Run to failure experiment C1

In this work remaining useful life (RUL) refers to the total flight time possible for a single mission. 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;

%load_trajectory; % load individually
```

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

```
% loop
% accelerated is 80
% normal is 300
for i = 1:n_missions
    if i < 20 && i >= 11
```

```
        lookback = 8;
        horizon = 3;
    elseif i >= 21
        lookback = 10;
        horizon = 4;
    end

    ruls(i) = rul_hat;
    load_trajectory;
    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

```
load_trajectory;
if trajectory.path_time > rul_hat
    fprintf("[INFO] DigitalTwin selecting trajectory: <%d> with path_time: %.2f to explore
else
    fprintf("[INFO] DigitalTwin selecting trajectory: <%d> with path_time: %.2f that meets
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
```

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,
    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\t sto
```

update rul

```
    updated = false;
    if low_soc > 1
        fprintf('[WARN] digital twin low soc threshold exceeded on i: %d\tmission_id: %d\n', i,
        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 t
        updated = true;
    end

    if pos_err > 1
        fprintf('[WARN] digital twin position error threshold exceeded on i: %d\tmission_id: %d
        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 t
        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(:))
            rul_hat = mean(times(:)) - 1;
        end
```

```
    elseif ~updated
        fprintf('[WARN] digital twin mission uncertain on i: %d\tmission_id: %d, rul_hat: %.2f
    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,missi
        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', 'curre
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: 632 rul_hat: 18.00 flight_time: 14.83 distance: 1083.34 R0: 0.00177 Q: 13.91 Req: 0.25144
[INFO] success on i: 1 mission_id: 632
[INFO] digital twin degradation parameters: 0.0027 15.4400 0.2578
[INFO] DigitalTwin selecting trajectory: <15> with path_time: 17.63 that meets constraint: path_time < 18.00
[INFO] simulating digital twin on i 1, mission_id: 632
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0014 14.2914 0.2549
[INFO] simulating digital twin on i 1, mission_id: 632
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0008 14.0380 0.2209
[INFO] simulating digital twin on i 1, mission_id: 632
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0018 15.5000 0.2436
[INFO] simulating digital twin on i 1, mission_id: 632
[INFO] digital twin degradation parameters: 0.0018 15.5000 0.2436
[INFO] digital twin mean parameter values: R0 = 0.00168  Q = 14.82  Req = 0.24429  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 1 mission_id: 632
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 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: 633 rul_hat: 18.00 flight_time: 14.83 distance: 1083.43 R0: 0.00059 Q: 14.90 Req: 0.23281
[INFO] success on i: 2 mission_id: 633
[INFO] digital twin degradation parameters: 0.0014 15.2674 0.2205
[INFO] DigitalTwin selecting trajectory: <15> with path_time: 17.63 that meets constraint: path_time < 18.00
[INFO] simulating digital twin on i 2, mission_id: 633
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0017 15.5000 0.2595
[INFO] simulating digital twin on i 2, mission_id: 633
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0008 15.0578 0.2136
[INFO] simulating digital twin on i 2, mission_id: 633
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0008 14.9829 0.2678
[INFO] simulating digital twin on i 2, mission_id: 633
[INFO] digital twin degradation parameters: 0.0008 14.9829 0.2678
[INFO] digital twin mean parameter values: R0 = 0.00116  Q = 15.20  Req = 0.24035  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 2 mission_id: 633
[INFO] TrueSystem selecting trajectory: <11> with path_time: 16.38 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: 634 rul_hat: 18.00 flight_time: 16.36 distance: 1218.62 R0: 0.00090 Q: 15.50 Req: 0.21682
[INFO] success on i: 3 mission_id: 634
[INFO] digital twin degradation parameters: 0.0011 15.4637 0.2595
[INFO] DigitalTwin selecting trajectory: <20> with path_time: 19.65 to explore constraint boundary < 18.00
[INFO] simulating digital twin on i 3, mission_id: 634
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0008 14.3242 0.2174
[INFO] simulating digital twin on i 3, mission_id: 634
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0034 14.4357 0.2526
[INFO] simulating digital twin on i 3, mission_id: 634
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0009 15.5000 0.2231
[INFO] simulating digital twin on i 3, mission_id: 634
[INFO] digital twin degradation parameters: 0.0009 15.5000 0.2231
[INFO] digital twin mean parameter values: R0 = 0.00156  Q = 14.93  Req = 0.23816  stop code counts: low_soc: 2 pos_
[WARN] digital twin low soc threshold exceeded on i: 3 mission_id: 634
[INFO] updating RUL from 18.00 to 18.43
[INFO] TrueSystem selecting trajectory: <15> with path_time: 17.63 that meets constraint: path_time < 18.43
[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: 635 rul_hat: 18.43 flight_time: 17.64 distance: 1283.61 R0: 0.00160 Q: 14.81 Req: 0.23476
[INFO] success on i: 4 mission_id: 635
[INFO] digital twin degradation parameters: 0.0025 15.2196 0.2423
[INFO] DigitalTwin selecting trajectory: <2> with path_time: 19.92 to explore constraint boundary < 18.43
[INFO] simulating digital twin on i 4, mission_id: 635
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0018 15.5000 0.2338
[INFO] simulating digital twin on i 4, mission_id: 635
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0013 13.9516 0.2164
[INFO] simulating digital twin on i 4, mission_id: 635
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0012 15.5000 0.2883
[INFO] simulating digital twin on i 4, mission_id: 635
[INFO] digital twin degradation parameters: 0.0012 15.5000 0.2883
[INFO] digital twin mean parameter values: R0 = 0.00172  Q = 15.04  Req = 0.24523  stop code counts: low_soc: 1 pos_
[INFO] digital twin mission success on i: 4 mission_id: 635
[INFO] new RUL update is available, 18.57 replaces 18.43
[INFO] TrueSystem selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 18.57
[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: 636 rul_hat: 18.57 flight_time: 16.36 distance: 1218.62 R0: 0.00106 Q: 13.29 Req: 0.23068
[INFO] success on i: 5 mission_id: 636
[INFO] digital twin degradation parameters: 0.0006 15.5000 0.2221
[INFO] DigitalTwin selecting trajectory: <3> with path_time: 17.83 that meets constraint: path_time < 18.57
[INFO] simulating digital twin on i 5, mission_id: 636
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0014 14.4380 0.2483
[INFO] simulating digital twin on i 5, mission_id: 636
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0018 15.5000 0.2353
[INFO] simulating digital twin on i 5, mission_id: 636
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0009 14.2323 0.2648
[INFO] simulating digital twin on i 5, mission_id: 636
[INFO] digital twin degradation parameters: 0.0009 14.2323 0.2648
[INFO] digital twin mean parameter values: R0 = 0.00119  Q = 14.92  Req = 0.24264  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 5 mission_id: 636
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 18.57
```

