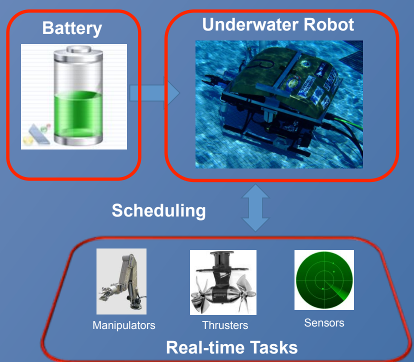
Battery Supported Cyber-physical Systems: A Robustness Perspective

Fumin Zhang, Zhenwu Shi, Shayok Mukhopadhyay and Marilyn Wolf

Objectives

- Schedule multiple tasks to meet real time control deadlines.
- Monitor perturbations online using dynamic schedulability test.
- Monitor battery status and switch battery before failure occurs.
- Establish metrics for comparing robustness of algorithms.



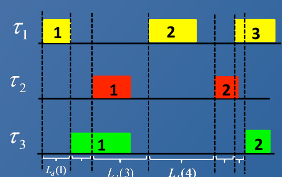
Goal:

Establish a Unified Theoretical Foundation for Robustness of CPS

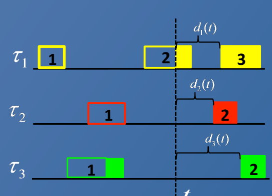
Dynamic Timing Model

Fixed Priority Window

- Decompose any time interval into consecutive fixed priority windows.
- Study the scheduled behavior within the fixed priority window $[t_d, t_d+L_d]$.



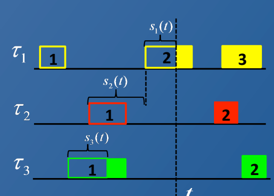
Dynamic Deadline



$$d_n(t_d) = d_n(t_d^-) + T_n(t_d)(1-\mathrm{sgn}(d_n(t_d^-)))$$

$$d_n(t) = d_n(t_d) - (t - t_d)$$

Spare Time



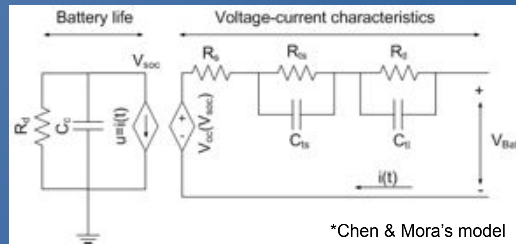
$$s_n(t_d) = s_n(t_d^-)\,\mathrm{sgn}(d_n(t_d))$$

$$s_n(t) = s_n(t_d) + \max\{0,\, t - t_d - \sum_{i\in I(n,t_d)-\{n\}} r_i(t_d)\}$$

where $r_i(t) = \max\{0, C_i(t) - s_i(t)\}$

Higher Priority Tasks

Battery dynamics



*Chen & Mora's model

Battery life ← $\dot{x}_1 = -\frac{1}{C_c} i$

Ah capacity

$$\dot{x}_2 = -\frac{x_2}{R_{ts}C_{ts}} + \frac{i}{C_{ts}}$$

Adaptive threshold

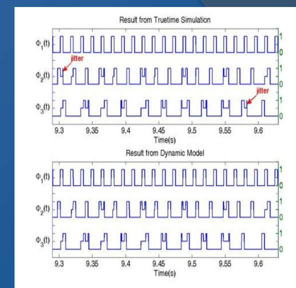
$$\dot{x}_3 = -\frac{x_3}{R_{tl}C_{tl}} + \frac{i}{C_{tl}}$$

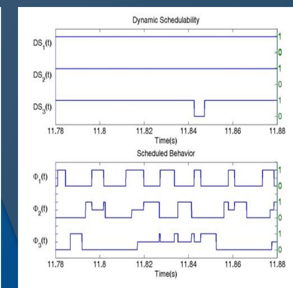
$$\beta = C_c\left(\frac{x_2}{C_{ts}} + \frac{x_3}{C_{tl}} - \frac{1}{i}\left(\frac{x_2^2}{R_{ts}C_{ts}} + \frac{x_3^2}{R_{tl}C_{tl}}\right)\right)$$

$$\delta_2 = \lambda_{max}(f(x_2, x_3))$$ → Current independent robustness limit.

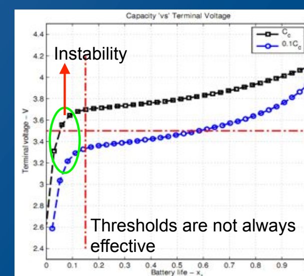
- Based on a state-space model for a Li-ion battery we obtain an adaptive threshold for switching out batteries.
- A limit is established to judge robustness of battery switching algorithms.
- R_{ts}, C_{ts}, R_{tl}, C_{tl} are all functions of x_1, ¯ > $\pm_2$ (So the threshold is robust).
- If x_1<¯, then V>0 (indicates instability), V is a Lyapunov like function.

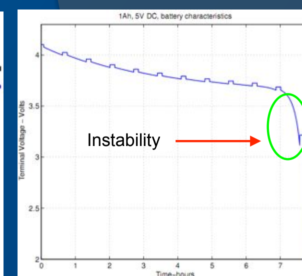
Model Verification



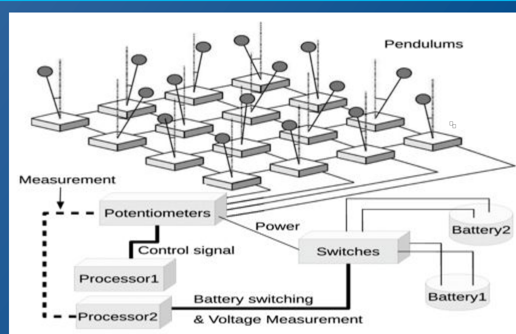


- $\Phi_n(t)=1$: task n is being executed;
- $\Phi_n(t)=0.5$: task n is being blocked;
- $\Phi_n(t)=0$: task n has finished.
- $DS_n(t)=1$: task n is schedulable;
- $DS_n(t)=0$: task n is unschedulable.

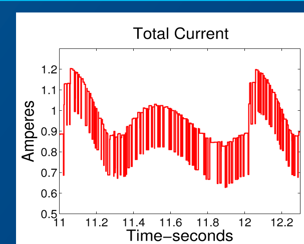




Application in the Cyber-physical System scenario



- Each pendulum is controlled by a permanent magnet DC motor.
- Processor 1 implements control based on real time tasks.
- Processor 2 implements the dynamic schedulability test and battery management algorithm.



Algorithm Type	DR	FAR	MDR
Voltage thresholding	40% 50%	60% 50%	0% 0%
Capacity thresholding	100% 70%	0% 30%	0% 50%
Adaptive thresholding	100% 100%	0% 0%	0% 0%

Our method has 0% false alarms.

DR = Detection rate
FAR = False alarm rate
MDR = Missed detection rate

The battery supplies currents to the following devices

- DC motors of each pendulum
- Processor 1
- Processor 2

We compare our adaptive battery switching strategy to fixed thresholding strategies based on capacity and voltage. For each test we use 10 different capacities of batteries

- Test 1: Multi-pendulum system.
- Test 2: Fixed loads.