ABSTRACT

This paper presents a semi-empirical model for predicting capability and life span of small size Lithium ion battery packs. The model consists of a simple Battery Management System (BMS) model, an existing electro-thermal model as well as calendar and cycle aging models. In this work we aimed to realize both fast calculation and high flexibility by using a simplified thermal and cycle aging model with Rainflow method, a method usually used for evaluating material fatigue. This paper details the mathematical structure of the model. The methodology is applied to a LiCoO₂/carbon BB-2590 type battery pack utilized for small Unmanned Ground Vehicles. Moreover, simulation results of a capability test of an on-board battery, a 10 year calendar life test and a cycle test with 500 charging and discharging cycles are shown.

1. Introduction

Battery-driven small Unmanned Ground Vehicles (UGVs) are frequently used by the U.S. Army for missions such as explosive ordinance disposal, demining and surveillance. In these UGVs, power consumption is a paramount factor in limiting the mission length as well as robotic capability. Accordingly, maximization of usable capacity as well as reduced capacity and power fade are especially important for small UGV batteries. Current UGVs, such as the iRobot Packbot, typically utilize BB-2590 Li ion batteries instead of proprietary batteries in order to ease logistical concerns, save money and increase energy density over lead acid alternatives. The BB-2590 is a battery pack with 18650 cylindrical LiCoO₂/carbon cells which is quite widely utilized for man portable communication and information technology equipment within the U.S. Department of Defense. As this battery is primarily designed for man portable C4I equipment, use in robotic applications results in unique effects on battery life and performance due to different power profiles and usage environments from assumed original conditions. An effective approach for maximizing the useable capacity and life of the battery is development of a power and energy management strategy considering fundamental physical and chemical phenomena. One of the well-known methods for developing such strategies is utilizing semi-empirical models. However, existing strategies for small UGVs currently do not take into consideration these fundamental aspects. To develop such strategies, we made a semi-empirical model for small robotic batteries and simulated capacity, age and health under some typical situations.

The electric properties and thermal characteristics of individual batteries affect capability and life of battery system. However, it is difficult to depict the whole effect due to complexity of physical and chemical mechanisms. In order to predict and real-time estimate capability and life of Li ion battery cells, many semi-empirical battery models have been described in literature over the last decade [1]-[6]. However, reports for semi-empirical models for whole battery pack system life are sparse. Especially for cycle degradation, it is difficult to deal with arbitrary working situations because there are few methods for automatically counting cycles. In some of the literature [7], [8], one origin of the capacity and impedance degradation is the swelling and shrinking of active material particles due to intercalation and declaration of Li ions. Therefore, the model [7] included the Wöhler relationship, which is a popular relationship to describe
certain repeated stress or strain amplitude and number. Of the methods to express relationships between random strain profiles and material fatigue, the Rainflow method is one general method[9]. In this work, the Rainflow method was adapted to estimate cycle degradation of Li-ion batteries with arbitrary electro-thermal profiles. Another problem is a paradox between fidelity and calculation time. The model minimizes the number of ordinary differential equations and uses a simple heat dissipation model to realize short calculation times. Also, this model can express a battery system with a distribution of battery cell electric properties, capacities, impedance and leakage currents.

This paper proposes a systematic modeling and simulation methodology to easily predict the capability and prognosis for on-board small battery packs and shows simulation results of the model under various situations.

This paper is organized as follows. Section 2 introduces the mathematical approach used for the electro-thermal and aging models for small battery packs utilized in UGVs. Section 3 describes parameter acquisition for the BB2590 battery. Section 4 shows simulation data under some typical situation and discusses the usefulness of the methodology.

### 2. Electrical-thermal model and aging model

In this section, a combined electro-thermal and aging model is formulated for small battery packs with cylindrical battery cells. Physical specifications of these battery cells in a pack, which are leak electric current $I_{\text{leak}}$, Ohmic resistance $R_{\text{es}}$ and capacity of cells $C_{\text{CAP}}$ have distributions derived with manufacturing process. A battery pack composed of $n$ series connected super