```
[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: 637 rul_hat: 18.57 flight_time: 14.83 distance: 1083.34 R0: 0.00126 Q: 15.50 Req: 0.20274
[INFO] success on i: 6 mission_id: 637
[INFO] digital twin degradation parameters: 0.0010 13.9155 0.2940
[INFO] DigitalTwin selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 18.57
[INFO] simulating digital twin on i 6, mission_id: 637
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0019 15.5000 0.2197
[INFO] simulating digital twin on i 6, mission_id: 637
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0008 14.7106 0.2601
[INFO] simulating digital twin on i 6, mission_id: 637
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0009 15.5000 0.2010
[INFO] simulating digital twin on i 6, mission_id: 637
[INFO] digital twin degradation parameters: 0.0009 15.5000 0.2010
[INFO] digital twin mean parameter values: R0 = 0.00113  Q = 14.91  Req = 0.24370  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 6 mission_id: 637
[INFO] TrueSystem selecting trajectory: <3> with path_time: 17.83 that meets constraint: path_time < 18.57
[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: 638 rul_hat: 18.57 flight_time: 17.83 distance: 1301.97 R0: 0.00032 Q: 15.36 Req: 0.24521
[INFO] success on i: 7 mission_id: 638
[INFO] forecasting degradation values: r_mu: 0.001108 q_mu: 15.942011 m_mu: 0.197733
[INFO] digital twin degradation parameters: 0.0011 14.8217 0.2186
[INFO] DigitalTwin selecting trajectory: <15> with path_time: 17.63 that meets constraint: path_time < 18.57
[INFO] simulating digital twin on i 7, mission_id: 638
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0011 15.7219 0.1654
[INFO] simulating digital twin on i 7, mission_id: 638
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0008 15.2437 0.1796
[INFO] simulating digital twin on i 7, mission_id: 638
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0000 15.4938 0.1607
[INFO] simulating digital twin on i 7, mission_id: 638
[INFO] digital twin degradation parameters: 0.0000 15.4938 0.1607
[INFO] digital twin mean parameter values: R0 = 0.00078  Q = 15.32  Req = 0.18106  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 7 mission_id: 638
[INFO] TrueSystem selecting trajectory: <20> with path_time: 19.65 to explore constraint boundary < 18.57
[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: 639 rul_hat: 18.57 flight_time: 19.63 distance: 1449.14 R0: 0.00115 Q: 14.89 Req: 0.22592
[INFO] success on i: 8 mission_id: 639
[INFO] forecasting degradation values: r_mu: 0.000774 q_mu: 15.249090 m_mu: 0.248130
[INFO] digital twin degradation parameters: 0.0017 15.1385 0.2351
[INFO] DigitalTwin selecting trajectory: <15> with path_time: 17.63 that meets constraint: path_time < 18.57
[INFO] simulating digital twin on i 8, mission_id: 639
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0002 15.0053 0.2327
[INFO] simulating digital twin on i 8, mission_id: 639
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: -0.0003 17.3457 0.2783
[INFO] simulating digital twin on i 8, mission_id: 639
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0011 14.2057 0.2323
[INFO] simulating digital twin on i 8, mission_id: 639
[INFO] digital twin degradation parameters: 0.0011 14.2057 0.2323
[INFO] digital twin mean parameter values: R0 = 0.00068  Q = 15.42  Req = 0.24461  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 8 mission_id: 639
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 18.57
```

