An Intelligent BMS for Drone-Based Inspection of Offshore Wind Turbines

Denggao Huang
School of Energy and Electronic Engineering
University of Portsmouth
Portsmouth, UK
denggao.huang@port.ac.uk

Victor Becerra
School of Energy and Electronic Engineering
University of Portsmouth
Portsmouth, UK
victor.becerra@port.ac.uk

Hongjie Ma
School of Energy and Electronic Engineering
University of Portsmouth
Portsmouth, UK
hongjie.ma@port.ac.uk

Sarinova Simandjuntak
School of Mechanical and Design Engineering
University of Portsmouth
Portsmouth, UK
sarinova.simandjuntak@port.ac.uk

Alexander Fraess-Ehrfeld
AIRBORNE ROBOTICS Limited
London, UK
alex@airborne-robotics.com

***Abstract*—As they are agile and versatile flying platforms, drones can be very useful for inspecting infrastructure and can significantly improve the safety and efficiency of these tasks. The lithium-ion battery is very often used as the power source of multi-rotor drones, a fundamental and core component that is determinant for the success of flying tasks. Because of the properties of the chemical reactions in lithium-ion batteries, proper battery management is often required in many applications to assure the system's safety. However, drone battery management systems have drawn little attention from researchers so far. Given the complexities associated with the ageing process of the lithium-ion battery, the incorrect capacity estimation is likely to lead to the unnecessarily early replacement of batteries. This study proposes a practical, intelligent battery management system (i-BMS) for drone batteries. The system requirements, architecture, hardware, software and algorithmic aspects of i-BMS are illustrated. Considering the communication requirements of the flight controller and automatic charging platform, an Internet of Things module is combined in the proposed i-BMS, which can provide multiple communication protocols. An unscented Kalman filter algorithm was applied to each cell in the drone battery to reinforce the confidence of the state of charge and state of health estimation. Experiments were conducted to validate the proposed i-BMS. The proposed i-BMS can precisely monitor every cell and successfully estimate the state of charge (SOC) and state of health (SOH) of the battery.**

Keywords—Battery management system, drone, power management, SOC/SOH, unscented Kalman filter.

I. INTRODUCTION

In recent years, drones have become more commonly used in a variety of areas, including entertainment, industrial, military and scientific applications, to name a few [1]. Drones provide a very agile platform to carry advanced scientific instruments enabling the inspection of infrastructure and other assets. There is a large market involving the application of drones for inspection and monitoring purposes. This includes, for example, water sampling, the inspection of landslides, volcanic activity, and archaeological sites, as well as long-corridor applications, such as the surveillance of transmission lines and borders. The safe and reliable operation of wind farms requires the periodic inspection of wind turbines [2]. In particular, for the case of offshore wind farms, the height of wind turbines can be above 150 meters, and the length of the blade is about 100 meters. Thus, their direct inspection by humans involves dangerous and complex operations, which bring about significant health and safety risks to the personnel that perform these tasks. Utilising an unmanned autonomous drone equipped with cameras and other sensors eliminates the health and safety risks and speeds up the inspection tasks. Furthermore, high-quality imaging or real-time data can be transmitted remotely by connecting the drone's communication system to 4G/5G networks or other local wireless networks [3].

The inspection of turbines in offshore wind farms involves the drones repeated flying from landing vessels to wind turbines and around the wind turbine's towers and blades. Thus, these drones require a reliable power source to minimise the risk of losing the drone and its onboard instruments. There are different types of power supplies used by drones. However, each has its limitations of weight contributions, charging and discharging times, size, energy density and power density [4]. Lithium-ion batteries offer a higher efficacy and tend to be more reliable than other sources, with the added benefit of having low to no greenhouse gas emissions and no vibration affecting the quality of inspection pictures[5]. When lithium-ion batteries power the drones used for the inspection of assets, they normally need to be periodically charged. Their battery charge state and available discharging capacity should be frequently calculated and monitored [6, 7].

Due to inaccuracies in battery state estimation, drone pilots customarily set conservative voltage limits for battery safety protection. When the voltage measured by the flight controller reaches a given voltage limit, the drone will fly back for recharging. However, the relation between battery voltage and battery charge state is non-linear, with the battery voltage sharply dropping off when approaching an empty state of charge [8]. Additionally, frequent charging will reduce the working time of each flight. To conservatively estimate the state of charge of a battery, extra capacity and weight are required for the same endurance. Moreover, the available discharge capacity of the battery is effectively decreased with inconsistent times and cell usage [9]. Various factors, such as ambient temperatures, discharge current, and vibration, affect the available energy from the batteries. Many algorithms have been developed to estimate the state of charge (SOC) and state of health (SOH), corresponding to the battery charge state and available capacity. The definition of SOC and SOH can be found in reference [10], and a review of these algorithms can be found in reference [11].