<table>
<thead>
<tr>
<th>Nomenclature</th>
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<tbody>
<tr>
<td>$C$: capacitance [F]</td>
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<tr>
<td>$C'$: heat capacitance [JK$^{-1}$]</td>
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<tr>
<td>$CAP$: battery capacity [Ah]</td>
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<td>$E_0$: activation energy [J]</td>
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<tr>
<td>$F$: Faraday constant 96485 [Cmol$^{-1}$]</td>
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<tr>
<td>$I$: electric current [A]</td>
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<tr>
<td>$N$: number of battery cells in the battery pack</td>
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<tr>
<td>$P$: thermal resistance [KW$^{-1}$]</td>
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<tr>
<td>$R$: electric resistance [Ohm]</td>
</tr>
<tr>
<td>$R_{\text{uni}}$: universal gas constant 8.3145 [JK$^{-1}$mol$^{-1}$]</td>
</tr>
<tr>
<td>$SoC$: state of charge</td>
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<tr>
<td>$T$: temperature [K]</td>
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<tr>
<td>$T_v$: volume averaged temperature of the battery cell [K]</td>
</tr>
<tr>
<td>$T_k$: elapsed time by the end of $k$th peak or valley of $\Delta DOD + \phi C$ $- rate$ curve [sec]</td>
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<tr>
<td>$V$: voltage [V]</td>
</tr>
<tr>
<td>$W$: volume [m$^3$]</td>
</tr>
<tr>
<td>$c_p$: specific heat coefficient [J kg$^{-1}$K$^{-1}$]</td>
</tr>
<tr>
<td>$h$: Convection coefficient [Wm$^{-2}$K$^{-1}$]</td>
</tr>
<tr>
<td>$k$: Thermal conductivity [WmK$^{-2}$]</td>
</tr>
<tr>
<td>$q$: Joule heat [J]</td>
</tr>
<tr>
<td>$r$: radius of battery cell [m]</td>
</tr>
<tr>
<td>$t_{\text{iso}}$: Time between peak and valley of the $\Delta DOD + \phi C$ $- rate$ curve [sec]</td>
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<th>Greek characters</th>
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<tr>
<td>$\alpha$: differentiated $V_{oc}$ with respect to $SoC$ when time is $t$ [Vsec$^{-1}$]</td>
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<th>Subscripts</th>
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<tr>
<td>$\text{amb}$: ambient</td>
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<tr>
<td>$\text{cal}$: calendar fade</td>
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<tr>
<td>$cc$: center of the cell</td>
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<tr>
<td>$\text{cell}$: battery cell</td>
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<tr>
<td>$cyc$: cycle fade</td>
</tr>
<tr>
<td>$\text{leak}$: leak current</td>
</tr>
<tr>
<td>$\text{nominat}$: the value which used parameter acquisition</td>
</tr>
<tr>
<td>$oc$: open circuit</td>
</tr>
<tr>
<td>$pack$: battery pack</td>
</tr>
<tr>
<td>$sc$: surface of the cell</td>
</tr>
<tr>
<td>$sp$: surface of the pack</td>
</tr>
<tr>
<td>$\text{supercell}$: supercell</td>
</tr>
<tr>
<td>$t$: specific observing time</td>
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<tr>
<td>$zs$: Ohmic resistance content in equivalent circuit</td>
</tr>
<tr>
<td>$z1$: first RC content in equivalent circuit</td>
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<tr>
<td>$z2$: second RC content in equivalent circuit</td>
</tr>
<tr>
<td>$C$: capacity of a battery cell</td>
</tr>
<tr>
<td>$R$: Ohmic resistance components of equivalent circuit of a battery cell</td>
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cells with m parallel connected cells is shown in Figure 1. The terminal voltage is described by an equivalent circuit and three-state heat dissipation model which estimates temperature of battery cells’ cores and surfaces and the surface of a battery pack. As for the equivalent circuit, its components, resistance and capacitance, are varied by temperature of the battery cells’ core temperatures, state of charge (SoC) as well as calendar and cycle life factors. The calendar and cycle life factors are described by the model reported by Smith et al.[7]. However, to adapt the reported model to various situations containing arbitrary real-time electric signals, we added a c-rate factor and utilized the Rainflow method. The Rainflow method is a well-known method to estimate material fatigue with random stress.

2.1 Electrical model
The schematic of the equivalent circuit model is shown in Figure 2. The input signal to the model is electric current or voltage applied to a battery pack. The ohmic resistance of the circuit: R_{z2} can be expressed as a function of temperature of the battery cell. The center of the cell temperature T_{cc}(t) is utilized for representing value of the cell temperature. The other components of the circuit R_{z1}, C_{z1}, R_{z2} and C_{z2} shown in Figure 2 can be expressed as the function of SoC(t) and T_{cc}(t).

\[ V_{cc}(t) = R_{z2}I(t) \] (3)

The third term of Equation (1), the V_{z1} is described as

\[ \frac{dV_{z1}(t)}{dt} = \frac{1}{R_{z1}C_{z1}}V_{z1}(t) + \frac{1}{C_{z1}}I(t) \quad (l = 1 \text{ or } 2) \] (4)

where R_{z1}, C_{z1} are equivalent resistance and capacitance, respectively. These R_{z1}, C_{z1} values are fitted to a function of cell core temperature, T_{cc} and SoC[1]. Both T_{cc} and SoC are a function of time. If we prepare discrete data points for electric current I(t), V(t) can be represented by difference equations instead of ordinary differential equations to save computational resources. We approximated a random electric current by the summation of the step functions shown as follows.

\[ I_{cell}(t) = \sum_{k=-\infty}^{\infty} I_{cell,k} \Delta t = \sum_{k=-n}^{n} (I_{cell,k+n\Delta t} - I_{cell,(k-1)\Delta t})u(t - k\Delta t) \] (5)

where u(t) is the unit step function and t − n\Delta t is equal to 0. \Delta t is the time interval between discrete step. Next we explain the discrete expression of the cell voltage V_{cell}(t). Before establishing the difference equation of Equation (1), the discrete
SoC should be shown. The integrated discrete SoC is described by expanded Equation (2) as

\[ \text{SOC}_{\text{cell}}(t)_{\text{cell}} = \text{SOC}_{\text{cell},0} - \int_{0}^{t} \frac{1}{3600 \text{CAP}_{\text{cell}}} I_{\text{cell}}(\tau) \, d\tau \]

\[ \equiv \text{SOC}_{\text{cell},0} - \sum_{k=-n}^{0} \frac{1}{3600 \text{CAP}_{\text{cell}}} I_{\text{cell},k} \Delta t \quad (6) \]

Thus the difference equation of \( \text{SOC}_{\text{cell},t} \) is described as

\[ \text{SOC}_{\text{cell},t} = \alpha_t \text{SOC}_{\text{cell},t-1} - \frac{1}{3600 \text{CAP}_{\text{cell}}} I_{\text{cell},t} \Delta t \quad (7) \]

In the first term of Equation (1), \( V_{\text{oc}} \) is defined as

\[ V_{\text{oc}} \equiv \alpha_t \text{SOC}_{\text{cell},t} + V_{\text{oc,t-1}} \quad (8) \]

Inserting Equation (7) into Equation (8) makes the difference equation for \( V_{\text{oc},t} \), which is described as

\[ V_{\text{oc},t} = V_{\text{oc,t-1}} + \frac{\alpha_t}{3600 \text{CAP}_{\text{cell}}} I_{\text{cell},t} \Delta t \quad (9) \]

Where \( \alpha_t \) is the value of differentiated \( V_{\text{oc,t}} \) with respect to SoC. \( \alpha_t \) can analytically be obtained by Equation (38) in Section 3.1. By inserting Equation (5) into Equation (3), \( V_{\text{cell},t} \) can be found as follows.

\[ V_{\text{cell},t} = R_{\text{cell}} I_{\text{cell},t} \quad (10) \]