```
[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: 640 rul_hat: 18.57 flight_time: 14.83 distance: 1083.17 R0: 0.00010 Q: 13.00 Req: 0.21490
[INFO] success on i: 9 mission_id: 640
[INFO] forecasting degradation values: r_mu: 0.000814 q_mu: 15.019909 m_mu: 0.233515
[INFO] digital twin degradation parameters: 0.0011 15.3408 0.2416
[INFO] DigitalTwin selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 18.57
[INFO] simulating digital twin on i 9, mission_id: 640
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0004 15.7268 0.2090
[INFO] simulating digital twin on i 9, mission_id: 640
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0012 14.3240 0.2275
[INFO] simulating digital twin on i 9, mission_id: 640
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0013 15.8720 0.2134
[INFO] simulating digital twin on i 9, mission_id: 640
[INFO] digital twin degradation parameters: 0.0013 15.8720 0.2134
[INFO] digital twin mean parameter values: R0 = 0.00101  Q = 15.32  Req = 0.22288  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 9 mission_id: 640
[INFO] TrueSystem selecting trajectory: <20> with path_time: 19.65 to explore constraint boundary < 18.57
[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: 641 rul_hat: 18.57 flight_time: 16.90 distance: 1266.72 R0: 0.00113 Q: 14.74 Req: 0.23762
[WARN] true system low soc threshold exceeded on i: 10 mission_id: 641
[INFO] forecasting degradation values: r_mu: -0.000183 q_mu: 13.734598 m_mu: 0.211924
[INFO] digital twin degradation parameters: 0.0005 13.7533 0.2128
[INFO] DigitalTwin selecting trajectory: <20> with path_time: 19.65 to explore constraint boundary < 18.57
[INFO] simulating digital twin on i 10, mission_id: 641
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0002 13.5647 0.2230
[INFO] simulating digital twin on i 10, mission_id: 641
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: -0.0000 12.9005 0.2288
[INFO] simulating digital twin on i 10, mission_id: 641
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0001 13.8441 0.2211
[INFO] simulating digital twin on i 10, mission_id: 641
[INFO] digital twin degradation parameters: 0.0001 13.8441 0.2211
[INFO] digital twin mean parameter values: R0 = 0.00020  Q = 13.52  Req = 0.22142  stop code counts: low_soc: 4 pos_
[WARN] digital twin low soc threshold exceeded on i: 10 mission_id: 641
[INFO] updating RUL from 18.57 to 17.08
[INFO] TrueSystem selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 17.08
[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: 642 rul_hat: 17.08 flight_time: 16.36 distance: 1218.69 R0: 0.00106 Q: 14.76 Req: 0.23267
[INFO] success on i: 11 mission_id: 642
[INFO] forecasting degradation values: r_mu: 0.000511 q_mu: 14.346059 m_mu: 0.232478
[INFO] digital twin degradation parameters: 0.0020 13.6455 0.2240
[INFO] DigitalTwin selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 17.08
[INFO] simulating digital twin on i 11, mission_id: 642
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0003 14.1268 0.2593
[INFO] simulating digital twin on i 11, mission_id: 642
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0003 13.4947 0.2605
[INFO] simulating digital twin on i 11, mission_id: 642
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0016 14.1624 0.2061
[INFO] simulating digital twin on i 11, mission_id: 642
[INFO] digital twin degradation parameters: 0.0016 14.1624 0.2061
[INFO] digital twin mean parameter values: R0 = 0.00107  Q = 13.86  Req = 0.23748  stop code counts: low_soc: 0 pos_
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[INFO] digital twin mission success on i: 11 mission_id: 642
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 17.08
[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
[INFO] i: 12 mission_id: 643 rul_hat: 17.08 flight_time: 14.83 distance: 1083.07 R0: 0.00147 Q: 14.66 Req: 0.25013
[INFO] success on i: 12 mission_id: 643
[INFO] forecasting degradation values: r_mu: 0.000562 q_mu: 14.557358 m_mu: 0.229635
[INFO] digital twin degradation parameters: 0.0009 13.5693 0.2133
[INFO] DigitalTwin selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 17.08
[INFO] simulating digital twin on i 12, mission_id: 643
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0003 14.5672 0.1774
[INFO] simulating digital twin on i 12, mission_id: 643
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0002 15.5389 0.2112
[INFO] simulating digital twin on i 12, mission_id: 643
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0014 14.8341 0.2291
[INFO] simulating digital twin on i 12, mission_id: 643
[INFO] digital twin degradation parameters: 0.0014 14.8341 0.2291
[INFO] digital twin mean parameter values: R0 = 0.00068  Q = 14.63  Req = 0.20776  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 12 mission_id: 643
[INFO] TrueSystem selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 17.08
[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: 644 rul_hat: 17.08 flight_time: 16.36 distance: 1218.58 R0: 0.00116 Q: 15.50 Req: 0.24466
[INFO] success on i: 13 mission_id: 644
[INFO] forecasting degradation values: r_mu: 0.001217 q_mu: 14.874292 m_mu: 0.247421
[INFO] digital twin degradation parameters: 0.0013 14.3016 0.2469
[INFO] DigitalTwin selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 17.08
[INFO] simulating digital twin on i 13, mission_id: 644
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0009 14.6899 0.2818
[INFO] simulating digital twin on i 13, mission_id: 644
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: -0.0008 16.6133 0.2532
[INFO] simulating digital twin on i 13, mission_id: 644
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0021 13.5762 0.2374
[INFO] simulating digital twin on i 13, mission_id: 644
[INFO] digital twin degradation parameters: 0.0021 13.5762 0.2374
[INFO] digital twin mean parameter values: R0 = 0.00087  Q = 14.80  Req = 0.25482  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 13 mission_id: 644
[INFO] TrueSystem selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 17.08
[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: 645 rul_hat: 17.08 flight_time: 13.94 distance: 1047.75 R0: 0.00020 Q: 15.20 Req: 0.22319
[INFO] success on i: 14 mission_id: 645
[INFO] forecasting degradation values: r_mu: 0.001365 q_mu: 14.986381 m_mu: 0.263424
[INFO] digital twin degradation parameters: 0.0014 15.4887 0.2689
[INFO] DigitalTwin selecting trajectory: <3> with path_time: 17.83 to explore constraint boundary < 17.08
[INFO] simulating digital twin on i 14, mission_id: 645
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0008 15.1843 0.2476
[INFO] simulating digital twin on i 14, mission_id: 645
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0002 15.6985 0.2634
[INFO] simulating digital twin on i 14, mission_id: 645
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0013 15.6879 0.2734
[INFO] simulating digital twin on i 14, mission_id: 645
[INFO] digital twin degradation parameters: 0.0013 15.6879 0.2734
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[INFO] digital twin mean parameter values: R0 = 0.00094  Q = 15.51  Req = 0.26333  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 14 mission_id: 645
[INFO] TrueSystem selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 17.08
[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: 646 rul_hat: 17.08 flight_time: 13.58 distance: 1020.86 R0: 0.00207 Q: 15.01 Req: 0.23263
[INFO] success on i: 15 mission_id: 646
[INFO] forecasting degradation values: r_mu: 0.001004 q_mu: 15.056590 m_mu: 0.235339
[INFO] digital twin degradation parameters: 0.0004 15.5000 0.2087
[INFO] DigitalTwin selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 17.08
[INFO] simulating digital twin on i 15, mission_id: 646
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0019 15.7115 0.2354
[INFO] simulating digital twin on i 15, mission_id: 646
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0009 13.1670 0.2449
[INFO] simulating digital twin on i 15, mission_id: 646
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: -0.0009 13.2939 0.2367
[INFO] simulating digital twin on i 15, mission_id: 646
[INFO] digital twin degradation parameters: -0.0009 13.2939 0.2367
[INFO] digital twin mean parameter values: R0 = 0.00060  Q = 14.42  Req = 0.23142  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 15 mission_id: 646
[INFO] TrueSystem selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 17.08
[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: 647 rul_hat: 17.08 flight_time: 13.58 distance: 1020.82 R0: 0.00186 Q: 15.46 Req: 0.23330
[INFO] success on i: 16 mission_id: 647
[INFO] forecasting degradation values: r_mu: 0.002213 q_mu: 15.080539 m_mu: 0.241944
[INFO] digital twin degradation parameters: 0.0026 15.1560 0.2554
[INFO] DigitalTwin selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 17.08
[INFO] simulating digital twin on i 16, mission_id: 647
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0021 14.9701 0.2583
[INFO] simulating digital twin on i 16, mission_id: 647
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0004 14.7021 0.2213
[INFO] simulating digital twin on i 16, mission_id: 647
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0019 15.5670 0.2554
[INFO] simulating digital twin on i 16, mission_id: 647
[INFO] digital twin degradation parameters: 0.0019 15.5670 0.2554
[INFO] digital twin mean parameter values: R0 = 0.00175  Q = 15.10  Req = 0.24759  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 16 mission_id: 647
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 17.08
[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: 648 rul_hat: 17.08 flight_time: 14.83 distance: 1083.16 R0: 0.00142 Q: 14.58 Req: 0.24988
[INFO] success on i: 17 mission_id: 648
[INFO] forecasting degradation values: r_mu: 0.002699 q_mu: 16.442537 m_mu: 0.240352
[INFO] digital twin degradation parameters: 0.0030 15.5000 0.2375
[INFO] DigitalTwin selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 17.08
[INFO] simulating digital twin on i 17, mission_id: 648
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0022 15.5517 0.2363
[INFO] simulating digital twin on i 17, mission_id: 648
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0015 16.4271 0.2314
[INFO] simulating digital twin on i 17, mission_id: 648
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0045 17.2850 0.2004
[INFO] simulating digital twin on i 17, mission_id: 648
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[INFO] digital twin degradation parameters: 0.0045 17.2850 0.2004
[INFO] digital twin mean parameter values: R0 = 0.00281  Q = 16.19  Req = 0.22640  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 17 mission_id: 648
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 17.08
[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: 649 rul_hat: 17.08 flight_time: 14.83 distance: 1083.33 R0: 0.00111 Q: 14.91 Req: 0.25735
[INFO] success on i: 18 mission_id: 649
[INFO] forecasting degradation values: r_mu: 0.002128 q_mu: 15.111826 m_mu: 0.241108
[INFO] digital twin degradation parameters: 0.0019 15.5000 0.2335
[INFO] DigitalTwin selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 17.08
[INFO] simulating digital twin on i 18, mission_id: 649
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0022 15.7549 0.2462
[INFO] simulating digital twin on i 18, mission_id: 649
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0015 13.7939 0.2704
[INFO] simulating digital twin on i 18, mission_id: 649
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0016 15.1873 0.2500
[INFO] simulating digital twin on i 18, mission_id: 649
[INFO] digital twin degradation parameters: 0.0016 15.1873 0.2500
[INFO] digital twin mean parameter values: R0 = 0.00180  Q = 15.06  Req = 0.25002  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 18 mission_id: 649
[INFO] TrueSystem selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 17.08
[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: 650 rul_hat: 17.08 flight_time: 16.36 distance: 1218.55 R0: 0.00096 Q: 14.68 Req: 0.26903
[INFO] success on i: 19 mission_id: 650
[INFO] forecasting degradation values: r_mu: 0.001726 q_mu: 15.033124 m_mu: 0.253443
[INFO] digital twin degradation parameters: 0.0010 15.5000 0.2582
[INFO] DigitalTwin selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 17.08
[INFO] simulating digital twin on i 19, mission_id: 650
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0015 14.9707 0.2307
[INFO] simulating digital twin on i 19, mission_id: 650
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0019 14.4411 0.2520
[INFO] simulating digital twin on i 19, mission_id: 650
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0020 14.3818 0.2490
[INFO] simulating digital twin on i 19, mission_id: 650
[INFO] digital twin degradation parameters: 0.0020 14.3818 0.2490
[INFO] digital twin mean parameter values: R0 = 0.00160  Q = 14.82  Req = 0.24746  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 19 mission_id: 650
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 17.08
[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: 651 rul_hat: 17.08 flight_time: 14.83 distance: 1083.72 R0: 0.00220 Q: 15.50 Req: 0.26127
[INFO] success on i: 20 mission_id: 651
[INFO] forecasting degradation values: r_mu: 0.000921 q_mu: 14.704837 m_mu: 0.267403
[INFO] digital twin degradation parameters: 0.0007 15.0092 0.2516
[INFO] DigitalTwin selecting trajectory: <3> with path_time: 17.83 to explore constraint boundary < 17.08
[INFO] simulating digital twin on i 20, mission_id: 651
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0016 14.0830 0.2723
[INFO] simulating digital twin on i 20, mission_id: 651
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0005 14.4837 0.2587
[INFO] simulating digital twin on i 20, mission_id: 651
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0001 14.0596 0.2642
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[INFO] simulating digital twin on i 20, mission_id: 651
[INFO] digital twin degradation parameters: 0.0001 14.0596 0.2642
[INFO] digital twin mean parameter values: R0 = 0.00070  Q = 14.41  Req = 0.26170  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 20 mission_id: 651
[INFO] TrueSystem selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 17.08
[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: 652 rul_hat: 17.08 flight_time: 13.94 distance: 1047.80 R0: 0.00129 Q: 15.23 Req: 0.25121
[INFO] success on i: 21 mission_id: 652
[INFO] forecasting degradation values: r_mu: 0.002161 q_mu: 15.224025 m_mu: 0.272709
[INFO] digital twin degradation parameters: 0.0026 14.1858 0.2574
[INFO] DigitalTwin selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 17.08
[INFO] simulating digital twin on i 21, mission_id: 652
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0031 15.0211 0.2916
[INFO] simulating digital twin on i 21, mission_id: 652
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0025 16.0459 0.2746
[INFO] simulating digital twin on i 21, mission_id: 652
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0016 14.1870 0.2750
[INFO] simulating digital twin on i 21, mission_id: 652
[INFO] digital twin degradation parameters: 0.0016 14.1870 0.2750
[INFO] digital twin mean parameter values: R0 = 0.00245  Q = 14.86  Req = 0.27467  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 21 mission_id: 652
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 17.08
[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: 653 rul_hat: 17.08 flight_time: 14.83 distance: 1083.47 R0: 0.00098 Q: 14.52 Req: 0.23153
[INFO] success on i: 22 mission_id: 653
[INFO] forecasting degradation values: r_mu: 0.000785 q_mu: 15.182107 m_mu: 0.265766
[INFO] digital twin degradation parameters: 0.0004 15.0574 0.2664
[INFO] DigitalTwin selecting trajectory: <10> with path_time: 13.57 that meets constraint: path_time < 17.08
[INFO] simulating digital twin on i 22, mission_id: 653
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0009 16.4338 0.2704
[INFO] simulating digital twin on i 22, mission_id: 653
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0022 14.6832 0.2735
[INFO] simulating digital twin on i 22, mission_id: 653
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0006 15.5962 0.2745
[INFO] simulating digital twin on i 22, mission_id: 653
[INFO] digital twin degradation parameters: 0.0006 15.5962 0.2745
[INFO] digital twin mean parameter values: R0 = 0.00101  Q = 15.44  Req = 0.27122  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 22 mission_id: 653
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 17.08
[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: 654 rul_hat: 17.08 flight_time: 14.83 distance: 1083.30 R0: 0.00031 Q: 14.99 Req: 0.26956
[INFO] success on i: 23 mission_id: 654
[INFO] forecasting degradation values: r_mu: 0.000698 q_mu: 14.592404 m_mu: 0.255911
[INFO] digital twin degradation parameters: 0.0004 15.1448 0.2638
[INFO] DigitalTwin selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 17.08
[INFO] simulating digital twin on i 23, mission_id: 654
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0001 15.6235 0.2554
[INFO] simulating digital twin on i 23, mission_id: 654
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0020 14.3034 0.2645
[INFO] simulating digital twin on i 23, mission_id: 654
[INFO] resampling for twin run # 4
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[INFO] digital twin degradation parameters: 0.0006 13.2175 0.2417
[INFO] simulating digital twin on i 23, mission_id: 654
[INFO] digital twin degradation parameters: 0.0006 13.2175 0.2417
[INFO] digital twin mean parameter values: R0 = 0.00079  Q = 14.57  Req = 0.25635  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 23 mission_id: 654
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 17.08
[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: 655 rul_hat: 17.08 flight_time: 14.83 distance: 1083.63 R0: 0.00059 Q: 14.28 Req: 0.25235
[INFO] success on i: 24 mission_id: 655
[INFO] forecasting degradation values: r_mu: 0.000806 q_mu: 14.809688 m_mu: 0.286992
[INFO] digital twin degradation parameters: 0.0001 15.4629 0.2779
[INFO] DigitalTwin selecting trajectory: <6> with path_time: 18.81 to explore constraint boundary < 17.08
[INFO] simulating digital twin on i 24, mission_id: 655
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0010 13.7906 0.2767
[INFO] simulating digital twin on i 24, mission_id: 655
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0003 15.0786 0.3004
[INFO] simulating digital twin on i 24, mission_id: 655
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0010 14.5597 0.2986
[INFO] simulating digital twin on i 24, mission_id: 655
[INFO] digital twin degradation parameters: 0.0010 14.5597 0.2986
[INFO] digital twin mean parameter values: R0 = 0.00061  Q = 14.72  Req = 0.28839  stop code counts: low_soc: 1 pos_
[INFO] digital twin mission success on i: 24 mission_id: 655
[INFO] new RUL update is available, 17.69 replaces 17.08
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 17.69
[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: 656 rul_hat: 17.69 flight_time: 14.83 distance: 1083.41 R0: 0.00192 Q: 14.95 Req: 0.23552
[INFO] success on i: 25 mission_id: 656
[INFO] forecasting degradation values: r_mu: 0.000076 q_mu: 14.455519 m_mu: 0.265071
[INFO] digital twin degradation parameters: 0.0007 14.0218 0.2566
[INFO] DigitalTwin selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 17.69
[INFO] simulating digital twin on i 25, mission_id: 656
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: -0.0000 14.8485 0.2797
[INFO] simulating digital twin on i 25, mission_id: 656
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: -0.0001 14.6718 0.2617
[INFO] simulating digital twin on i 25, mission_id: 656
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0003 14.7459 0.2564
[INFO] simulating digital twin on i 25, mission_id: 656
[INFO] digital twin degradation parameters: 0.0003 14.7459 0.2564
[INFO] digital twin mean parameter values: R0 = 0.00020  Q = 14.57  Req = 0.26363  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 25 mission_id: 656
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 17.69
[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: 657 rul_hat: 17.69 flight_time: 14.83 distance: 1083.37 R0: 0.00158 Q: 15.50 Req: 0.24152
[INFO] success on i: 26 mission_id: 657
[INFO] forecasting degradation values: r_mu: 0.000817 q_mu: 14.555128 m_mu: 0.250420
[INFO] digital twin degradation parameters: 0.0003 13.4177 0.2629
[INFO] DigitalTwin selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 17.69
[INFO] simulating digital twin on i 26, mission_id: 657
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0015 14.6745 0.2544
[INFO] simulating digital twin on i 26, mission_id: 657
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0009 14.8411 0.2518
```