A Battery Management System (BMS) is an electric control unit that measures voltage, temperature and current and performs calculations to estimate the SOC and SOH [12]. A practical battery management system will play a crucial role in enhancing battery performance, including accurate monitoring, charging-discharging control, heat management, battery safety, and protection. Hossam[13] analysed the details of BMS for electric transportation and large-scale (stationary) energy storage, including covering testing, component, functionalities, topology, operation, architecture, and BMS safety aspects. In the context of their application to drones, MelihField [14] classified battery management systems as analogue or digital. Considering the high reliability and safety requirements of aerial vehicles, digital BMS are advised for this application. A comparison of the above types of battery management systems used in drones is given in Table 1.

Table 1 Comparison of battery management systems used in drones

Function list	**Drone VP**	**BPB**	**i-BMS**
Measured variables			
Pack voltage	√	√	√
Pack current	√	√	√
Cell voltages	✗	√	√
Cell temperatures	✗	√	√
State estimation			
Cell state of charge	✗	✗	√
Battery state of charge	✗	√	√
Battery state of health	✗	✗	√
Cell or battery failure diagnosis			
Over-voltage	√	✗	√
Under-voltage	√	√	√
Over-temperature	✗	√	√
Under-temperature	✗	✗	√
Over-current	✗	√	√
Failure protection			
Charge shut off	✗	√	√
Discharge shut off	✗	√	√
Communication	✗	✗	√
Balance control	✗	√	√
Thermal control	✗	✗	√
Charge control	✗	✗	√

One type of battery management approach used in drones is the Drone Voltage Protection (Drone VP) embedded in some drone flight controllers. As its simplicity helps to reduce the cost of the battery, a relatively large number of drones are equipped with Drone VP. With Drone VP, serial cell stacks are directly connected to electric speed controllers (ESC), and their total voltage and current are measured by the flight controller [15, 16]. Comparing the measured total voltage/current to the set limits, the flight controllers make flight decisions to avoid under-voltage failure and drone crashes. Due to the inconsistency of serial cells, the total voltage cannot represent cell voltages. As a result, some cells will go beyond the voltage limits while the full voltage is still in the safe operating range. Then, these cells will be damaged by over-ranged discharge/charge.

The second type of battery management approach used in drones is the battery protection board (BPB), which measures the cell voltage and temperature, containing balance circuits for each cell. BPB provides special protection of under-voltage, over-temperature and over-current for each serial cell, with the ability to shut off circuits and cell voltage balance [17-19]. The battery SOC can be roughly calculated based on the pack voltage and current. Due to the cell's balance circuits, the inconsistency between cells is reduced. The SOC approximately represents the remaining charge of the battery.

The third approach used in drones is intelligent battery management systems (i-BMS). i-BMS is an electronic control unit that monitors and regulates the charging and discharging of batteries using microcomputer running management strategies. i-BMS provides complete serial cell measurements and estimates the SOC and SOH for all cells. Failures can be fully diagnosed, and the battery power circuit can be shut off in an extreme situation. Cooperating with the charging platform, the battery charge current can be controlled. By implementing advanced algorithms in i-BMS, the drone battery will get many benefits. i-BMS can offer a longer battery lifetime, improved safety, more energy from used batteries, and reduced hazardous lithium-ion battery waste. [20],

In this study, an intelligent battery management system is built for a drone. A whole new design process of i-BMS is illustrated, including battery system requirements, architecture, hardware, software and algorithms. Furthermore, to build the communication of i-BMS, the drone's flight controllers and automatic charging platforms, an Internet of Things module is combined, which can provide multiple communication protocols. Finally, an unscented Kalman filter algorithm was applied to each cell to estimate SOC and SOH, followed by experiments to validate the i-BMS for the studied drone.

The remaining of the paper is structured as follows. Section II describes the design of the battery management system. Section III presents the outputs of battery plants and experimental test bench. The results from the experiments are illustrated in Section IV. Finally, Section V concludes the paper, offering some guidelines for future research.

