: 0.00286 Q: 13.24 Req: 0.22886
[INFO] success on i: 8 mission_id: 771
[INFO] forecasting degradation values: r_mu: 0.002893 q_mu: 14.804769 m_mu: 0.275110
[INFO] digital twin degradation parameters: 0.0027 14.9278 0.2426
[INFO] DigitalTwin selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 18.64
[INFO] simulating digital twin on i 8, mission_id: 771
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0020 14.5896 0.2530
[INFO] simulating digital twin on i 8, mission_id: 771
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0044 15.1148 0.2705
[INFO] simulating digital twin on i 8, mission_id: 771
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0020 14.8867 0.3058
[INFO] simulating digital twin on i 8, mission_id: 771
[INFO] digital twin degradation parameters: 0.0020 14.8867 0.3058
[INFO] DigitalTwin mean parameter values: R0 = 0.00279  Q = 14.88  Req = 0.26797
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 8 mission_id: 771
   trajectory <14> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 18.64
[INFO] simulating true system on i: 9
[INFO] updating degradation parameter variance on i: 9
[INFO] updating degradation parameter values via random sampling on i: 9
[INFO] i: 9 mission_id: 772 rul_hat: 18.64 flight_time: 14.83 distance: 1083.34 R0: 0.00143 Q: 15.20 Req: 0.21937
[INFO] success on i: 9 mission_id: 772
[INFO] forecasting degradation values: r_mu: 0.002687 q_mu: 13.737318 m_mu: 0.233261
[INFO] digital twin degradation parameters: 0.0028 14.3738 0.2084
[INFO] DigitalTwin selecting trajectory: <20> with path_time: 19.65 to explore constraint boundary < 18.64
[INFO] simulating digital twin on i 9, mission_id: 772
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0013 12.0427 0.2320
[INFO] simulating digital twin on i 9, mission_id: 772
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0034 13.6704 0.2304
[INFO] simulating digital twin on i 9, mission_id: 772
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0027 12.8643 0.2037
[INFO] simulating digital twin on i 9, mission_id: 772
[INFO] digital twin degradation parameters: 0.0027 12.8643 0.2037
[INFO] DigitalTwin mean parameter values: R0 = 0.00254  Q = 13.24  Req = 0.21861
  stop code counts: low_soc: 4 pos_err: 0  success: 0
[WARN] DigitalTwin low soc threshold exceeded on i: 9 mission_id: 772
[INFO] updating RUL from 18.64 to 16.78
[INFO] selecting new trajectory to repeat DigitalTwin simulation
[INFO] DigitalTwin selecting trajectory: <15> with path_time: 17.63 to explore constraint boundary < 16.78
[INFO] simulating digital twin on i 9, mission_id: 772
[INFO] resampling for twin run # 2
```

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[INFO] digital twin degradation parameters: 0.0016 14.6196 0.2099
[INFO] simulating digital twin on i 9, mission_id: 772
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0026 14.3448 0.2181
[INFO] simulating digital twin on i 9, mission_id: 772
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0024 13.7616 0.2684
[INFO] simulating digital twin on i 9, mission_id: 772
[INFO] digital twin degradation parameters: 0.0024 13.7616 0.2684
[INFO] DigitalTwin mean parameter values: R0 = 0.00231  Q = 13.90  Req = 0.22503
  stop code counts: low_soc: 1 pos_err: 0  success: 3
[INFO] digital twin mission success on i: 9 mission_id: 772
   trajectory <15> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <15> with path_time: 17.63 to explore constraint boundary < 16.78
[INFO] simulating true system on i: 10
[INFO] updating degradation parameter variance on i: 10
[INFO] updating degradation parameter values via random sampling on i: 10
[INFO] i: 10 mission_id: 773 rul_hat: 16.78 flight_time: 17.63 distance: 1283.71 R0: 0.00161 Q: 14.57 Req: 0.23748
[INFO] success on i: 10 mission_id: 773
[INFO] forecasting degradation values: r_mu: 0.002156 q_mu: 15.878460 m_mu: 0.202266
[INFO] digital twin degradation parameters: 0.0019 15.5000 0.1972
[INFO] DigitalTwin selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 10, mission_id: 773
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0021 16.5210 0.2193
[INFO] simulating digital twin on i 10, mission_id: 773
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0031 16.4027 0.2135
[INFO] simulating digital twin on i 10, mission_id: 773
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0039 14.9388 0.1961
[INFO] simulating digital twin on i 10, mission_id: 773
[INFO] digital twin degradation parameters: 0.0039 14.9388 0.1961