```
[INFO] simulating digital twin on i 26, mission_id: 657
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0029 13.7968 0.2249
[INFO] simulating digital twin on i 26, mission_id: 657
[INFO] digital twin degradation parameters: 0.0029 13.7968 0.2249
[INFO] digital twin mean parameter values: R0 = 0.00139  Q = 14.18  Req = 0.24852  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 26 mission_id: 657
[INFO] TrueSystem selecting trajectory: <15> with path_time: 17.63 that meets constraint: path_time < 17.69
[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: 658 rul_hat: 17.69 flight_time: 17.64 distance: 1283.77 R0: 0.00122 Q: 14.54 Req: 0.24749
[INFO] success on i: 27 mission_id: 658
[INFO] forecasting degradation values: r_mu: 0.001206 q_mu: 15.216962 m_mu: 0.241653
[INFO] digital twin degradation parameters: 0.0016 15.4661 0.2518
[INFO] DigitalTwin selecting trajectory: <6> with path_time: 18.81 to explore constraint boundary < 17.69
[INFO] simulating digital twin on i 27, mission_id: 658
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0003 13.7264 0.2538
[INFO] simulating digital twin on i 27, mission_id: 658
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: -0.0002 15.2597 0.2421
[INFO] simulating digital twin on i 27, mission_id: 658
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0029 15.1727 0.2348
[INFO] simulating digital twin on i 27, mission_id: 658
[INFO] digital twin degradation parameters: 0.0029 15.1727 0.2348
[INFO] digital twin mean parameter values: R0 = 0.00114  Q = 14.91  Req = 0.24564  stop code counts: low_soc: 1 pos_
[INFO] digital twin mission success on i: 27 mission_id: 658
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 17.69
[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: 659 rul_hat: 17.69 flight_time: 14.83 distance: 1083.29 R0: 0.00162 Q: 14.25 Req: 0.23480
[INFO] success on i: 28 mission_id: 659
[INFO] forecasting degradation values: r_mu: 0.001306 q_mu: 14.757533 m_mu: 0.238549
[INFO] digital twin degradation parameters: 0.0015 13.9115 0.2249
[INFO] DigitalTwin selecting trajectory: <15> with path_time: 17.63 that meets constraint: path_time < 17.69
[INFO] simulating digital twin on i 28, mission_id: 659
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0012 15.3244 0.2346
[INFO] simulating digital twin on i 28, mission_id: 659
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0021 14.5401 0.2520
[INFO] simulating digital twin on i 28, mission_id: 659
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0018 14.6233 0.2271
[INFO] simulating digital twin on i 28, mission_id: 659
[INFO] digital twin degradation parameters: 0.0018 14.6233 0.2271
[INFO] digital twin mean parameter values: R0 = 0.00164  Q = 14.60  Req = 0.23462  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 28 mission_id: 659
[INFO] TrueSystem selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 17.69
[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: 660 rul_hat: 17.69 flight_time: 16.36 distance: 1218.60 R0: 0.00129 Q: 14.37 Req: 0.26435
[INFO] success on i: 29 mission_id: 660
[INFO] forecasting degradation values: r_mu: 0.001530 q_mu: 14.349544 m_mu: 0.222604
[INFO] digital twin degradation parameters: 0.0013 15.0586 0.2157
[INFO] DigitalTwin selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 17.69
[INFO] simulating digital twin on i 29, mission_id: 660
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0017 14.9514 0.2172
[INFO] simulating digital twin on i 29, mission_id: 660
[INFO] resampling for twin run # 3
```