II. INTELLIGENT BATTERY MANAGEMENT SYSTEM DESIGN

A. *Battery management system requirements for drones*

Risks affecting drone batteries should be mitigated and controlled, as they have health and safety implications. A complete failure of the battery will cause a potentially catastrophic drop. At the same time, damages to third parties may occur. To void these problems, thought must be given to what might cause harm to batteries. In a battery management system, reasonable, pragmatic steps are taken to prevent that harm from occurring. Three main risks, seven characters of risks and eight requirements are summarised, shown in Table 2. Wireless communication and historical data memory are required to transmit warning messages from the BMS to flight controllers. Close cooperation with the drone flight controller and charge platform is essential.

B. *The Battery System Architecture Design*

Responding to the system requirements of the battery management system, the system architecture of the battery system is shown in Figure 1. The centre block is an intelligent battery management system; the left serial block is the welded connected battery cell stack. All cell voltages, one typical cell temperature, and total current through the cell stack are measured. The right parts are drone subsystems, including the flight controller and electronic speed controllers for motors. The flight controller can be connected through a CAN bus wire. The flight controller receives the data from the battery management system and executes flying tasks.

Table 2 BMS requirements for drone

Risks	Characters	BMS requirements
Safety risks	Cell fire or explode.	Voltage protection
		Current protection
		Temperature protection
	Untended power off	Precise charge estimation
		Precise capacity estimation
Lifetime risks	Cell inconsistence	Serial cell balance control
	Maximum current	Current protection
	over-discharge/charge	Voltage protection
Drone interface	Communication	Wi-Fi, BLE and LTE
	Store historical data	Memory chips

As shown in the inner section of the i-BMS, input channels are designed to measure cell voltage, cell temperature and cell balance circuits. The current shunt is inserted in the battery negative power busbar and treated as a current sensor. Two N-MOSFETs (metal-oxide-semiconductor field-effect transistor) are installed on the battery positive power busbar, which can shut off/ turn on the electric power circuit of drones. The N- MOSFET can cut off the electric power circuit when the cells are overcharged. One N-channel MOSFET controls the discharge circuit, and the other N- channel MOSFET is designed to maintain the charge circuit.

C. *The hardware of the intelligent BMS*

The primary subsystems of the intelligent battery management system are described in this section and shown in Figure 2. There are four significant subsystems, including the Cell balancing FET circuit subsystem, AFE subsystem, microcontroller subsystem and Internet of Things subsystem.

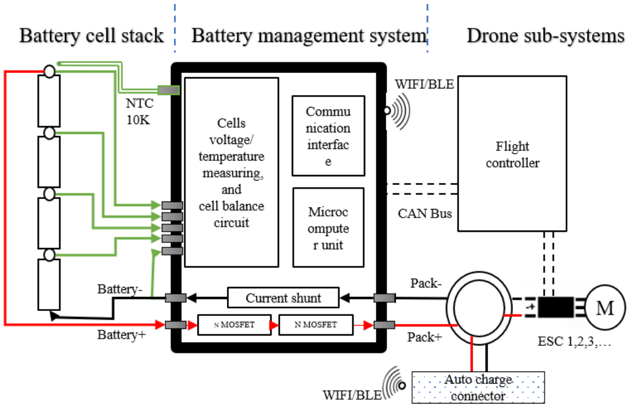

Figure 1 System architecture of the drones' battery system

The AFE subsystem collects the analogue sensor signals and feeds the processed signal data to the embedded processor. A high precision cell monitor chip TI BQ7690 was selected from Texas Instruments. Referencing the datasheet, TI BQ7690 can provide five points of cell voltage measurement, one end of NTC temperature measurement, and one channel of deviation voltage measurement. Associated with the shunt resistance, the current through the shunt resistance can be measured by the deviation voltage between two ends of the shunt resistance. With the shift of MOSFET drivers, the AFE subsystem can control the gates of the battery power circuit.

In the cell balancing FET circuit subsystem, passive and active balance methods are two frequently adopted balance methods. The number of serial cells is small in the drone application, and an independent external charge station can separately charge the relatively low voltage cells. To reduce the weight of the battery system, a passive balancing method was selected in the design of the cell balance FET circuit subsystem.

In the microcontroller subsystem, the STM32F104 processor offers a reasonably powerful computing platform with 72 MHz, 64Kbytes of flash memory and 20 Kbytes of SRAM. This platform is sufficient to run the battery prognostics algorithm and interface with other components through I2C and USART protocols. In addition, the flash memory was divided into two parts storing historical data and program data.