[INFO] DigitalTwin mean parameter values: R0 = 0.00275  Q = 15.84  Req = 0.20653
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 10 mission_id: 773
   trajectory <13> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 11
[INFO] updating degradation parameter variance on i: 11
[INFO] updating degradation parameter values via random sampling on i: 11
[INFO] i: 11 mission_id: 774 rul_hat: 16.78 flight_time: 13.94 distance: 1047.94 R0: 0.00032 Q: 15.50 Req: 0.24236
[INFO] success on i: 11 mission_id: 774
[INFO] forecasting degradation values: r_mu: 0.001140 q_mu: 14.579328 m_mu: 0.219775
[INFO] digital twin degradation parameters: 0.0009 13.2025 0.2230
[INFO] DigitalTwin selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 11, mission_id: 774
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0001 13.9697 0.2154
[INFO] simulating digital twin on i 11, mission_id: 774
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: -0.0003 14.4337 0.2305
[INFO] simulating digital twin on i 11, mission_id: 774
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0008 14.0209 0.2251
[INFO] simulating digital twin on i 11, mission_id: 774
[INFO] digital twin degradation parameters: 0.0008 14.0209 0.2251
[INFO] DigitalTwin mean parameter values: R0 = 0.00036  Q = 13.91  Req = 0.22351
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 11 mission_id: 774
   trajectory <11> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 12
[INFO] updating degradation parameter variance on i: 12
[INFO] updating degradation parameter values via random sampling on i: 12
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[INFO] i: 12 mission_id: 775 rul_hat: 16.78 flight_time: 16.36 distance: 1218.69 R0: 0.00220 Q: 14.52 Req: 0.23443
[INFO] success on i: 12 mission_id: 775
[INFO] forecasting degradation values: r_mu: 0.000466 q_mu: 15.576741 m_mu: 0.218871
[INFO] digital twin degradation parameters: 0.0008 14.8043 0.2293
[INFO] DigitalTwin selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 12, mission_id: 775
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0011 15.8736 0.2321
[INFO] simulating digital twin on i 12, mission_id: 775
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0018 16.0324 0.2262
[INFO] simulating digital twin on i 12, mission_id: 775
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0004 14.5954 0.2102
[INFO] simulating digital twin on i 12, mission_id: 775
[INFO] digital twin degradation parameters: 0.0004 14.5954 0.2102
[INFO] DigitalTwin mean parameter values: R0 = 0.00103  Q = 15.33  Req = 0.22445
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 12 mission_id: 775
   trajectory <13> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 13
[INFO] updating degradation parameter variance on i: 13
[INFO] updating degradation parameter values via random sampling on i: 13
[INFO] i: 13 mission_id: 776 rul_hat: 16.78 flight_time: 13.94 distance: 1047.97 R0: 0.00152 Q: 13.99 Req: 0.25095
[INFO] success on i: 13 mission_id: 776
[INFO] forecasting degradation values: r_mu: 0.001600 q_mu: 14.885382 m_mu: 0.244205
[INFO] digital twin degradation parameters: 0.0019 14.9634 0.2493
[INFO] DigitalTwin selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 13, mission_id: 776
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0016 15.6104 0.2427
[INFO] simulating digital twin on i 13, mission_id: 776
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: -0.0007 14.5062 0.2475
[INFO] simulating digital twin on i 13, mission_id: 776
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0024 15.9620 0.2282
[INFO] simulating digital twin on i 13, mission_id: 776
[INFO] digital twin degradation parameters: 0.0024 15.9620 0.2282
[INFO] DigitalTwin mean parameter values: R0 = 0.00130  Q = 15.26  Req = 0.24193
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 13 mission_id: 776
   trajectory <14> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 14
[INFO] updating degradation parameter variance on i: 14
[INFO] updating degradation parameter values via random sampling on i: 14
[INFO] i: 14 mission_id: 777 rul_hat: 16.78 flight_time: 14.83 distance: 1083.37 R0: 0.00191 Q: 15.02 Req: 0.24001
[INFO] success on i: 14 mission_id: 777
[INFO] forecasting degradation values: r_mu: 0.000380 q_mu: 13.545685 m_mu: 0.239034
[INFO] digital twin degradation parameters: 0.0004 13.5241 0.2414
[INFO] DigitalTwin selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 14, mission_id: 777
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: -0.0005 14.2893 0.2354