```
[INFO] digital twin degradation parameters: 0.0012 15.5916 0.2350
[INFO] simulating digital twin on i 29, mission_id: 660
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0012 14.7519 0.2179
[INFO] simulating digital twin on i 29, mission_id: 660
[INFO] digital twin degradation parameters: 0.0012 14.7519 0.2179
[INFO] digital twin mean parameter values: R0 = 0.00135  Q = 15.09  Req = 0.22145  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 29 mission_id: 660
[INFO] TrueSystem selecting trajectory: <6> with path_time: 18.81 to explore constraint boundary < 17.69
[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: 661 rul_hat: 17.69 flight_time: 18.77 distance: 1386.88 R0: 0.00050 Q: 15.23 Req: 0.27072
[INFO] success on i: 30 mission_id: 661
[INFO] forecasting degradation values: r_mu: 0.001263 q_mu: 13.992178 m_mu: 0.245812
[INFO] digital twin degradation parameters: 0.0013 15.0574 0.2478
[INFO] DigitalTwin selecting trajectory: <15> with path_time: 17.63 that meets constraint: path_time < 17.69
[INFO] simulating digital twin on i 30, mission_id: 661
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0010 14.4274 0.2499
[INFO] simulating digital twin on i 30, mission_id: 661
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0016 13.6402 0.2476
[INFO] simulating digital twin on i 30, mission_id: 661
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0001 13.5285 0.2354
[INFO] simulating digital twin on i 30, mission_id: 661
[INFO] digital twin degradation parameters: 0.0001 13.5285 0.2354
[INFO] digital twin mean parameter values: R0 = 0.00099  Q = 14.16  Req = 0.24517  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 30 mission_id: 661
[INFO] TrueSystem selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 17.69
[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: 662 rul_hat: 17.69 flight_time: 16.36 distance: 1218.80 R0: 0.00086 Q: 14.58 Req: 0.24407
[INFO] success on i: 31 mission_id: 662
[INFO] forecasting degradation values: r_mu: 0.001199 q_mu: 14.641354 m_mu: 0.261076
[INFO] digital twin degradation parameters: 0.0007 15.1598 0.2625
[INFO] DigitalTwin selecting trajectory: <6> with path_time: 18.81 to explore constraint boundary < 17.69
[INFO] simulating digital twin on i 31, mission_id: 662
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0013 14.9719 0.2696
[INFO] simulating digital twin on i 31, mission_id: 662
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0020 14.9269 0.2787
[INFO] simulating digital twin on i 31, mission_id: 662
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0012 14.6126 0.2823
[INFO] simulating digital twin on i 31, mission_id: 662
[INFO] digital twin degradation parameters: 0.0012 14.6126 0.2823
[INFO] digital twin mean parameter values: R0 = 0.00132  Q = 14.92  Req = 0.27329  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 31 mission_id: 662
[INFO] new RUL update is available, 17.78 replaces 17.69
[INFO] TrueSystem selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 17.78
[INFO] simulating true system on i: 32
[INFO] updating degradation parameter variance on i: 32
[INFO] updating degradation parameter values via random sampling on i: 32
[INFO] i: 32 mission_id: 663 rul_hat: 17.78 flight_time: 16.36 distance: 1218.65 R0: 0.00235 Q: 14.66 Req: 0.27048
[INFO] success on i: 32 mission_id: 663
[INFO] forecasting degradation values: r_mu: 0.001204 q_mu: 14.617321 m_mu: 0.259826
[INFO] digital twin degradation parameters: 0.0019 14.7893 0.2503
[INFO] DigitalTwin selecting trajectory: <15> with path_time: 17.63 that meets constraint: path_time < 17.78
[INFO] simulating digital twin on i 32, mission_id: 663
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0014 15.0943 0.2624
```