For the Internet of Things subsystem, the Arduino module was adopted. The Arduino module is a popular development platform for the Internet of Things (IoT) communication and provides WIFI, Bluetooth, CAN Bus, and LIN bus to the flight controller and ground control stations. The Arduino module brings together wired and wireless communications. The version of the Arduino modules used in this project is ESP Nodemcu32. MQTT is a standard messaging protocol for IoT. It is a significantly lightweight publish/subscribe messaging for remote devices. The messages between BMS and the charging platform are transmitted using the MQTT protocol.

This interface allows the charging process to be fully under control and adequately monitored. Besides, some features often used in electric vehicles can also be developed for drone swarm applications, including fast-charging control, line charging, and emergency stop.

Unlike other integrated designs, the microcontroller and the IoT subsystem are relatively separated in this solution. The microcontroller subsystem mainly focuses on battery monitoring, and the IoT sub-system primarily focuses on communication management. As a result, there was no interaction between these two when one of them was updated.

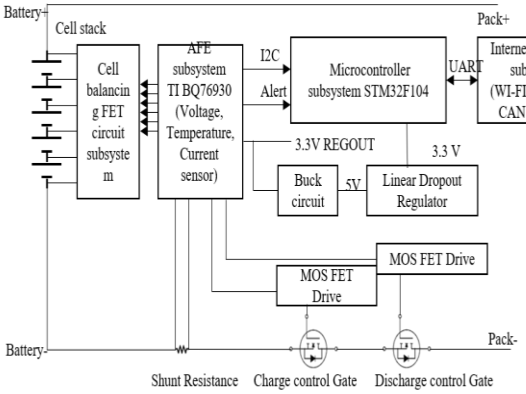

Figure 2 Hardware of intelligent battery management system

D. *Software and Algorithm Design*

The software architecture of the battery management system is divided into two parts. The first part is micro-controller chip software based on the Microcontroller unit STM32F104, which consists of essential software, and real-time environment and application software. The essential software provides drivers of hardware communication, cell measurement, power management, and clock and data memory. The measured variables can be updated to the application layer, and the control instructions can be executed in hardware. The primary function of the application layer includes six components, which can be used for failure diagnosis, security protection, balance control, thermal management, charge control and SOC/SOH estimation. The second part of the software architecture is Arduino platform software, based on the Arduino ESP Nodemcu-32s. Arduino software is an open-source electronics platform based on easy-to-use hardware and software. The protocols of WIFI, Bluetooth, CAN bus, and serial bus were all applied in the Arduino App, and the platform library realized their drivers.

To improve the accuracy of state estimation, a model-based SOC/SOH estimation algorithm was designed and implemented in Matlab/Simulink. A multi-scale unscented Kalman filter (UKF) was applied to realize the estimation algorithms of SOC/SOH. The state transfer equation and iterative calculation steps of UKF can be found in references [21, 22]. Compared with current model-based estimation algorithms, the UKF exhibits reasonable computational complexity, great flexibility, and nonlinear compatibility for battery state estimation[23].

III. BATTERY SYSTEM AND EXPERIMENTAL ENVIRONMENT

A. *Drone and integrated battery system*

AIR-4 LIGHT drone from Airborne Robotics company was selected to execute an unmanned autonomous inspection of offshore wind farms. The AIR-4 LIGHT is a powerful and compact system that combines the latest UAS technology features, equipped with a 9AH lithium-ion battery and a complete open-platform architecture which is optimal for R&D . The parameters of the AIR-4 LIGHT drone are shown in Table 3. The overview of the AIR-4 LIGHT is shown in Figure 4.

The developed intelligent battery system was used to pack a new battery for the drone, replacing the original one. Twelve LG18650HG2 cells were welded to form the battery system of the drone, shown in Figure 5. The new battery pack consists of the proposed intelligent battery system and cell stacks. The intelligent battery management contains a battery management board and an IoT board. The battery shell box provides the cover of cell stacks, boards and cables. The specification of the battery management system and accomplished drone battery parameters are shown in Table 4.