To describe \( V_{\text{el}} \) by difference function, we use Laplace transform and inverse Laplace transform as shown in the following calculations. The Laplace transform of Equation (4) is expressed as

\[ V_{\text{el}}(s) = \frac{1}{s \left( s + \frac{R_{\text{el}}}{R_{\text{cell}}} \right)} R_{\text{el}} I_{\text{cell}}(s) \quad (l = 1 \text{ or } 2) \quad (11) \]

By inserting the Laplace transform of Equation (5) into Equation (11), Equation (11) is expanded as

\[ V_{\text{el}}(s) = \sum_{k=-n}^{0} \frac{R_{\text{el}} C_{\text{el}} R_{\text{cell}}}{s \left( s + \frac{R_{\text{el}}}{R_{\text{cell}}} \right)} \frac{1}{R_{\text{cell}} I_{\text{cell}}(k \Delta t)} R_{\text{cell}} \left( I_{\text{cell},k} \right) \Delta t \quad (l = 1 \text{ or } 2) \quad (12) \]

Moreover, inverse Laplace transformation of Equation (12) is described as

\[ V_{\text{el}}(s) = \sum_{k=-n}^{0} \frac{R_{\text{el}} \Delta t}{s \left( s + \frac{R_{\text{el}}}{R_{\text{cell}}} \right)} \frac{1}{R_{\text{cell}} I_{\text{cell}}(k \Delta t)} \frac{1}{R_{\text{cell}} I_{\text{cell}}(k \Delta t)} \quad (l = 1 \text{ or } 2) \quad (13) \]

where \( \delta \) represents Kronecker delta. By expanding Equation (13) the difference equation of \( V_{\text{el},t} \) is obtained as

\[ V_{\text{el},t} = R_{\text{el}} \left( I_{\text{cell},t} \Delta t \right) \left( 1 - e^{-\frac{\Delta t}{R_{\text{el}} C_{\text{el}}}} \right) \]

\[ + e^{-\frac{\Delta t}{R_{\text{el}} C_{\text{el}}}} \left( 1 + e^{-\frac{\Delta t}{R_{\text{el}} C_{\text{el}}}} \right) \quad (l = 1 \text{ or } 2) \quad (14) \]

In Equation (14), \( R_{\text{el}}, \Delta \) and \( C_{\text{el}} \Delta \) are regarded as the same value of \( R_{\text{el}}, \Delta \) and \( C_{\text{el}} \Delta \), respectively. Thus, Equation (1) can be expanded by Equations (9), (10) and (14) as

\[ V_{\text{cell},t} = V_{\text{oc},t} + \alpha_t \text{SOC}_{\text{cell},t} \Delta t \]

\[ - R_{\text{el}} \left( I_{\text{cell},t} \right) \Delta t \]

\[ - \sum_{l=1}^{m} R_{\text{el}} \left( I_{\text{cell},t} \right) \Delta t \]

\[ + e^{-\frac{\Delta t}{R_{\text{el}} C_{\text{el}}}} \]

\[ \left[ 1 - e^{-\frac{\Delta t}{R_{\text{el}} C_{\text{el}}}} \right] \quad (l = 1 \text{ or } 2) \quad (15) \]

This equation shows the external voltage of a battery cell of the electric model.

As the next step, a battery pack composed of \( n \) series connected supercells with \( m \) parallel connected cells as shown in Figure 2 is considered. The BB-2590 is composed of eight series supercells which have three parallel cells. In this case, the relationship between the electric current and voltage of the battery pack, super cells and battery cells can be described as

\[ I_{\text{pack}} = \sum_{j=1}^{m} I_{\text{supercell},i} \quad (16a) \]

\[ V_{\text{pack}} = \sum_{j=1}^{n} V_{\text{supercell},i} \quad (16b) \]

\[ V_{\text{supercell},i} = V_{\text{cell},i} \quad (16c) \]

Where, \( I_{\text{pack}} \) is the input signal of the electrical model of a battery pack, \( V_{\text{pack}} \) is the voltage of the whole battery pack, \( I_{\text{supercell},i} \) and \( V_{\text{supercell},i} \) are the electric current and voltage of \( j \)th supercell, respectively. Next, the method to obtain electric current of each cells in a supercell is shown. The voltage of \( j \)th supercell can be described utilizing Equation (15) and Equations (16) by

\[ V_{ij} = V_{\text{supercell},i} = -A_{ij} I_{\text{cell},i} + B_{ij} \quad (17a) \]

\[ A_{ij} = \frac{\alpha_{ij}}{\text{CAP}_{\text{cell},i}} \Delta t + R_{\text{cell},i} \quad (17b) \]
\[ B_{ij} = V_{oc,ij} \Delta t - \sum_{l=1}^{2} R_{z,ij-l} \Delta t I_{cell,ij} \left( 1 - e^{-\frac{R_{z,ij-l} \Delta t}{\Delta t}} \right) + e^{-\frac{R_{z,ij-l} \Delta t}{\Delta t}} V_{z,ij-l} \Delta t \]  

\[
I_{cell,ij,t} = \frac{B_{ij} \sum_{l=1}^{m} \frac{1}{A_{ij,t-l}} + I_{pack,t} \sum_{l=1}^{m} \frac{B_{ij} \gamma_{l}}{A_{ij,t-l}}}{\sum_{l=1}^{m} \frac{1}{A_{ij,t-l}}} \quad (17) 
\]

The \( I_{cell,ij,t} \) can be expressed by expanded Equations (16) and (17) as

\[
I_{cell,ij,t} = \frac{B_{ij} \sum_{l=1}^{m} \frac{1}{A_{ij,t-l}} + I_{pack,t} \sum_{l=1}^{m} \frac{B_{ij} \gamma_{l}}{A_{ij,t-l}}}{\sum_{l=1}^{m} \frac{1}{A_{ij,t-l}}} \quad (18) 
\]