[INFO] simulating digital twin on i 14, mission_id: 777
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0016 12.8341 0.2291
[INFO] simulating digital twin on i 14, mission_id: 777
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0016 14.6295 0.2218
[INFO] simulating digital twin on i 14, mission_id: 777
[INFO] digital twin degradation parameters: 0.0016 14.6295 0.2218
[INFO] DigitalTwin mean parameter values: R0 = 0.00077  Q = 13.82  Req = 0.23190
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  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 14 mission_id: 777
   trajectory <14> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 15
[INFO] updating degradation parameter variance on i: 15
[INFO] updating degradation parameter values via random sampling on i: 15
[INFO] i: 15 mission_id: 778 rul_hat: 16.78 flight_time: 14.83 distance: 1083.19 R0: 0.00144 Q: 15.50 Req: 0.26601
[INFO] success on i: 15 mission_id: 778
[INFO] forecasting degradation values: r_mu: 0.001048 q_mu: 14.703978 m_mu: 0.240376
[INFO] digital twin degradation parameters: 0.0001 15.5000 0.2513
[INFO] DigitalTwin selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 15, mission_id: 778
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0002 14.7762 0.2361
[INFO] simulating digital twin on i 15, mission_id: 778
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0030 14.8484 0.2375
[INFO] simulating digital twin on i 15, mission_id: 778
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0010 14.2383 0.2746
[INFO] simulating digital twin on i 15, mission_id: 778
[INFO] digital twin degradation parameters: 0.0010 14.2383 0.2746
[INFO] DigitalTwin mean parameter values: R0 = 0.00110  Q = 14.84  Req = 0.24988
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 15 mission_id: 778
   trajectory <14> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 16
[INFO] updating degradation parameter variance on i: 16
[INFO] updating degradation parameter values via random sampling on i: 16
[INFO] i: 16 mission_id: 779 rul_hat: 16.78 flight_time: 14.83 distance: 1083.79 R0: 0.00183 Q: 14.87 Req: 0.26279
[INFO] success on i: 16 mission_id: 779
[INFO] forecasting degradation values: r_mu: 0.001153 q_mu: 15.798706 m_mu: 0.272106
[INFO] digital twin degradation parameters: 0.0011 15.5000 0.2631
[INFO] DigitalTwin selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 16, mission_id: 779
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0018 15.8639 0.2998
[INFO] simulating digital twin on i 16, mission_id: 779
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0012 16.0162 0.2490
[INFO] simulating digital twin on i 16, mission_id: 779
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0016 14.7132 0.2560
[INFO] simulating digital twin on i 16, mission_id: 779
[INFO] digital twin degradation parameters: 0.0016 14.7132 0.2560
[INFO] DigitalTwin mean parameter values: R0 = 0.00142  Q = 15.52  Req = 0.26699
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 16 mission_id: 779
   trajectory <10> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 17
[INFO] updating degradation parameter variance on i: 17
[INFO] updating degradation parameter values via random sampling on i: 17
[INFO] i: 17 mission_id: 780 rul_hat: 16.78 flight_time: 13.58 distance: 1020.97 R0: 0.00210 Q: 15.06 Req: 0.23110
[INFO] success on i: 17 mission_id: 780
[INFO] forecasting degradation values: r_mu: 0.001873 q_mu: 14.942521 m_mu: 0.280067
[INFO] digital twin degradation parameters: 0.0015 15.1323 0.2836
[INFO] DigitalTwin selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 17, mission_id: 780
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0004 14.8889 0.2525
[INFO] simulating digital twin on i 17, mission_id: 780
[INFO] resampling for twin run # 3
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[INFO] digital twin degradation parameters: 0.0025 14.1985 0.2624
[INFO] simulating digital twin on i 17, mission_id: 780
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0034 16.5427 0.2670
[INFO] simulating digital twin on i 17, mission_id: 780
[INFO] digital twin degradation parameters: 0.0034 16.5427 0.2670
[INFO] DigitalTwin mean parameter values: R0 = 0.00194  Q = 15.19  Req = 0.26636
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 17 mission_id: 780
   trajectory <11> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 18
[INFO] updating degradation parameter variance on i: 18