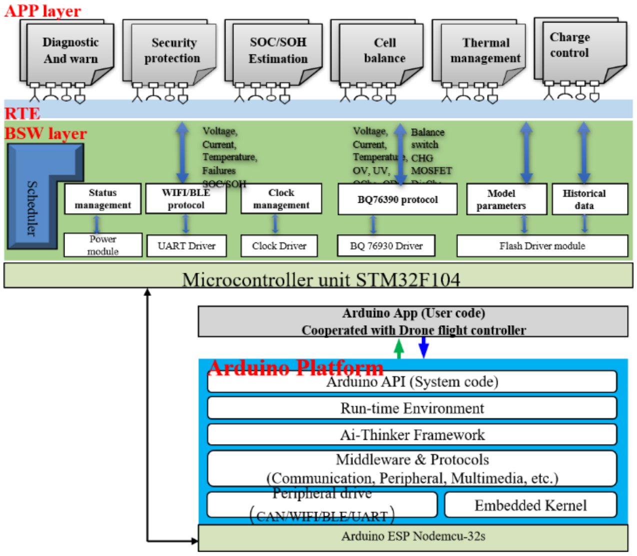

Figure 3 Software architecture of components

Table 3 Parameters of AIR 4 LIGHT drone

No.	Items	Parameters
1	UAV type	Multi-rotor copter with 4 motors
2	Weight	2.0 kg (including standard batteries)
3	Payload	Recommended: 0.4 – 0.5kg
4	Operating temperature	-20 to 50°C
5	Flight time	Up to 40 minutes
6	Maximum Speed	90km/h
7	Motors	4 x 250W brushless
9	Batteries	Standard: 9 Ah, maximum discharge current 60A, normal charge current 4.5A and maximum charge current 9A
10	Navigation	Pixhawk Cube
11	Ground station	FrSky Horus X10S + 10.1" Tablet

Figure 4 Overview of AIR 4 LIGHT, 1-body, 2-detachable arms, 3-battery

Table 4 Specifications of the accomplished battery

No.	Items	Parameters
1	Cell type	HG 18650 HG2
2	Cell capacity	3000mAh
3	Number of serial/parallel	4 serial and 3 parallel
4	Cell normal voltage	3.6V
5	Battery normal voltage	14.4V
6	Maximum charge/discharge current	-12A/60A
7	Size	160mm,110mm,90mm
9	Weight	100g±5g
10	Power connector	XT60
11	Communication interface	WIFI, Bluetooth, CAN
12	Battery capacity	9AH

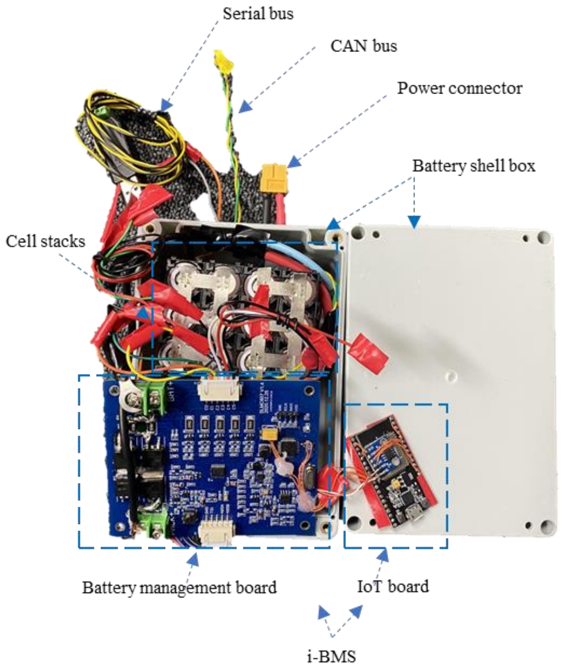

Figure 5 Overview of the implemented battery pack

B. *Experiment simulation environment*

To emulate the work environment of the drone battery, a charge and discharge test bench was set up, shown in Figure 6. The main functions of the environment are to simulate the battery power load of the drone and build the communication between i-BMS and the drone flight controller.