```
[INFO] simulating digital twin on i 32, mission_id: 663
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0018 15.8203 0.2711
[INFO] simulating digital twin on i 32, mission_id: 663
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0014 14.9959 0.2650
[INFO] simulating digital twin on i 32, mission_id: 663
[INFO] digital twin degradation parameters: 0.0014 14.9959 0.2650
[INFO] digital twin mean parameter values: R0 = 0.00162  Q = 15.17  Req = 0.26223  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 32 mission_id: 663
[INFO] TrueSystem selecting trajectory: <15> with path_time: 17.63 that meets constraint: path_time < 17.78
[INFO] simulating true system on i: 33
[INFO] updating degradation parameter variance on i: 33
[INFO] updating degradation parameter values via random sampling on i: 33
[INFO] i: 33 mission_id: 664 rul_hat: 17.78 flight_time: 17.64 distance: 1283.96 R0: 0.00258 Q: 14.53 Req: 0.26084
[INFO] success on i: 33 mission_id: 664
[INFO] forecasting degradation values: r_mu: 0.002036 q_mu: 14.470837 m_mu: 0.266846
[INFO] digital twin degradation parameters: 0.0014 14.5083 0.2740
[INFO] DigitalTwin selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 17.78
[INFO] simulating digital twin on i 33, mission_id: 664
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0019 13.9259 0.2664
[INFO] simulating digital twin on i 33, mission_id: 664
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0007 13.2366 0.2527
[INFO] simulating digital twin on i 33, mission_id: 664
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0014 13.7905 0.2461
[INFO] simulating digital twin on i 33, mission_id: 664
[INFO] digital twin degradation parameters: 0.0014 13.7905 0.2461
[INFO] digital twin mean parameter values: R0 = 0.00134  Q = 13.87  Req = 0.25983  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 33 mission_id: 664
[INFO] TrueSystem selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 17.78
[INFO] simulating true system on i: 34
[INFO] updating degradation parameter variance on i: 34
[INFO] updating degradation parameter values via random sampling on i: 34
[INFO] i: 34 mission_id: 665 rul_hat: 17.78 flight_time: 16.36 distance: 1218.73 R0: 0.00187 Q: 14.98 Req: 0.25440
[INFO] success on i: 34 mission_id: 665
[INFO] forecasting degradation values: r_mu: 0.002346 q_mu: 14.579510 m_mu: 0.275015
[INFO] digital twin degradation parameters: 0.0024 14.3640 0.2576
[INFO] DigitalTwin selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 17.78
[INFO] simulating digital twin on i 34, mission_id: 665
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0035 14.3343 0.2559
[INFO] simulating digital twin on i 34, mission_id: 665
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0025 14.7940 0.2723
[INFO] simulating digital twin on i 34, mission_id: 665
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0016 15.7334 0.2473
[INFO] simulating digital twin on i 34, mission_id: 665
[INFO] digital twin degradation parameters: 0.0016 15.7334 0.2473
[INFO] digital twin mean parameter values: R0 = 0.00249  Q = 14.81  Req = 0.25828  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 34 mission_id: 665
[INFO] TrueSystem selecting trajectory: <15> with path_time: 17.63 that meets constraint: path_time < 17.78
[INFO] simulating true system on i: 35
[INFO] updating degradation parameter variance on i: 35
[INFO] updating degradation parameter values via random sampling on i: 35
[INFO] i: 35 mission_id: 666 rul_hat: 17.78 flight_time: 17.64 distance: 1283.81 R0: 0.00142 Q: 14.69 Req: 0.25660
[INFO] success on i: 35 mission_id: 666
[INFO] forecasting degradation values: r_mu: 0.002009 q_mu: 14.593859 m_mu: 0.276154
[INFO] digital twin degradation parameters: 0.0015 15.0290 0.2833
[INFO] DigitalTwin selecting trajectory: <15> with path_time: 17.63 that meets constraint: path_time < 17.78
[INFO] simulating digital twin on i 35, mission_id: 666
[INFO] resampling for twin run # 2
```