[INFO] updating degradation parameter values via random sampling on i: 18
[INFO] i: 18 mission_id: 781 rul_hat: 16.78 flight_time: 16.36 distance: 1218.72 R0: 0.00129 Q: 15.50 Req: 0.23707
[INFO] success on i: 18 mission_id: 781
[INFO] forecasting degradation values: r_mu: 0.001940 q_mu: 15.240045 m_mu: 0.254478
[INFO] digital twin degradation parameters: 0.0034 15.5000 0.2554
[INFO] DigitalTwin selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 18, mission_id: 781
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0025 14.7781 0.2607
[INFO] simulating digital twin on i 18, mission_id: 781
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0012 15.3488 0.2786
[INFO] simulating digital twin on i 18, mission_id: 781
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0024 14.6855 0.2600
[INFO] simulating digital twin on i 18, mission_id: 781
[INFO] digital twin degradation parameters: 0.0024 14.6855 0.2600
[INFO] DigitalTwin mean parameter values: R0 = 0.00237  Q = 15.08  Req = 0.26365
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 18 mission_id: 781
   trajectory <10> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 19
[INFO] updating degradation parameter variance on i: 19
[INFO] updating degradation parameter values via random sampling on i: 19
[INFO] i: 19 mission_id: 782 rul_hat: 16.78 flight_time: 13.58 distance: 1021.04 R0: 0.00077 Q: 15.50 Req: 0.21830
[INFO] success on i: 19 mission_id: 782
[INFO] forecasting degradation values: r_mu: 0.002366 q_mu: 15.423359 m_mu: 0.245122
[INFO] digital twin degradation parameters: 0.0018 15.5000 0.2324
[INFO] DigitalTwin selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 19, mission_id: 782
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0034 14.7559 0.2425
[INFO] simulating digital twin on i 19, mission_id: 782
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0020 15.3411 0.2508
[INFO] simulating digital twin on i 19, mission_id: 782
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0019 15.9994 0.2517
[INFO] simulating digital twin on i 19, mission_id: 782
[INFO] digital twin degradation parameters: 0.0019 15.9994 0.2517
[INFO] DigitalTwin mean parameter values: R0 = 0.00227  Q = 15.40  Req = 0.24437
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 19 mission_id: 782
   trajectory <10> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 20
[INFO] updating degradation parameter variance on i: 20
[INFO] updating degradation parameter values via random sampling on i: 20
[INFO] i: 20 mission_id: 783 rul_hat: 16.78 flight_time: 13.58 distance: 1020.94 R0: 0.00098 Q: 14.95 Req: 0.26164
[INFO] success on i: 20 mission_id: 783
[INFO] forecasting degradation values: r_mu: 0.000754 q_mu: 15.895088 m_mu: 0.225844
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[INFO] digital twin degradation parameters: 0.0016 15.5000 0.2249
[INFO] DigitalTwin selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 20, mission_id: 783
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0004 15.6593 0.2399
[INFO] simulating digital twin on i 20, mission_id: 783
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0019 16.3181 0.2572
[INFO] simulating digital twin on i 20, mission_id: 783
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: -0.0005 15.9112 0.2273
[INFO] simulating digital twin on i 20, mission_id: 783
[INFO] digital twin degradation parameters: -0.0005 15.9112 0.2273
[INFO] DigitalTwin mean parameter values: R0 = 0.00084  Q = 15.85  Req = 0.23731
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 20 mission_id: 783
   trajectory <13> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 21
[INFO] updating degradation parameter variance on i: 21
[INFO] updating degradation parameter values via random sampling on i: 21
[INFO] i: 21 mission_id: 784 rul_hat: 16.78 flight_time: 13.94 distance: 1047.73 R0: 0.00267 Q: 15.09 Req: 0.24231
[INFO] success on i: 21 mission_id: 784
[INFO] forecasting degradation values: r_mu: 0.001549 q_mu: 15.426218 m_mu: 0.248188
[INFO] digital twin degradation parameters: 0.0020 15.5000 0.2509
[INFO] DigitalTwin selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 21, mission_id: 784
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: -0.0012 15.5029 0.2249
[INFO] simulating digital twin on i 21, mission_id: 784
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0013 16.4052 0.2405
[INFO] simulating digital twin on i 21, mission_id: 784
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0031 15.9711 0.2445