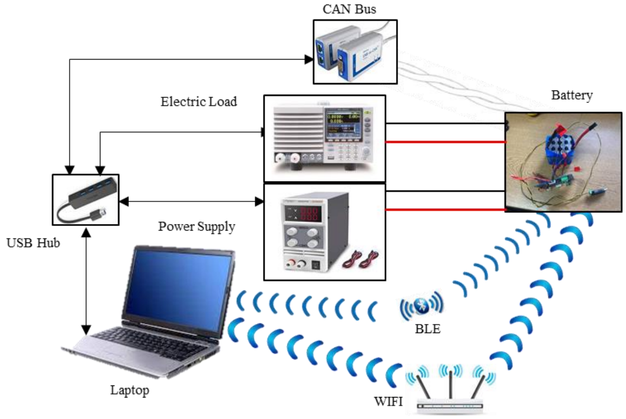

Figure 6 Drone battery test bench

For the simulation of the battery power load of the drone, a laptop computer was connected to the electric load and the power supply by wires, which allowed to control of the charge and discharge currents using software. To simulate the discharge process of drones, a GW Instek PEL-3041 programmable electronic load was selected. The electronic load can discharge the battery with the range of voltage 0~150V and current 0-70 A. The electronic load provides a single-channel load with 0.01 mA current resolution and 16 A/μs current slew rate. A LOGNWEIDC power supply was selected to charge the battery, with a current range of 05 A and voltage range of 0~60 V. The display accuracy of the power supply is ±1%. Linear regulation of the power supply is below 0.2% FS. The laptop computer was connected to i-BMS through Bluetooth and a WI-FI router. The laptop simulated the protocols of the drone flight controller. The measurement and battery state estimation values from i-BMS were sent to the computer and logged. The CAN bus was employed to establish the communication link between i-BMS and the laptop computer.

IV. EXPERIMENTAL TEST RESULTS

Three experiments were conducted to validate the intelligent battery management system. The first experiment is the validation of i-BMS measurement. Three contrastive analyses of experiment values and BMS measure values are shown in Figure 7, 8 and Figure 9. The maximum voltage measure error of four cells is below ±5 mV. The maximum cell temperature error is below ±1 ºC. The maximum current measurement error is below ±1 %. The results show that the performance of i–BMS is good.

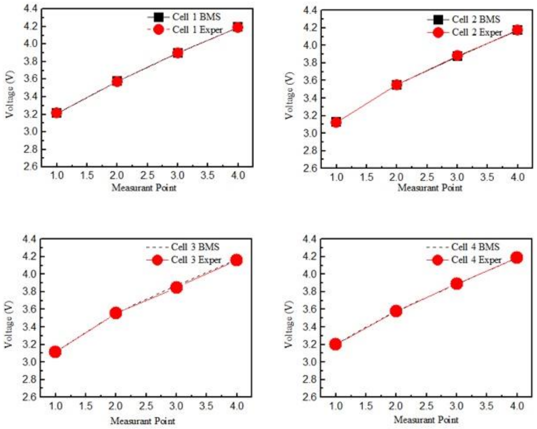

Figure 7 Cell voltage measurements of BMS

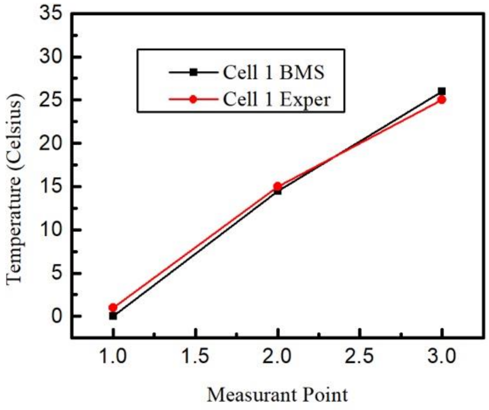

Figure 8 Temperature measurements of BMS

The second experiment validates the full charge process, shown in Figure 10 and Figure 11. The battery was charged with a constant current. The charging current started at 5.2A and was reduced to 0.15A when the maximum cell voltage reached 4.2V. In the charging process, the voltages of four cells and temperature were measured. At the same time, the state of charge, state of health and total charge capacity were separately logged. The total charging capacity by current integration was treated as the actual value during the charging process.

Referencing the Hybrid Power Pulse Characterization test profiles, the third experiment validates the battery empty discharge process, shown in Figure 12 and Figure 13. The maximum discharge current is -18A. The top cell temperature raised to 305K during the final part of the experiment. The current integration calculated the total discharge capacity through the discharge process. The discharge process started with a maximum cell voltage of 4.2V and ended with minimum cell voltage of 2.0V.

