Supplement of “Offline Guarantee and Online Management of Power Demand and Supply in Cyber-Physical Systems”

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I. Supplement of Section V

Lemma 1: $P^{\mathrm{s}}_{\mathtt{uni}}$ is at least as much as the minimum of $P^{\mathrm{s}}_{\mathrm{UC}}$ and $\sum_{\Gamma_i \in \Gamma'} \frac{P^{\mathrm{s}}_i \cdot L^{\mathrm{s}}_i}{T^{\mathrm{s}}_i}$, if Γ' satisfies Eq. (1).

$$\sum_{\Gamma_i \in \Gamma'} (T^{\mathrm{s}}_i - L^{\mathrm{s}}_i) \cdot \frac{P^{\mathrm{s}}_i \cdot L^{\mathrm{s}}_i}{T^{\mathrm{s}}_i} \leq P^{\mathrm{s}}_{\mathrm{UC}} \cdot L^{\mathrm{s}}_{\mathrm{UC}}. \quad (1)$$

We will explain how to find Γ' after the lemma.

Proof: Since Γ_{UC} can supply power at most P_{UC}, $P^{\mathrm{s}}_{\mathtt{uni}}$ should be no larger than P_{UC}. Otherwise, there should exist some Γ_i that always generate power, which is impossible because we cannot control when each Γ_i generates power.

While $\frac{P^{\mathrm{s}}_i \cdot L^{\mathrm{s}}_i}{T^{\mathrm{s}}_i}$ is the average rate of power generation by Γ_i, it cannot entirely contribute $P^{\mathrm{s}}_{\mathtt{uni}}$, because there is no power generation in $[0, T^{\mathrm{s}}_i - L^{\mathrm{s}}_i)$. To supply $\frac{P^{\mathrm{s}}_i \cdot L^{\mathrm{s}}_i}{T^{\mathrm{s}}_i}$-rate power in $[0, T^{\mathrm{s}}_i - L^{\mathrm{s}}_i)$, we need to use $(T^{\mathrm{s}}_i - L^{\mathrm{s}}_i) \cdot \frac{P^{\mathrm{s}}_i \cdot L^{\mathrm{s}}_i}{T^{\mathrm{s}}_i}$ amount of power from Γ_{UC}. Then, the generated energy from Γ_i in $[x \cdot T^{\mathrm{s}}_i - L^{\mathrm{s}}_i, x \cdot T^{\mathrm{s}}_i)$ (as much as $P^{\mathrm{s}}_i \cdot L^{\mathrm{s}}_i$) enables to supply $\frac{P^{\mathrm{s}}_i \cdot L^{\mathrm{s}}_i}{T^{\mathrm{s}}_i}$-rate power in $[x \cdot T^{\mathrm{s}}_i - L^{\mathrm{s}}_i, (x+1) \cdot T^{\mathrm{s}}_i - L^{\mathrm{s}}_i)$. Therefore, the LHS of Eq. (1) is an upper-bound of the amount of energy for every operation $\lambda_i \in \lambda'$ to contribute $\frac{P^{\mathrm{s}}_i \cdot L^{\mathrm{s}}_i}{T^{\mathrm{s}}_i}$ to $P^{\mathrm{s}}_{\mathtt{uni}}$.

Since the amount of power in Γ_{UC} at $t = 0$ is $P^{\mathrm{s}}_{\mathrm{UC}} \cdot L^{\mathrm{s}}_{\mathrm{UC}}$, we enforce the constraint Eq. (1). ■

To calculate $P^{\mathrm{s}}_{\mathtt{uni}}$ using Lemma 1, we introduce a heuristic to find Γ' that satisfies Eq. (1). Staring from $\Gamma' = \emptyset$, we repeat to add an operation in $\Gamma \setminus \Gamma'$ to Γ' until Eq. (1) is satisfied. Here, the order to be selected from $\Gamma \setminus \Gamma'$ is based on the following criteria (the larger value, the earlier selection):

$$\frac{\frac{P^{\mathrm{s}}_i \cdot L^{\mathrm{s}}_i}{T^{\mathrm{s}}_i}}{\frac{T^{\mathrm{s}}_i - L^{\mathrm{s}}_i}{T^{\mathrm{s}}_i} \cdot P^{\mathrm{s}}_i \cdot L^{\mathrm{s}}_i} = \frac{1}{T^{\mathrm{s}}_i - L^{\mathrm{s}}_i}. \quad (2)$$

We use the above criteria because the larger value of $\frac{1}{T^{\mathrm{s}}_i - L^{\mathrm{s}}_i}$ means the high contribution of $P^{\mathrm{s}}_{\mathtt{uni}}$ (i.e., denominator) per usage of $P^{\mathrm{s}}_{\mathrm{UC}} \cdot L^{\mathrm{s}}_{\mathrm{UC}}$ (i.e., numerator).