In Equations (17), \( I_{cell,ij,t} \) and all variables with subscripts \( t - \Delta t \) are known values at time \( t \). On the other hand, \( R_{z,i,j-l}, \alpha_{ij,t} \) are unknown values at time \( t \). Therefore, A self-consistent calculations between Equations (17) and (18) are conducted in this model. To calculate \( I_{cell,ij,t} \) of time \( t \), \( R_{z,i,j-l}, \alpha_{ij,t} \) are inserted in the Equation (17) instead of \( R_{0ij,t}, \alpha_{ij,t} \). Through Equations (7), (17) and (18), \( I_{cell,ij,t}, SoC_{cell,ij,t}, \alpha_{ij,t} \) and \( R_{z,i,j-l} \) are obtained. By inserting those obtained values into Equation (17) again and re-calculating Equations (17) and (18), a more accurate \( I_{ij,t} \) is obtained. As far as our conducted calculation, \( I_{cell,ij,t}, SoC_{cell,ij,t}, \alpha_{ij,t} \) and \( R_{z,i,j-l} \) are converged within 0.001% error in several recalculation. Moreover, the \( SoC_{super,cell,t} \) are defined as

\[
SoC_{super,cell,t} = SoC_{super,cell,t-l} - \sum_{l=1}^{m} I_{cell,ij,t-l} \Delta t \quad (19a) 
\]

\[
SoC_{pack,t} = \frac{\sum_{l=1}^{m} \left( SoC_{super,cell,t-l} \sum_{l=1}^{m} \frac{1}{A_{j,l}} \right)}{\sum_{l=1}^{m} \frac{1}{A_{j,l}}} \quad (19b) 
\]

Moreover, \( V_{pack,t} \) is obtained by Equation (16b). In the case where \( V_{pack,t} \) is the input signal, such as constant voltage charging mode, the values of \( V_{cell,ij,t} \) should be expressed by \( V_{pack,t} \). By expanding Equations (16) and (17), \( V_{pack,t} \) is expressed by

\[
I_{pack,t} = \sum_{l=1}^{m} I_{ij} = \sum_{l=1}^{m} \frac{B_{ij}}{A_{ij,t-l}} - V_{super,cell,t} \sum_{l=1}^{m} \frac{1}{A_{ij,t-l}} \quad (20) 
\]

By expanding Equations (16) and (20), \( V_{pack,t} \) is expressed by

\[
V_{pack,t} = \sum_{j=1}^{n} \frac{1}{m} V_{super,cell,j,t} = -I_{pack,t} \sum_{j=1}^{n} \frac{1}{m} \sum_{l=1}^{m} \frac{B_{ij}}{A_{ij,t-l}} \quad (21) 
\]

By inserting expanded Equation (18) to (21), \( I_{ij,t} \) is expressed by \( V_{pack,t}, A_{ij,t} \) and \( B_{ij} \) as

\[
I_{cell,ij,t} = \frac{B_{ij} \sum_{l=1}^{m} \frac{1}{A_{ij,t-l}} - I_{pack,t} \sum_{l=1}^{m} \frac{B_{ij} \gamma_{l}}{A_{ij,t-l}} V_{z,ij-l} \Delta t}{A_{ij,t} \sum_{l=1}^{m} \frac{1}{A_{ij,t-l}}} \quad (22) 
\]

So \( C_{super,cell,t} \), \( SoC_{pack,t} \) and \( V_{pack} \) are also obtained by Equations (19a), (19b) and (16a), respectively.

### 2.2 Thermal model

The thermal model of a cylindrical cell in a thermal chamber with evenly distributed heat generation, ignoring the thermal distribution along the positive-negative pole axis, can described as in Equation (23)[10].

\[
\frac{dx}{dt} = Ax + Bu 
\]

\[
y = Cx + D 
\]

where \( x = [\hat{T} \ \hat{y}]^T \), \( u = [q \ T_{sp}]^T \) and \( y = [T_{cc} \ T_{sc} \ T_{sp}]^T \) are system status, input and output respectively. \( T_{cc} \), \( T_{sc} \) and \( T_{sp} \) are the temperature of center, surface of a battery cell and the surface of a battery pack. System matrix \( A, B, C \) and \( D \) can be defined as

\[
A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} 
\]

\[
B = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} 
\]

\[
C = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} 
\]

\[
D = \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix} 
\]

where \( r \) and \( W_{cell} \) are radius and volume of the battery cell and \( k_t \) is the radial direction thermal conductivity of the cell.
Where \( h \) shows the heat transfer coefficient, in case a battery cell is bared ambient air. However, the value should be changed in this model because the battery cells are surrounded by battery pack housing and the distance between of housing and battery cells are as short as several millimeters. Therefore the heat conduction between battery cells and pack surface are considered to decide the \( h \) value. The generated heat \( q \) is a byproduct of the chemical reaction occurring in the jelly roll and Joule heat at the electrode during battery operation. The \( q \) is defined by the electric model as

\[
q \equiv V_{cell}' + \frac{V_z^2}{R_{z1}} + \frac{V_z^2}{R_{z2}}
\]  

(25)

As for our model, in order to depict the battery pack heat dissipation, Equation (26) is added to Equations (23). The temperature of battery pack surface or \( T_{sp} \) can be defined as functions of \( T_{sc} \) and \( T_{amb} \):

\[
\frac{c_{pack}}{N} \frac{dT_{sp}}{dt} = \frac{T_{amb} - T_{sp}}{P_{pack}} + \frac{T_{sp} - T_{sc}}{P_{cell}}
\]  

(26)

where \( P_{pack} \) and \( P_{cell} \) shows the heat capacitance of the battery pack except for the battery cells, including the pack housing and BMS board. In addition \( N \) shows number of battery cells in a battery pack. This Equation indicates the approximation of generated heat from each cell dissipated to a specific area of the pack surface like a “window”, which area is equal to the total pack area divided by the number of cells in the pack. The \( T_{amb} \), ambient temperature, is one of the input signal of this model. This value can be replaced by a function such as a sinusoidal day and night temperature variation. \( T_{sc} \) is described by \( T_z \) and \( T_{sp} \) as

\[
T_{sc} = \frac{24k_t}{24k_t + rh} T_z + \frac{15r k_t}{2(24k_t + rh)} \bar{y} + \frac{rh}{24k_t + rh} T_{sp}
\]  