[INFO] simulating digital twin on i 21, mission_id: 784
[INFO] digital twin degradation parameters: 0.0031 15.9711 0.2445
[INFO] DigitalTwin mean parameter values: R0 = 0.00127  Q = 15.84  Req = 0.24021
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 21 mission_id: 784
   trajectory <10> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 22
[INFO] updating degradation parameter variance on i: 22
[INFO] updating degradation parameter values via random sampling on i: 22
[INFO] i: 22 mission_id: 785 rul_hat: 16.78 flight_time: 13.58 distance: 1020.98 R0: 0.00069 Q: 14.39 Req: 0.25323
[INFO] success on i: 22 mission_id: 785
[INFO] forecasting degradation values: r_mu: 0.001528 q_mu: 15.581808 m_mu: 0.240688
[INFO] digital twin degradation parameters: 0.0003 15.5000 0.2448
[INFO] DigitalTwin selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 22, mission_id: 785
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0013 14.9052 0.2581
[INFO] simulating digital twin on i 22, mission_id: 785
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0022 15.4832 0.2319
[INFO] simulating digital twin on i 22, mission_id: 785
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0017 14.8023 0.2417
[INFO] simulating digital twin on i 22, mission_id: 785
[INFO] digital twin degradation parameters: 0.0017 14.8023 0.2417
[INFO] DigitalTwin mean parameter values: R0 = 0.00139  Q = 15.17  Req = 0.24412
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 22 mission_id: 785
   trajectory <10> selected for TrueSystem
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[INFO] TrueSystem selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 23
[INFO] updating degradation parameter variance on i: 23
[INFO] updating degradation parameter values via random sampling on i: 23
[INFO] i: 23 mission_id: 786 rul_hat: 16.78 flight_time: 13.58 distance: 1021.07 R0: 0.00093 Q: 14.16 Req: 0.26228
[INFO] success on i: 23 mission_id: 786
[INFO] forecasting degradation values: r_mu: 0.000280 q_mu: 15.165358 m_mu: 0.240676
[INFO] digital twin degradation parameters: 0.0003 15.5000 0.2249
[INFO] DigitalTwin selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 23, mission_id: 786
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0008 16.0528 0.2555
[INFO] simulating digital twin on i 23, mission_id: 786
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: -0.0014 15.6289 0.2408
[INFO] simulating digital twin on i 23, mission_id: 786
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0005 14.7931 0.2167
[INFO] simulating digital twin on i 23, mission_id: 786
[INFO] digital twin degradation parameters: 0.0005 14.7931 0.2167
[INFO] DigitalTwin mean parameter values: R0 = 0.00006  Q = 15.49  Req = 0.23450
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 23 mission_id: 786
   trajectory <11> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 24
[INFO] updating degradation parameter variance on i: 24
[INFO] updating degradation parameter values via random sampling on i: 24
[INFO] i: 24 mission_id: 787 rul_hat: 16.78 flight_time: 16.36 distance: 1218.88 R0: 0.00214 Q: 14.36 Req: 0.24409
[INFO] success on i: 24 mission_id: 787
[INFO] forecasting degradation values: r_mu: 0.000148 q_mu: 14.227122 m_mu: 0.252629
[INFO] digital twin degradation parameters: 0.0003 15.5000 0.2853
[INFO] DigitalTwin selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 24, mission_id: 787
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0009 12.8382 0.2704
[INFO] simulating digital twin on i 24, mission_id: 787
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: -0.0001 15.1646 0.2401
[INFO] simulating digital twin on i 24, mission_id: 787
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: -0.0006 15.7778 0.2610
[INFO] simulating digital twin on i 24, mission_id: 787
[INFO] digital twin degradation parameters: -0.0006 15.7778 0.2610
[INFO] DigitalTwin mean parameter values: R0 = 0.00013  Q = 14.82  Req = 0.26419
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 24 mission_id: 787
   trajectory <14> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 25
[INFO] updating degradation parameter variance on i: 25
[INFO] updating degradation parameter values via random sampling on i: 25
[INFO] i: 25 mission_id: 788 rul_hat: 16.78 flight_time: 14.83 distance: 1083.48 R0: 0.00125 Q: 14.00 Req: 0.26478
[INFO] success on i: 25 mission_id: 788
[INFO] forecasting degradation values: r_mu: 0.001027 q_mu: 13.883913 m_mu: 0.244497
[INFO] digital twin degradation parameters: 0.0013 12.3897 0.2319