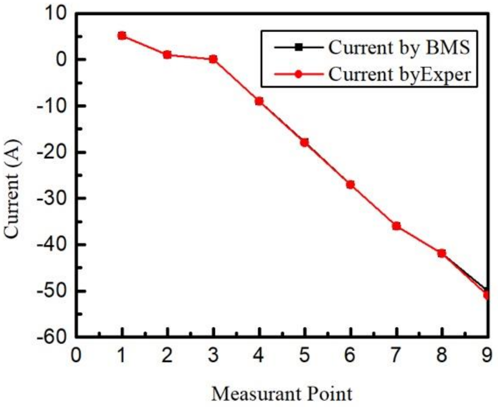

Figure 9 Current measurements of BMS

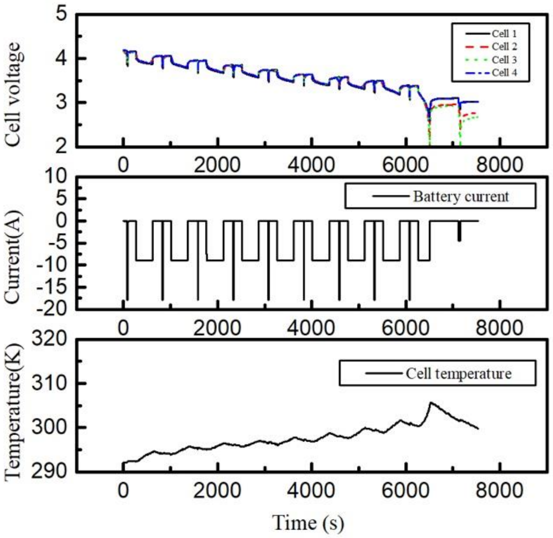

Figure 10 BMS measurements of battery charge process

A static summary of the last two experimental results is shown in Table 5 and Table 6. The cells started with the initial estimated SOC 32.5%~33.3% and ended with the final estimated SOC 96.6%~100% for the battery charge process. The cells began with the initial estimated SOC 96.4%~98.7% for the battery discharge process and ended with the final estimated SOC 2.4%~7.2%. The cells are new, and the estimated state of health of the four cells is 100%, equaling to 9 Ah.

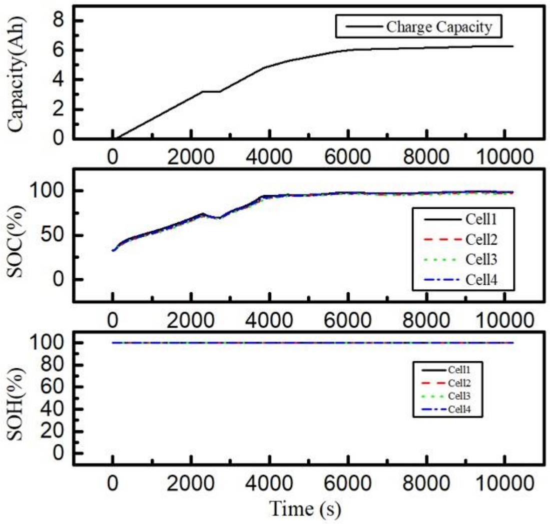

Figure 11 BMS estimating results of battery charge process

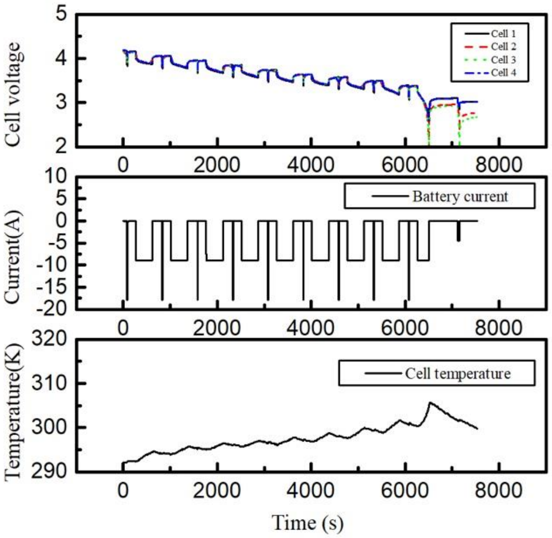

Figure 12 BMS measurements of the battery discharge process

The estimated state of charge deviation is the difference between the initial estimated SOC and the final estimated SOC by BMS, shown in column 'Δ Est. SOC'. The current integration values for the serial four cells are the same, which are 6.19Ah in the charging process and 8.21Ah in the discharge process, shown in the column entitled 'Meas. Capacity' (measured capacity). Divided with the normal battery capacity, the measured capacity can be transformed to the deviation of the measured state of charge, shown in the column 'Δ Meas. SOC'. Compared with the measured deviation of the estimated SOC, the estimation error of SOC ware calculated, shown in the column 'Error of Est. SOC'. The maximum state estimation error for four cells is below ±5 %.