(27)

From Equations (26) and (27), the \( T_{sp} \) is describes as

\[
\frac{dT_{sp}}{dt} = e_1 \bar{T} + e_2 \bar{y} + e_3 T_{sp} + e_4 T_{amb}
\]  

(28a)

\[
e_1 = \frac{24Nk_t}{c_{pack}P_{cell}(24k_t + rh)}
\]  

(28b)

\[
e_2 = -\frac{15Nrk_t}{2c_{pack}P_{cell}(24k_t + rh)}
\]  

(28c)

\[
e_3 = \frac{N}{c_{pack}P_{pack}} \left( \frac{1}{P_{cell}} + \frac{1}{P_{cell}} \left( 1 - \frac{rh}{24k_t + rh} \right) \right)
\]  

(28d)

\[
e_4 = \frac{N}{c_{pack}P_{pack}}
\]  

(28e)

The battery pack thermal model is described by expanded Equations (23), (24) and (28) as

\[
\frac{dx}{dt} = A'x' + B'u'
\]  

(29a)

\[
y' = C'x' + D'
\]  

(29b)

where \( x' = [\bar{T} \: \bar{y} \: T_{sp}]^T \), \( u' = [\dot{q} \: 0 \: T_{amb}]^T \) and \( y' = [T_{cc} \: T_{sc} \: T_{sp}]^T \) are system status, input and output respectively. System matrix \( A' \), \( B' \), \( C' \) and \( D' \) can be defined as

\[
A' = \begin{bmatrix}
    a_{11} & a_{12} & b_{12} \\
    a_{21} & a_{22} & b_{22} \\
    e_1 & e_2 & e_3
\end{bmatrix}
\]  

(30a)

\[
B' = \begin{bmatrix}
    b_{11} \\
    0 \\
    0
\end{bmatrix}
\]  

(30b)

\[
C' = \begin{bmatrix}
    c_{11} & c_{12} & d_{12} \\
    c_{21} & c_{22} & d_{22} \\
    0 & 0 & 1
\end{bmatrix}
\]  

(30c)

\[D' = [0]
\]  

(30d)

The various \( T_{sp} \) values are obtained by Equations (30) for each cell. After \( T_{sp} \) values are calculated for all cells in each step, these values are averaged and the averaged values is used \( T_{sp} \) of next step. This averaging means the approximation that any part of battery pack housing have the exact the same temperature. To increase the fidelity of the model, cell to cell heat transportation needs to be considered. However, in the case of a small battery pack, the temperature distribution is relatively small [11] and the system, including cell to cell heat transportation, should be described as a set of ordinary differential equations. Therefore in order to achieve fast calculation, the temperature distribution in the battery pack and battery housing is regarded as negligible in this model.

### 2.3 Aging model

The aging model consists of both calendar and cycle aging models. The battery degradation model considered cell temperature, open circuit voltage: \( V_{oc} \), and depth of discharge: \( \Delta DOD \) was reported by Smith et al.[7],[12]. The remarkable point of their model is that both calendar and cycle fade as well as both capacity and impedance fade were expressed in one model. The impedance fade of the model is described as the sum of Li ion reduction due to SEI growth factor and active material site loss factors. Meanwhile, the capacity fade of this model is described as the maximum value of Li ion reduction or active material site loss. The stress factor of the battery cell’s temperature, \( V_{oc} \) and \( \Delta DOD \) is expressed by Arrhenius, Tafel and Wöhler dependence, respectively. Wöhler dependence is a kind of relationship utilized to describe material fatigue by cycle stresses [13]. The cycle number where the material is destroyed
is a function of stress amplitude. This dependence has been utilized to assess the potential for crack nucleation of active material particles due to ΔDOD [8]. The stress of active material surfaces is also affected by C-rate [14] and is related to capacity degradation by cycle tests [15]. Therefore effect of both ΔDOD and C-rate on cycle fade are unified in the one Wöhler dependence equation in this work. As mentioned in Section 2.1, the equivalent circuit of our model has three resistances and two capacitance. Therefore degradation of all components should be defined. As for calendar fade, it is reported that battery cells preserved 33 months without any measurement have very little defined. As for cycle fade, all components increase with increasing ohmic resistance[16]. Thus, calendar degradation except Rxx are ignored in this model. On the contrary, as for cycle fade, all components increase with increasing ohmic resistance[17][18]. Therefore, the Rxx degradation is defined by the results of cycle test and other components of the equivalent circuit are defined as a proportion of cycle degradation of Rxx. To deal with a battery pack which has Rxx and CAPcell distribution, the degradation amount of each cell should be defined as a proportion of the initial value or just adding functions of stress factors. According to the cycle life measurement of eight SONY 18650 cells [19], the increasing amount of impedance seems independent with different initial resistance values. Meanwhile, as for increase in the amount of capacity, the definition described in literature [7] which mentioned the reduction amount of capacity by cycle fade is a proportion of the initial amount of capacity is applied. Accordingly, the Rxx and CAPcell distribution of this model is defined as

\[ R_{xx}(t)_{ref} \equiv R_{xx} = R_{xx,0} + \theta_{ref,1} \frac{\theta_{voc,R1} t^2}{1 + \theta_{ref,2} \theta_{voc,R2} \Delta DOD - C_R V} \]

\[ CAP_{cell}(t)_{ref} \equiv CAP_{cell,t} = CAP_{cell,0} \left( 1 - \frac{1}{CAP_{cell,0, nominal}} \left( \theta_{ref,1} \theta_{voc,c1} t^2 + \theta_{ref,2} \theta_{voc,c2} \Delta DOD - C_R V \right) \right) \]