[INFO] DigitalTwin selecting trajectory: <3> with path_time: 17.83 to explore constraint boundary < 16.78
[INFO] simulating digital twin on i 25, mission_id: 788
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: -0.0005 13.2978 0.2386
[INFO] simulating digital twin on i 25, mission_id: 788
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0016 13.7765 0.2459
[INFO] simulating digital twin on i 25, mission_id: 788
[INFO] resampling for twin run # 4
```

```
[INFO] digital twin degradation parameters: 0.0010 13.2501 0.2609
[INFO] simulating digital twin on i 25, mission_id: 788
[INFO] digital twin degradation parameters: 0.0010 13.2501 0.2609
[INFO] DigitalTwin mean parameter values: R0 = 0.00084  Q = 13.18  Req = 0.24433
  stop code counts: low_soc: 1 pos_err: 0  success: 3
[INFO] digital twin mission success on i: 25 mission_id: 788
   trajectory <3> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <3> with path_time: 17.83 to explore constraint boundary < 16.78
[INFO] simulating true system on i: 26
[INFO] updating degradation parameter variance on i: 26
[INFO] updating degradation parameter values via random sampling on i: 26
[INFO] i: 26 mission_id: 789 rul_hat: 16.78 flight_time: 17.84 distance: 1302.04 R0: 0.00124 Q: 14.37 Req: 0.25257
[INFO] success on i: 26 mission_id: 789
[INFO] forecasting degradation values: r_mu: 0.000796 q_mu: 13.646336 m_mu: 0.263218
[INFO] digital twin degradation parameters: 0.0007 13.3073 0.2650
[INFO] DigitalTwin selecting trajectory: <15> with path_time: 17.63 to explore constraint boundary < 16.78
[INFO] simulating digital twin on i 26, mission_id: 789
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0003 13.0811 0.2599
[INFO] simulating digital twin on i 26, mission_id: 789
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: -0.0004 14.8331 0.2660
[INFO] simulating digital twin on i 26, mission_id: 789
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: -0.0001 13.7247 0.2434
[INFO] simulating digital twin on i 26, mission_id: 789
[INFO] digital twin degradation parameters: -0.0001 13.7247 0.2434
[INFO] DigitalTwin mean parameter values: R0 = 0.00015  Q = 13.74  Req = 0.25857
  stop code counts: low_soc: 1 pos_err: 0  success: 3
[INFO] digital twin mission success on i: 26 mission_id: 789
   trajectory <15> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <15> with path_time: 17.63 to explore constraint boundary < 16.78
[INFO] simulating true system on i: 27
[INFO] updating degradation parameter variance on i: 27
[INFO] updating degradation parameter values via random sampling on i: 27
[INFO] i: 27 mission_id: 790 rul_hat: 16.78 flight_time: 17.63 distance: 1283.82 R0: 0.00197 Q: 14.53 Req: 0.25101
[INFO] success on i: 27 mission_id: 790
[INFO] forecasting degradation values: r_mu: 0.000728 q_mu: 13.469790 m_mu: 0.273058
[INFO] digital twin degradation parameters: 0.0010 14.0162 0.2621
[INFO] DigitalTwin selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 27, mission_id: 790
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0001 13.7418 0.2480
[INFO] simulating digital twin on i 27, mission_id: 790
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0014 13.6659 0.2581
[INFO] simulating digital twin on i 27, mission_id: 790
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0005 14.0060 0.3058
[INFO] simulating digital twin on i 27, mission_id: 790
[INFO] digital twin degradation parameters: 0.0005 14.0060 0.3058
[INFO] DigitalTwin mean parameter values: R0 = 0.00074  Q = 13.86  Req = 0.26850
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 27 mission_id: 790
   trajectory <14> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 28
[INFO] updating degradation parameter variance on i: 28
[INFO] updating degradation parameter values via random sampling on i: 28
[INFO] i: 28 mission_id: 791 rul_hat: 16.78 flight_time: 14.83 distance: 1083.44 R0: 0.00131 Q: 15.50 Req: 0.23960
[INFO] success on i: 28 mission_id: 791
[INFO] forecasting degradation values: r_mu: 0.001920 q_mu: 13.500822 m_mu: 0.268099
[INFO] digital twin degradation parameters: 0.0021 13.3701 0.2726
[INFO] DigitalTwin selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 28, mission_id: 791
```

```
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0017 13.7778 0.2614
[INFO] simulating digital twin on i 28, mission_id: 791
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0018 13.7541 0.2752
[INFO] simulating digital twin on i 28, mission_id: 791