Lemma 2: Every instance of every operation $\lambda_k \in \lambda_{\mathtt{ded}}$ finishes its power execution at the end of each period (i.e., $[r + T^{\mathrm{d}}_k - L^{\mathrm{d}}_k, r + T^{\mathrm{d}}_k)$ where r is the release time of an instance of λ_k), only with Γ and Γ_{UC}, if the following inequality holds.

$$\sum_{\lambda_i \in \lambda^{\mathtt{ded}}} \frac{P^{\mathrm{d}}_i \cdot L^{\mathrm{d}}_i}{T^{\mathrm{d}}_i} \leq P^{\mathrm{s}}_{\mathtt{uni}} \text{ in Lemma 1.} \quad (3)$$

Proof: By the meaning of $P^{\mathrm{s}}_{\mathtt{uni}}$, Γ and Γ_{UC} can *always* supply $P^{\mathrm{s}}_{\mathtt{uni}}$-rate power. Since each operation $\lambda_k \in \lambda_{\mathtt{ded}}$ executes its instances at the end of their periods, their cumulative demand is always not larger than $P^{\mathrm{s}}_{\mathtt{uni}}$-rate power. Therefore, as long as their total demanded power rate (i.e., the LHS of Eq. (3)) is no larger than $P^{\mathrm{s}}_{\mathtt{uni}}$, every instance of every operation $\lambda_k \in \lambda_{\mathtt{ded}}$ finishes its execution within its period of length T^{d}_k, only with Γ and Γ_{UC}. ■

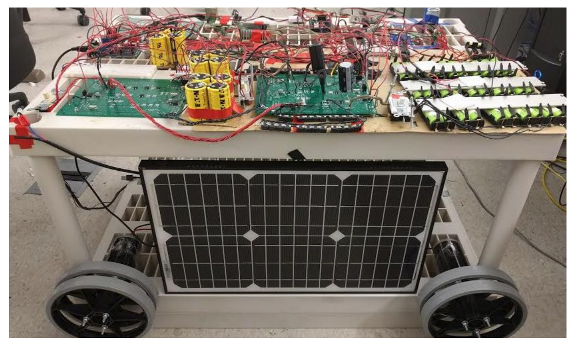

Fig. 1. Prototype implementation

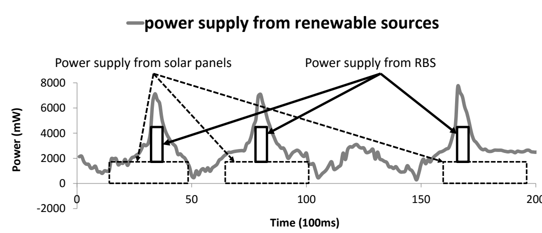

Fig. 2. An example that shows power supplies from renewable energy sources: based on the observation, solar panels' parameters can be $T^{\mathrm{s}}_x = 10$s, $P^{\mathrm{s}}_x = 1500$mW, $L^{\mathrm{s}}_x = 3.5$s, and RBS' parameters can be $T^{\mathrm{s}}_y = 20$s, $P^{\mathrm{s}}_y = 2000$mW, $L^{\mathrm{s}}_y = 0.5$s

II. Details of Prototype

To validate the proposed approaches, we built a prototype consisting of a battery-centric HESS and several sub-devices as seen in Fig. 1. NXP iMX6 board is used as our master board, and manages all sub-devices in the prototype. It schedules requested operations, actuates the sub-devices, and monitors the system's states. It communicates with other devices through its own CAN driver. Local Arduino controllers need CAN bus shield to communicate with other boards. Each controller has its own CAN ID to identify the messages' senders and receivers. The master board sends messages having receivers ID and control variables, and local controllers should send messages to inform their states. Whenever the master controller recognizes serious situations such as excessive chip temperature or battery malfunction, it has to take proper actions for system safety.

For device operations, we used three wheel motors which have 18W of maximum power, one auxiliary motor which has 5W of maximum power, and one stepper motor whose maximum power is 5W. A local controller needs motor drivers to regulate speed or position of the motors. Also, our motor drivers are equipped with a regenerative braking system which can generate power when the system decelerates. The master control board and battery temperature are controlled by thermal fins with heat spreaders. We used thermo-electric coolers (TEC) as the thermal fins for batteries and the master controller. A local controller determines thermal fins temperature and regulates control input (voltage level) of the TEC fins achieving the target temperature. We programmed two thermal applications for the master board's temperature and battery temperature. We used one thermal fin for master board temperature with 3W maximum power, and we used three thermal fins for batteries with 10W maximum power.