Where

\[ \theta_{voc,c1} = \exp \left( \frac{-E_{cell}}{R_{asg} \left( \frac{1}{T_{cc}} \frac{1}{T_{cc,ref}} \right)} \right) \] (l = R or C)

\[ \theta_{voc,c2} = \exp \left( \frac{\beta f \left( \frac{V_{oc}}{R_{asg}} - V_{oc,ref} \frac{1}{T_{cc}} \right)}{R_{asg} \left( \frac{1}{T_{cc}} \frac{1}{T_{cc,ref}} \right)} \right) \] (l = R1, R2, C1 or C2)

\[ \theta_{\Delta DOD - C} = \left( \frac{\Delta DOD_{ref} + C \ - rate_{t}}{\Delta DOD_{ref} - C \ - rate_{ref}} \right)^{\eta_1} \] (l = R or C)

where \( \theta_{voc,c} \) shows the Arrhenius dependence on cell temperature. In this model we use \( T_{cc} \) as representative value of the cell temperature. As the viewpoint of safer design, this is an appropriate value because the high temperature proceed to battery cell degradation. \( \theta_{ref,1} \) shows the Tafel dependence on \( V_{oc} \) and \( \theta_{\Delta DOD - C, l} \) shows the Wöhler dependence on ΔDOD and C-rate in one cycle. The relationship between ΔDOD and C-rate is described as a simple linear combination. In Equations (32) \( \theta_{ref,1}, E_{cell}, \beta f, \eta_1 \) and \( \phi_1 \) are fitting parameters, \( R_{asg} \) and \( F \) are the universal gas constant and Faraday constant, respectively. \( CAP_{cell, nominal} \) is the initial capacity of the cell which is used for parameter acquisition. \( V \) is the cycle number when time is \( t . T_{cc,ref}, V_{oc,ref}, \Delta DOD_{ref}, C \ - rate_{ref} \) and \( C \ - rate_{t} \) are arbitrary constants for convenience of calculation. As mentioned in Section 1, the value of ΔDOD and C-rate are strongly correlated with stress on active materials [8],[14]. In addition, the strain on active material particles monotonically increases with increasing stress [20],[21]. Therefore, the value of \( \Delta DOD + \phi_1 C \ - rate_{t} \) is regarded as a proportion of strain on the active material in this model. The Rainflow method [9],[22] which is a popular method to evaluate material damage by random stress from strain-elapsed time curves can be adapted to battery degradation estimation under this assumption. To adapt to a real-time arbitrary system, \( R_{xx,t} \) and \( CAP_{cell,t} \) can be expanded from Equations (33) and (34) as

\[ R_{xx,t} = R_{xx,0} + \psi_{cal,R,t} \psi_{cycle,t} \]

\[ CAP_{cell,t} = CAP_{cell,0} \left( 1 - \frac{1}{CAP_{cell,0, nominal}} (\psi_{cal,C,t} + \psi_{cycle,t}) \right) \]

where the values of \( \psi \) are the degradation amount of \( R_{xx,t} \) and \( CAP_{cell,t} \) by calendar factor and cycle factors. The calendar degradation factor are easily described as

\[ \psi_{cal,R,t} = \theta_{ref,1} \int_{0}^{t} \theta_{voc,R1} \frac{1}{V_{oc}} \frac{1}{\sqrt{2}} \frac{1}{\tau^2} d\tau \equiv \theta_{ref,1} \sum_{k=-(n-1)}^{1} \theta_{voc,R1 + \Delta \tau} \theta_{voc,R1 + \Delta \tau} \left( (t + k \tau) \right)^{2} \]

\[ - (t + (k - 1) \Delta \tau)^{2} \]

\[ \psi_{cal,C,t} = \theta_{ref,1} \int_{0}^{t} \theta_{voc,C1} \frac{1}{V_{oc}} \frac{1}{\sqrt{2}} \frac{1}{\tau^2} d\tau \equiv \theta_{ref,1} \sum_{k=-(n-1)}^{1} \theta_{voc,C1 + \Delta \tau} \theta_{voc,C1 + \Delta \tau} \left( (t + k \tau) \right)^{2} \]

\[ - (t + (k - 1) \Delta \tau)^{2} \]

Cycle degradation factors in Equations (34) are calculated by the algorithm of the Rainflow method. The flow chart of the algorithm is shown in Figure 3. The Rainflow list shown in Figure 3 is a kind of the look up table which records the essential information for cycle fade calculations. In addition, the algorithm have the Unchanged value: \( a_{uc} \) which is the cycle degradation value calculated by previous time step, the cycle degradation is expressed by the sum of \( a_{uc} \) and the value calculated by the Rainflow list. \( \theta_{\Delta DOD - C} \) and \( t_{pp} \) indicate the difference of ΔDOD + \phi_1 C \ - rate and time between peak to valley of time versus ΔDOD + \phi_1 C \ - rate curve. \( \theta_{voc} \) is the
normalized value of the $\theta_{\text{Voc,b}}$ or $\theta_{\text{Voc,c}}$ described as Equations (35).

\[
\overline{\theta}_{\text{Voc}} = \frac{1}{t_{p,k}} \int_{t_{p,k-1}}^{t_{p,k}} \theta_{\text{Voc}} \, dt \quad (35a)
\]

\[
T_k = \sum_{i=1}^{k} t_{p,i} \quad (35b)
\]

The model detects the inflection point of the $\Delta DOD + \phi_i C$ curve, $\theta_{\Delta DOD-c}$, $t_{pv}$ and $\theta_{\text{Voc}}$ are recorded at the top of the Rainflow list as $\theta_{\Delta DOD-c,0}$, $t_{pv0}$ and $\theta_{\text{Voc,0}}$.