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0014 13.3317 0.2796
[INFO] simulating digital twin on i 28, mission_id: 791
[INFO] digital twin degradation parameters: 0.0014 13.3317 0.2796
[INFO] DigitalTwin mean parameter values: R0 = 0.00174  Q = 13.56  Req = 0.27222
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 28 mission_id: 791
   trajectory <11> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 29
[INFO] updating degradation parameter variance on i: 29
[INFO] updating degradation parameter values via random sampling on i: 29
[INFO] i: 29 mission_id: 792 rul_hat: 16.78 flight_time: 16.36 distance: 1218.66 R0: 0.00184 Q: 13.78 Req: 0.27169
[INFO] success on i: 29 mission_id: 792
[INFO] forecasting degradation values: r_mu: 0.001951 q_mu: 14.378790 m_mu: 0.261118
[INFO] digital twin degradation parameters: 0.0015 13.9457 0.2426
[INFO] DigitalTwin selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 29, mission_id: 792
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0017 13.8582 0.2395
[INFO] simulating digital twin on i 29, mission_id: 792
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0041 15.3093 0.2565
[INFO] simulating digital twin on i 29, mission_id: 792
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0019 14.6013 0.2610
[INFO] simulating digital twin on i 29, mission_id: 792
[INFO] digital twin degradation parameters: 0.0019 14.6013 0.2610
[INFO] DigitalTwin mean parameter values: R0 = 0.00230  Q = 14.43  Req = 0.24989
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 29 mission_id: 792
   trajectory <14> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 30
[INFO] updating degradation parameter variance on i: 30
[INFO] updating degradation parameter values via random sampling on i: 30
[INFO] i: 30 mission_id: 793 rul_hat: 16.78 flight_time: 14.83 distance: 1083.70 R0: 0.00123 Q: 15.17 Req: 0.23761
[INFO] success on i: 30 mission_id: 793
[INFO] forecasting degradation values: r_mu: 0.002201 q_mu: 13.567125 m_mu: 0.258951
[INFO] digital twin degradation parameters: 0.0036 12.4916 0.2548
[INFO] DigitalTwin selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 16.78
[INFO] simulating digital twin on i 30, mission_id: 793
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0011 14.1294 0.2610
[INFO] simulating digital twin on i 30, mission_id: 793
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0016 13.8134 0.2686
[INFO] simulating digital twin on i 30, mission_id: 793
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0038 13.5099 0.2552
[INFO] simulating digital twin on i 30, mission_id: 793
[INFO] digital twin degradation parameters: 0.0038 13.5099 0.2552
[INFO] DigitalTwin mean parameter values: R0 = 0.00252  Q = 13.49  Req = 0.25991
  stop code counts: low_soc: 0 pos_err: 0  success: 4
[INFO] digital twin mission success on i: 30 mission_id: 793
   trajectory <13> selected for TrueSystem
[INFO] TrueSystem selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 16.78
[INFO] simulating true system on i: 31
[INFO] updating degradation parameter variance on i: 31
```

```
[INFO] updating degradation parameter values via random sampling on i: 31
[INFO] i: 31 mission_id:
Unable to resolve the name trajectory.path_time.
```

********** end of simulation code

test sim digital twin (for testing)

```
i = 1;
sys = "DigitalTwin";
octomodel.sampletime = true_sample_rate;
sprintf('[INFO] simulating digital twin on mission: %d', i);
tic
sim('digitaltwin1c.slx');
toc
```

```
 clear('trajectory', 'battery_actual', 'battery_observed', 'ctrl_err', 'current', 'current_rs',
```

test sim true system (for testing)

```
i = 1;
sys = "TrueSystem";
octomodel.sampletime = true_sample_rate;
sprintf('[INFO] simulating true system on mission: %d', i);
tic
sim('truesystem.slx');
toc
```

define placeholder variables

```
twin_ctr = 1;
twin_count = 4;
times = zeros(1, twin_count);
vs = zeros(1, twin_count);
socs = zeros(1, twin_count);
r0s = zeros(1, twin_count);
qs = zeros(1, twin_count);
ms = zeros(1, twin_count);
dist = zeros(1, twin_count);
errs = zeros(1, twin_count);
degs = zeros(3, twin_count);
codes = zeros(3, twin_count);
```

Update twin degradation parameters

```
if i > lookback
    x = double(((i - (lookback-1)):1:i)');
    r_poly = polyfit(x, smoothdata(r_deg(x), 'rlowess', 5), 1);
```

```
    q_poly = polyfit(x, smoothdata(q_deg(x), 'rlowess', 5), 1);
    m_poly = polyfit(x, smoothdata(m_deg(x), 'rlowess', 5), 1);

    polys(i, 1, :) = r_poly;
    polys(i, 2, :) = q_poly;