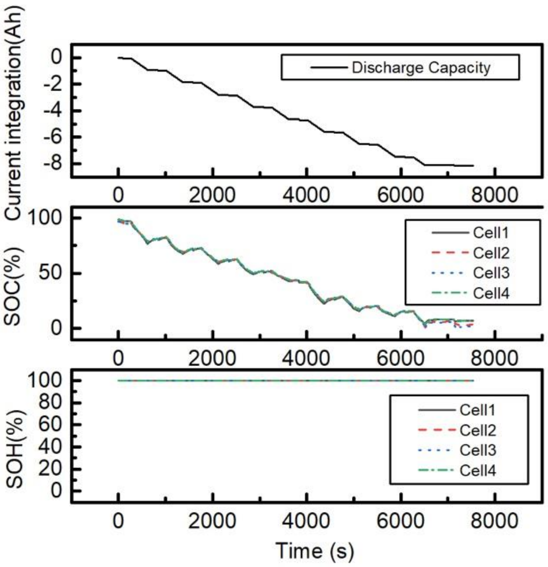

Figure 13 BMS estimating results of the battery discharge process

Table 5 Results of battery state estimation

	Estimated SOH	**Initial estimated SOC**	**Final estimated SOC**
Unit	**%**	**%**	**%**
Battery charge process			
Cell 1	100	33.3	98.9
Cell 2	100	32.6	97.4
Cell 3	100	32.5	96.6
Cell 4	100	32.8	99
Battery discharge process			
Cell 1	100	98.6	7.2
Cell 2	100	97.2	3.6
Cell 3	100	96.4	2.4
Cell 4	100	98.7	7.2

Table 6 Estimation error of battery state estimation

	Δ Est. SOC	**Meas. Capacity**	**Normal capacity**	**Δ Meas. SOC**	**Error of Est. SOC**
Unit	*%*	***Ah***	***Ah***	*%*	*%*
Battery charge process					
Cell 1	65.6	6.19	9	68.78	-3.18
Cell 2	64.8	6.19	9	68.78	-3.98
Cell 3	64.1	6.19	9	68.78	-4.68
Cell 4	66.2	6.19	9	68.78	-2.58
Battery discharge process					
Cell 1	91.4	-8.21	9	91.22	0.18
Cell 2	93.6	-8.21	9	91.22	2.38
Cell 3	94	-8.21	9	91.22	2.78
Cell 4	91.5	-8.21	9	91.22	0.28

V. CONCLUSIONS

Power management is critical to flight safety for unmanned aerial vehicles and drones. Lithium cells are widely applied because of their energy and power density but often require a battery management system. Three types of battery management systems used in drones were discussed: drone voltage protection, battery protection board, and intelligent battery management system. Considering the features of the three types of battery management systems used in drones, the intelligent battery management system is best recommended in drone applications. The system requirements, architecture, hardware, software and algorithms of i-BMS are illustrated. The contributions of this work are summarised below.

- An intelligent battery management system was designed and integrated with lithium-ion cell stacks. Derived from the aspects of drone safety and battery lifetime, three main risks, seven characters of risks and eight requirements are summarised for the design of a battery management system.

- In relation to system design, the cell voltage, current, and temperature can be monitored in real-time, as well as each cell's charge state and available capacity. The i-BMS can cooperate with drone flight controllers by CAN bus and supports wireless communication with a charging platform by MQTT. Some features typically used in electric vehicle charging can be further developed when the communication is built between i-BMS, flight controllers and charging platforms.

- In relation to hardware design, the intelligent battery management system consists of four major subsystems: the cell balancing FET circuit, AFE subsystem, microcontroller subsystem, and Internet of Things subsystem. Unlike other integrated designs, the microcontroller and the IoT subsystem are separated computing platforms. As a result, there was no interaction between these two when one of them was updated.

- Regarding the software design, the software architecture of battery management is divided into two parts. The first microcontroller chip's software is in charge of the measurements and state estimation, and the second Arduino software platform performs communication and protocol management. Aiming to improve the accuracy of state estimation, a multi-scale unscented Kalman filter runs on the microcontroller chip.

The developed intelligent battery system was used to pack a new battery for the drone, replacing the original one. To simulate the work environment of the drone battery, a charge and discharge test bench was set up, which can emulate the battery power load of the drone, and imitate the communication between i-BMS and the drone flight controller. Three experiments were conducted to validate the intelligent battery management system. The results show that the measurement performance of i–BMS is good. The maximum voltage measure error of four cells is below ±5 mV. The top cell temperature error is below ±1 ºC. The highest current measurement error is below ±1 %. In the full charge/discharge experiments, the estimation error of SOC is below 5%, compared with experimental current integration values. For the new cells, the estimated SOH of i-BMS is 100%, as the cells are new.

In the near future, ageing cycle experiments will be conducted to validate the whole life cycle, and the intelligent battery management system will be installed into drones and tested on actual flights.

ACKNOWLEDGEMENT

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