```
[INFO] digital twin degradation parameters: 0.0027 14.9639 0.3050
[INFO] simulating digital twin on i 35, mission_id: 666
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0027 15.2417 0.2768
[INFO] simulating digital twin on i 35, mission_id: 666
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0012 14.3860 0.2674
[INFO] simulating digital twin on i 35, mission_id: 666
[INFO] digital twin degradation parameters: 0.0012 14.3860 0.2674
[INFO] digital twin mean parameter values: R0 = 0.00203  Q = 14.91  Req = 0.28313  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 35 mission_id: 666
[INFO] TrueSystem selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 17.78
[INFO] simulating true system on i: 36
[INFO] updating degradation parameter variance on i: 36
[INFO] updating degradation parameter values via random sampling on i: 36
[INFO] i: 36 mission_id: 667 rul_hat: 17.78 flight_time: 13.94 distance: 1047.88 R0: 0.00152 Q: 14.01 Req: 0.25099
[INFO] success on i: 36 mission_id: 667
[INFO] forecasting degradation values: r_mu: 0.002034 q_mu: 14.559920 m_mu: 0.273096
[INFO] digital twin degradation parameters: 0.0019 14.7851 0.2624
[INFO] DigitalTwin selecting trajectory: <6> with path_time: 18.81 to explore constraint boundary < 17.78
[INFO] simulating digital twin on i 36, mission_id: 667
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0029 14.4427 0.2716
[INFO] simulating digital twin on i 36, mission_id: 667
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0013 13.7980 0.2766
[INFO] simulating digital twin on i 36, mission_id: 667
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0019 14.8370 0.2631
[INFO] simulating digital twin on i 36, mission_id: 667
[INFO] digital twin degradation parameters: 0.0019 14.8370 0.2631
[INFO] digital twin mean parameter values: R0 = 0.00199  Q = 14.47  Req = 0.26840  stop code counts: low_soc: 1 pos_
[INFO] digital twin mission success on i: 36 mission_id: 667
[INFO] TrueSystem selecting trajectory: <6> with path_time: 18.81 to explore constraint boundary < 17.78
[INFO] simulating true system on i: 37
[INFO] updating degradation parameter variance on i: 37
[INFO] updating degradation parameter values via random sampling on i: 37
[INFO] i: 37 mission_id: 668 rul_hat: 17.78 flight_time: 18.38 distance: 1341.73 R0: 0.00260 Q: 14.36 Req: 0.25440
[WARN] true system low soc threshold exceeded on i: 37 mission_id: 668
[INFO] forecasting degradation values: r_mu: 0.002086 q_mu: 14.504974 m_mu: 0.261496
[INFO] digital twin degradation parameters: 0.0025 14.8051 0.2492
[INFO] DigitalTwin selecting trajectory: <11> with path_time: 16.38 that meets constraint: path_time < 17.78
[INFO] simulating digital twin on i 37, mission_id: 668
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0012 14.5371 0.2570
[INFO] simulating digital twin on i 37, mission_id: 668
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0019 13.7701 0.2701
[INFO] simulating digital twin on i 37, mission_id: 668
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0024 14.4566 0.2727
[INFO] simulating digital twin on i 37, mission_id: 668
[INFO] digital twin degradation parameters: 0.0024 14.4566 0.2727
[INFO] digital twin mean parameter values: R0 = 0.00198  Q = 14.39  Req = 0.26224  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 37 mission_id: 668
[INFO] TrueSystem selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 17.78
[INFO] simulating true system on i: 38
[INFO] updating degradation parameter variance on i: 38
[INFO] updating degradation parameter values via random sampling on i: 38
[INFO] i: 38 mission_id: 669 rul_hat: 17.78 flight_time: 14.83 distance: 1083.35 R0: 0.00220 Q: 14.65 Req: 0.24895
[INFO] success on i: 38 mission_id: 669
[INFO] forecasting degradation values: r_mu: 0.002614 q_mu: 14.472869 m_mu: 0.258719
[INFO] digital twin degradation parameters: 0.0028 14.2000 0.2491
[INFO] DigitalTwin selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 17.78
[INFO] simulating digital twin on i 38, mission_id: 669
```