    polys(i, 3, :) = m_poly;

    r_mu = polyval(r_poly, i + horizon);
    q_mu = polyval(q_poly, i + horizon);
    m_mu = polyval(m_poly, i + horizon);
    fprintf('[INFO] forecasting degradation values: r_mu: %.6f\tq_mu: %.6f\tm_mu: %.6f', r_mu,
    batterytwin.R0 = max(abs(normrnd(r_mu, r_var)), .0001);
    batterytwin.Q = min(abs(normrnd(q_mu, q_var)), 15.5);
    Motortwin2.Req = max(abs(normrnd(m_mu, m_var)), .001);
else
    batterytwin.R0 = max(abs(normrnd(rdeg(i), r_var)), .0001);
    batterytwin.Q = min(abs(normrnd(qdeg(i), q_var)), 15.5);
    Motortwin2.Req = max(abs(normrnd(mdeg(i), m_var)), .001);
end
fprintf("[INFO] digital twin degradation parameters: %.4f\t%.4f\t%.4f", batterytwin.R0, battery
write_degradation_data;
```

now simulate digital twin

```
load_trajectory;
if trajectory.path_time > rul_hat
    fprintf("[INFO] DigitalTwin selecting trajectory: <%d> with path_time: %.2f to explore cons
else
    fprintf("[INFO] DigitalTwin selecting trajectory: <%d> with path_time: %.2f that meets cons
end
sys = "DigitalTwin";
octomodel.sampletime = twin_sample_rate;
for twin_ctr=1:twin_count
    fprintf('[INFO] simulating digital twin on i %d, mission_id: %d\n', i, mission_id)
    out = sim('digitaltwin1c.slx');
    %        get the output from each parallel worker
    times(twin_ctr) = flight_time.Data(end);
    vs(twin_ctr) = battery_actual.Data(end, 1);
    socs(twin_ctr) = battery_actual.Data(end, 2);
    r0s(twin_ctr) = battery_actual.Data(end, 3);
    qs(twin_ctr) = battery_actual.Data(end, 6);
    ms(twin_ctr) = motors.Data(end, 1);
    errs(twin_ctr) = mean(euclidean_pos_err);
    dist(twin_ctr) = calculatedistance([pos_actual.Data(:,1) pos_actual.Data(:,2)]);
    degs(:, twin_ctr) = [batterytwin.R0 batterytwin.Q Motortwin2.Req]';
    codes(:, twin_ctr) = [any(stop_code.Data(:,1)); any(stop_code.Data(:,2)); any(stop_code.Dat
```

write digital twin parameters to db

```
    write_twin_params_data;
```

resample the degradation parameters for the next digital twin simulation

```
    if twin_count > 1 && twin_ctr < twin_count
```

```
        fprintf('[INFO] resampling for twin run # %d', twin_ctr + 1);
        if i > lookback
             batterytwin.R0 = normrnd(r_mu, r_var);
             batterytwin.Q = normrnd(q_mu, q_var);
             Motortwin2.Req = normrnd(m_mu, m_var);
         else
             batterytwin.R0 = max(abs(normrnd(rdeg(i), r_var)), .00075);
             batterytwin.Q = min(abs(normrnd(qdeg(i), q_var)), 15.5);
             Motortwin2.Req = max(abs(normrnd(mdeg(i), m_var)), .001);
         end
    end
    fprintf("[INFO] digital twin degradation parameters: %.4f\t%.4f\t%.4f", batterytwin.R0, bat
end

low_soc = sum(codes(1,:) == 1);
pos_err = sum(codes(2,:) == 1);
success = sum(codes(3,:) == 1);
fprintf("[INFO] digital twin mean parameter values: R0 = %.5f\t Q = %.2f\t Req = %.5f\n\t stop
```

update rul

```
updated = false;
if low_soc > 1
    fprintf('[WARN] digital twin low soc threshold exceeded on i: %d\tmission_id: %d\n', i, mis
    fprintf('[INFO] updating RUL from %.2f to %.2f', rul_hat, min(mean(times(:)) - 1))
    rul_hat = mean(times(:)) - 1; % rul is now 1 minute less than the digital twin flight time
    updated = true;
end

if pos_err > 1
    fprintf('[WARN] digital twin position error threshold exceeded on i: %d\tmission_id: %d\n',
    fprintf('[INFO] updating RUL from %.2f to %.2f', rul_hat, min(mean(times(:)) - 1))
    rul_hat = mean(times(:)) - 1; % rul is now 1 minute less than the digital twin flight time
    updated = true;
end

if success >= 3 && pos_err < 2 && low_soc < 2
    fprintf('[INFO] digital twin mission success on i: %d\tmission_id: %d\n', i, mission_id)
    if mean(times(:)) - 1 > rul_hat
        fprintf('[INFO] new RUL update is available, %.2f replaces %.2f\n', mean(times(:)) - 1,
        rul_hat = mean(times(:)) - 1;
    end
elseif ~updated
    fprintf('[WARN] digital twin mission uncertain on i: %d\tmission_id: %d, rul_hat: %.2f rema
end
% otherwise, end of life was never reached so the current rul estimate
% is the best estimate

if rul_hat <= rul_threshold
    fail_count = fail_count + 1;
    fprintf('[INFO] digital twin rul_hat: %.2f does not meet the threshold: %.2f on i,mission %
    if fail_count == 10
        fprintf('[INFO] fail_count reached limit. Stopping simulation.')
        end_sim = 1;
```

```
        %break;
    end
end
    clear('trajectory', 'battery_actual', 'battery_observed', 'ctrl_err', 'current', 'current_r
```