We deployed two solar panels on the prototype. One solar panel can generate 10W, and the other 25W at sunny day. However, its performance dropped largely at cloudy. We assumed the minimum power rate would be 1W for the small panel and 2W for the large one at our application environment. We used ultra capacitor pack for the energy buffer. Each ultra capacitor has 400F capacitance, 2.7V of rated-voltage and 26A of rated-current. Therefore, it can store 1,458J and 70 W of maximum power. We have 30 lithium-ion batteries that have 1400mAH (18,600 J) of energy capacity and 7.4W of power capability. We have to determine the number of battery cells to guarantee power capability for the power demand operations. We designed switched mode DC/DC converter to move energy between the UCs and battery cells. The converter is designed to be capable of moving current up to 20A at 30V. The converter controller must be cautious because surges of recharging current can damage the batteries.

We can identify parameters of renewable energy sources, as described in Fig. 2.

III. Additional Figures

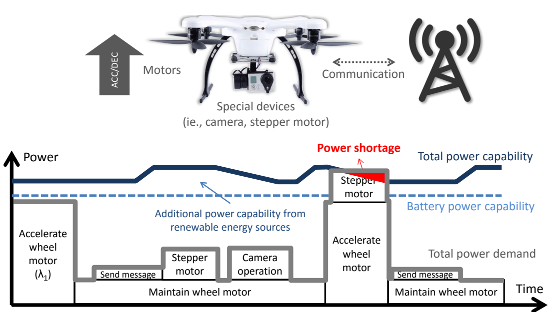

Fig. 3. The upper figure presents diverse power-demand mechanical/electrical operations for a drone, and the lower figure shows scheduling of power-demand operations on power-supply sources over time. If many power-demand operations are scheduled at the same time, the operations may suffer from insufficient power, which should be avoided.

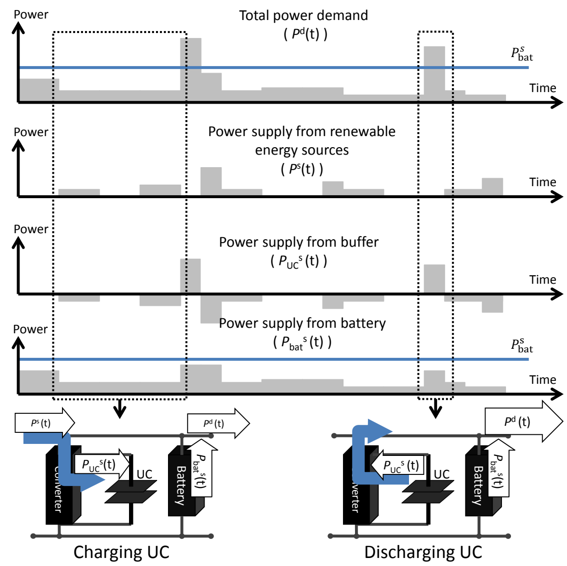

Fig. 4. An example of how an energy buffer works considering power demand: The energy buffer temporarily stores energy supplied from renewable sources when power demand is low, and helps powering operations when power demand is high with battery. Total power demand ($P^{\mathrm{d}}(t)$) must be the sum of power supply from renewable energy sources ($P^{\mathrm{s}}(t)$), energy buffer ($P^{\mathrm{s}}_{\mathtt{UC}}(t)$) and battery ($P^{\mathrm{s}}_{\mathtt{bat}}(t)$), yielding $P^{\mathrm{d}}(t) = P^{\mathrm{s}}(t) + P^{\mathrm{s}}_{\mathtt{UC}}(t) + P^{\mathrm{s}}_{\mathtt{bat}}(t)$. For reliability of batteries, battery power supply should be lower than its power capability ($P^{\mathrm{s}}_{\mathtt{bat}}$) to protect main energy storage.

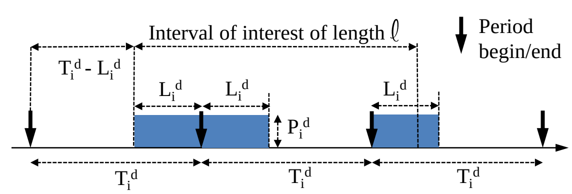

Fig. 5. An example of $W_i(\ell)$ with $N_i(\ell) = 2$

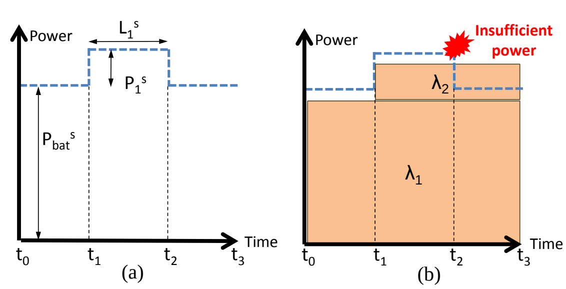

Fig. 6. An example that shows a scheduling challenge with additional sporadic power-supply sources