```
[INFO] resampling for twin run # 2
[INFO] digital twin degradation parameters: 0.0021 14.3812 0.2457
[INFO] simulating digital twin on i 38, mission_id: 669
[INFO] resampling for twin run # 3
[INFO] digital twin degradation parameters: 0.0024 12.7599 0.2470
[INFO] simulating digital twin on i 38, mission_id: 669
[INFO] resampling for twin run # 4
[INFO] digital twin degradation parameters: 0.0017 13.9352 0.2564
[INFO] simulating digital twin on i 38, mission_id: 669
[INFO] digital twin degradation parameters: 0.0017 13.9352 0.2564
[INFO] digital twin mean parameter values: R0 = 0.00226  Q = 13.82  Req = 0.24957  stop code counts: low_soc: 0 pos_
[INFO] digital twin mission success on i: 38 mission_id: 669
[INFO] TrueSystem selecting trajectory: <13> with path_time: 13.94 that meets constraint: path_time < 17.78
[INFO] simulating true system on i: 39
[INFO] updating degradation parameter variance on i: 39
[INFO] updating degradation parameter values via random sampling on i: 39
[INFO] i: 39 mission_id: 670 rul_hat: 17.78 flight_time: 13.94 distance: 1047.89 R0: 0.00168 Q: 14.31 Req: 0.24091
Error using database.odbc.connection/sqlwrite (line 245)
ODBC Error: ODBC Driver Error: server closed the connection unexpectedly
 This probably means the server terminated abnormally
 before or while processing the request.
;
The connection has been lost.

Error in write_flight_data (line 31)
sqlwrite(conn, 'flight_sensor_tb', flight_sensor_tb);
```

********** 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
```

```
[INFO] forecasting degradation values: r_mu: 0.002878 q_mu: 14.474475 m_mu: 0.239971
```

```
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
```

```
[INFO] DigitalTwin selecting trajectory: <14> with path_time: 14.81 that meets constraint: path_time < 17.78
```

```
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)
    fprintf("[INFO] digital twin degradation parameters: %.4f\t%.4f\t%.4f", batterytwin.R0, bat
    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
end
```

```
[INFO] simulating digital twin on i 39, mission_id: 670
[INFO] digital twin degradation parameters: 0.0026 13.7787 0.2403
[INFO] resampling for twin run # 2
[INFO] simulating digital twin on i 39, mission_id: 670
[INFO] digital twin degradation parameters: 0.0024 13.6266 0.2553
[INFO] resampling for twin run # 3
[INFO] simulating digital twin on i 39, mission_id: 670
[INFO] digital twin degradation parameters: 0.0041 14.5371 0.2296
[INFO] resampling for twin run # 4
[INFO] simulating digital twin on i 39, mission_id: 670
[INFO] digital twin degradation parameters: 0.0036 14.1663 0.2350
```

```
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\t stop co
```

```
[INFO] digital twin mean parameter values: R0 = 0.00320  Q = 14.03  Req = 0.24005  stop code counts: low_soc: 0 pos_
```

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
```

```
[INFO] digital twin mission success on i: 39 mission_id: 670
```

```
% 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
```