The Rainflow list is reconstructed (Rainflow list reconstruction (a) in Figure 3) when the $\theta_{\Delta DOD-c}$ match two conditions as follows. The first condition is that $n_{\text{row}} \geq 3$ as well as $\theta_{\Delta DOD-c,0} \geq \theta_{\Delta DOD-c,1}$ and $\theta_{\Delta DOD-c,2} > \theta_{\Delta DOD-c,1}$. $\theta_{\Delta DOD-c,0}$ and $\theta_{\Delta DOD-c,2}$ are calculated by Equations (36). The subscript new shows the newest calculated values in the first row of the Rainflow list and Unchangeable values.

\[
\theta_{\Delta DOD-c,0,\text{new}} = \theta_{\Delta DOD-c,0} + \theta_{\Delta DOD-c,2} - \theta_{\Delta DOD-c,1} \quad (36a)
\]

\[
t_{pv0,\text{new}} = t_{pv,0} + t_{pv,1} + t_{pv,2} \quad (36b)
\]

\[
\theta_{\text{Voc,0,\text{new}}} = \theta_{\text{Voc,0}} \quad (36c)
\]

where $t_{p,k}$ is the time at the $k$th inflection point of time versus $\Delta DOD_i + \phi_i C$ curve. Moreover, the first 3 rows of the list are deleted and $\theta_{\text{ref}},\theta_{\text{Voc}},\theta_{\Delta DOD-c,i}$ is added to $a_{uc}$. If the reconstructed list have more than three rows, the model repeat the same process.

If the $n_{\text{row}} = 2$ as well as $\theta_{\Delta DOD-c,0} \geq \theta_{\Delta DOD-c,1}$, the Rainflow list is also reconstructed. The second row of the Rainflow list is deleted and $0.5\theta_{\text{ref}},\theta_{\text{Voc}},\theta_{\Delta DOD-c,1}$ is added to $a_{uc}$.

The other cases, the cycle degradation $\psi_{\text{cyc}}$ is expressed as

\[
\psi_{\text{cyc}} = \frac{1}{2} \sum_{i=1}^{n_{\text{row}}} \theta_{\text{Voc,0,\text{new}}} \theta_{\Delta DOD-c,i} + a_{uc} \quad (37)
\]

The value of $\psi_{\text{cyc}}$ is only renewed when the model detects the inflection point of the $\Delta DOD + \phi_i C$ curve, the other time steps, the value is the same as previous time step.

### 3 Parameter Acquisition

In this section, parameters acquisition for the model is presented. As for the electrical model, $V_{\text{oc}}$ and equivalent circuit components, which are as the functions of $SoC$ and temperature

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of the battery cell, is estimated by the fitting of reported test data for the 2.37Ah Molicel 18650 cells[23]. The thermal model parameters are estimated by material constants of Molicel 18650 cells [10] and the geometry of the BB-2590 battery pack. The parameters for the aging model are estimated by using 1.4Ah SONY 18650 cell data because they have the same LiCoO2/carbon chemistry and plenty of experimental data was reported[24]-[26].

3.1 Electrical and Thermal model

The function $V_{oc}(SoC)$ is estimated by SoC-$V_{oc}$ curve of 2.37Ah Molicel 18650 cells [23]. This curve is fitted by

$$V_{oc}(SoC) = K_0 + K_1 \frac{1}{1 + e^{L_1(SoC-M_1)}} + K_2 \frac{1}{1 + e^{L_2(SoC-M_2)}} + K_3 \frac{1}{1 + e^{L_3(SoC-M_3)}} + K_4 \frac{1}{1 + e^{L_4(SoC-M_4)}} + K_5 \frac{1}{1 + e^{L_5(SoC-M_5)}} + K_6 SoC$$

Equation (38) is based on the fitting formula reported by Weng et al [24]. The fitting result is shown as Figure 4. The seventh and eighth terms of Equation (38) is added to original formula to reduce fitting error of $V_{oc}$ especially near SoC = 0 and 1 area. The average and maximum fitting error is 4.5mV and 21mV, respectively.

The coefficients $K_1-5$, $L_1-6$, $M_1-4$, are obtained by the least-square method. The 6th and 7th term of this fitting curve are added.

The functions $R_{zz}(T_{cc})$, $R_{zz}(SoC,T_{cc})$, $R_{zz}(SoC,T_{ex})$, $C_{zz}(SoC,T_{ex})$, and $C_{zz}(SoC,T_{ex})$ are estimated by the product of resistance and capacitance versus SoC curve measured under various temperature[23]. The reported fitting function for a cylindrical battery [1] is adapted to use this estimation. The function is shown as Equations (39)

$$R_{zz} = R_{0,zz} \exp \left( \frac{T_{ref,zz} - T_{cc}}{T_{cc} - T_{ref,zz}} \right)$$

Equation (39a) is based on the fitting formula reported by Weng et al [24]. The fitting result is shown as Figure 4. The seventh and eighth terms of Equation (38) is added to original formula to reduce fitting error of $V_{oc}$ especially near SoC = 0 and 1 area. The average and maximum fitting error is 4.5mV and 21mV, respectively.

The coefficients $K_1-5$, $L_1-6$, $M_1-4$, are obtained by the least-square method. The 6th and 7th term of this fitting curve are added.

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$$R_{zz} = R_{0,zz} \exp \left( \frac{T_{ref,zz} - T_{cc}}{T_{cc} - T_{ref,zz}} \right)$$

Equation (39a) is based on the fitting formula reported by Weng et al [24]. The fitting result is shown as Figure 4. The seventh and eighth terms of Equation (38) is added to original formula to reduce fitting error of $V_{oc}$ especially near SoC = 0 and 1 area. The average and maximum fitting error is 4.5mV and 21mV, respectively.

The coefficients $K_1-5$, $L_1-6$, $M_1-4$, are obtained by the least-square method. The 6th and 7th term of this fitting curve are added.

The functions $R_{zz}(T_{cc})$, $R_{zz}(SoC,T_{cc})$, $R_{zz}(SoC,T_{ex})$, $C_{zz}(SoC,T_{ex})$, and $C_{zz}(SoC,T_{ex})$ are estimated by the product of resistance and capacitance versus SoC curve measured under various temperature[23]. The reported fitting function for a cylindrical battery [1] is adapted to use this estimation. The function is shown as Equations (39)
\[ R_{st} = (R_{0_{1,2}} + D_{1,2}SOC + D_{2,2}SOC^2) \exp \left( \frac{T_{ref_{1,2}}}{T_{cc}} T_{shift_{1,2}} \right) \quad (i = 1 \text{ or } 2) \]  

\[ C_{st} = (C_{0_{1,2}} + D_{3,2}SOC + D_{4,2}SOC^2) + (D_{5,2} + D_{6,2}SOC + D_{7,2}SOC^2)T_{cc} \quad (i = 1 \text{ or } 2) \]  

where \( T_{ref}, T_{shift}, R_0, C_0 \) and \( D_{1-7} \) are fitting parameters. The fitting results are shown in Figure 5(a), (b) and (c).

As for the thermal model, the parameters are defined in Table 1. In this work, we assumed the embedded batteries on the iRobot Pack-bot are as shown in Figure 6. As the picture shows, the battery is connected to power outlet by one smallest plain and fixed the chassis by the one largest plain. Therefore, the model has two thermal insulated walls and four air cooling surface. This means the generated heat from a battery cell can dissipate limited surface of the battery pack.

### 3.2 Aging model

The 1.4Ah SONY 18650 cells data [24]-[26] are fitted by equations (32) and (33). The fitted data is shown in Figure 7. The fitting for the calendar life curve partially agrees with the experimental data. However, the fitting for the cycle test data is less accurate. One possibility of this error is the lack of measurement and time information. Electrical measurements such as capacity measurement to the battery often affect the cycle degradation. Moreover the time interval between cycles causes calendar fade.
In this section, the results of the simulation model are demonstrated. In all simulation, $I_{\text{leak}}$, $R_z$, and $C_{\text{cell}}$ of cells have distributions. The average value of $I_{\text{leak}}$ is 0.0074 mA and the value have 1% distribution within 6σ. $R_z$ have also 1.3% distribution within 6σ. The average value of $C_{\text{cell}}$ is 2.37Ah and the value have 0.5% distribution within 3σ. These values are estimated by the experimental results and catalog specification.

In section 4.1, the voltage and temperature profiles are simulated under various $T_{\text{amb}}$ conditions. In section 4.2, the simulation results of simple calendar life and cycle life tests are shown.

### 4.1 Capability Simulation

The voltage profile of the on-board BB-2590 battery pack model under various $T_{\text{amb}}$ is shown in Figure 8. The model battery pack was brand-new before starting this simulation. The electrical current, which is the input data of this simulation, is measured by certain Pack-bot driving data on various terrains such as pea gravel, sand, crushed concrete, and hill. The pack SoC changes from 0.93 to 0.85 in this profile. The data seems appropriate qualitatively. For instance, the voltage drop amount increases with decreasing $T_{\text{amb}}$ due to high $R_z$ at low temperature as shown in Figure 5(a). Moreover, the peak of the voltage drop amount at around 1000 seconds of this profile decreases from 26V to 25V due to voltage drop of the RC pair in the equivalent circuit.

The voltage and temperature profiles of the battery pack and a typical cell are shown in Figure 9. These profiles seem reasonable. The increase in the rate of temperature by electric current increases with decreasing $T_{\text{amb}}$. In the case where $T_{\text{amb}}$ is low, the Joule heat from the battery increases due to high impedance. $T_{cc}$ and $T_{sc}$ values are very similar in this model. The heat conductivity of LiCoO$_2$ is as high as 3.4 W/K/m[27], fives times larger than the heat conductivity of LiFePO$_4$ [10]. Moreover, strictly speaking, the $T_{sc}$ value is not the real battery cell surface covered can or

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**Figure 8.** Calculated voltage profile of an on-board BB-2590 battery under various ambient temperature conditions.

**Figure 9.** Calculated temperature profile of an on-board BB-2590 battery pack and its typical battery cell under various ambient temperature conditions. (a) $T_{\text{amb}} = 45°C$; (b) $T_{\text{amb}} = 30°C$; (c) $T_{\text{amb}} = 15°C$; (d) $T_{\text{amb}} = 0°C$. 

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pack but the surface of the jelly roll. Accordingly, the $T_{cc}$ and $T_{zc}$ in the results of this simulation are the almost the same value.

4.2 Life span order simulation

The battery model utilized in the lifespan test also assumes an onboard BB-2590 battery pack reported in [19] and [28]. Both calculations are conducted under the simulated 15 °C ambient temperature. The resistance and capacity degradation in Figure 10 is much lower than Figure 7 because the ambient temperature of the calendar fade data shown in Figure 7 are conducted as high as 40, 50 and 60°C. The tendency of fade amount and tendency seems roughly reasonable. The distribution of cell capacity slightly decreases as time proceed from 0.238% to 0.224%. On the other hand, the distribution of cell capacity is almost the same as far as this simulation (<10⁻⁵% order). The total calculation time is as short as 58 hours. This calculation time is 0.07% of the real time.

The simulation results of cycle aging is shown as Figure 11. The total cycle number is 500 times and elapsed time is 250 days. A cycle consist of a two-hours “discharge phase” (2.6A discharging), and a ten-hours “CCCV phase” (charging under CC-CV program). The discharging current, 2.6A is the average of a robot operation on the various terrain [29]. During the CCCV phase, at first the battery pack is charged at 1A. When the battery pack voltage reaches 4.1V, electric current is decreased. At last, when the charging current reach 50mV, the current is turned off. The result of the simulation seems natural as well as calendar life data. The distribution of cell capacity slightly increases from 0.238% to 0.241% in 500 cycles. This tendency is opposite tendency compared with the calendar life simulation. The distribution of ohmic resistance decreases from 0.278% to 0.249%. The total calculation time is as short as 32 hours. This calculation time is 0.55% of the real time. Those simulation results have a room for improving by the measurement results of basic data such as HPPC or cycle test data under various conditions and should be validated by experimental data.

5. Conclusion

A semi-empirical model for predicting capability and life span of small size Li ion battery packs is established in this work. The model consists of a simple BMS model, existing electro-thermal model, and calendar and cycle aging models. Moreover the capability and life span data of BB-2590 battery packs which are embedded on the packbot were obtained. All simulation results seem reasonable and the calculation time is short enough to be real-time. The next step is evaluating the model using actual experimental data. Once the model is fully validated, the algorithm will be useful for design and development of small battery packs for UGVs.
References


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