EF1113 Project report - SÓLFAR

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***Abstract*—This project focused on selecting a Battery Managements System (BMS) IC, implementing and verifying functionality for a fixed wing Unmanned Aerial Vehicle (UAV). The project consisted of designing and manufacturing of a PCB with the selected IC, development of C code on a STM32 microcontroller for communication with the IC, and testing and verification of the complete BMS. Testing displayed measurement precision of 100 mV for all 5 series cells in the tested battery package, and the possibility to discharge each individual cell over a series resistor. The BMS needs integration and verification within the complete aircraft's electronic system. However, this project demonstrates a working BMS, featuring individual cell monitoring, discharging and control through microcontroller.**

I. Introduction

This report is the result of a project within the course EF1113 at KTH Royal Institute of Technology. The project was started with a specific goal in mind; getting the SÓLFAR aircraft up in the air. SÓLFAR is currently a fuselage designed to be a glider. The main goal of the aircraft is to be able to stay in the air for as long as possible while performing missions such as patrolling the air looking for forest fires.

As the fuselage is mostly built, it was the goal of this project to mount all the necessary electronics in the aircraft, make it flight ready and perform its maiden flight. This would rely on several previous projects such as [1] and [2]. However, some problems were found while studying the earlier work that would present serious challenges in the completion of the SÓLFAR aircraft.

II. Background

Previous work had assumed a 1S battery pack with $3.7\,\mathrm{V}$ nominal voltage. The main advantage of a 1S configuration is the self balancing properties that comes from having all cells in parallel. The chosen motors, Turnigy AeroDrive 3548, can operate on 3S - 6S, meaning the battery voltage would have to be boosted. This had been accounted for in previous work, but what had been neglected is the peak current that the booster would have to handle at the input. It would have to handle around $300\,\mathrm{W}$, found from doing a bench test of the motor with a propeller mounted on it. For a 1S battery, that is about $300\,\mathrm{W}/3.7\,\mathrm{V} \approx 80\,\mathrm{A}$ of current. This kind of current would have required large inductors and MOSFETs, unreasonable in weight and inefficient for a solar powered aircraft. The observation caused this project to be redirected towards developing a Battery Management System (BMS) that is necessary for a battery pack with several cells in series. A BMS system would allow for the use of 5S or 6S battery packages, avoiding any voltage boosting between the battery and motors. Additionally, this configuration is more similar to previously constructed aircraft like Alpha, Nimbus and Phoenix, which used 3S, 5S and 3S batteries respectively. This project will focus on constructing and validating an overvoltage protection BMS.

The work done by Y. Obreykov [2] covered the construction of voltage converters between Solar-Motor, Solar-Battery and Battery-Motor. Everything was constructed to run on an FPGA and STM32. Therefore, the BMS will be constructed to also be able to communicate with the same STM32 microcontroller for easy integration of the two systems.

A. BMS Theory

A BMS' purpose is to ensure that all cells in a battery stack are within voltage limits. In a new cell package with equal cells the charge will be evenly distributed. However, after several battery cycles the wear on the cells may differ and that will cause the cell voltages to no longer be equal. This in turn may lead to cells charging over their voltage limit if the system lacks a BMS. The BMS is tasked with continuously measuring all individual cell voltages differentially, and when one cell is at maximum voltage the charge speed must be reduced to avoid overcharging. The BMS also connects a small load to the fully charged cell to trickle away charge while the other cells continue charging but at a slow pace. If the cell capacity difference is small the voltage differences will also be small resulting in a short time period of slow charging. However, for an aged battery where cells may experience large differences in capacity the voltage will begin to differ as the batteries with least capacity will become full first and reach the voltage threshold. Resulting in an reduction in charge speed when several cells may be far from their maximum charge. Lastly, there are BMS topologies where charge can be moved between cells to avoid burning the excess in a dummy load. This method is more energy-efficient but requires a significantly more complex circuit.

III. Method

Several different BMS chips were evaluated. The requirements were an ability to handle 5S batteries and to have integrated balancing transistors. The option of charge redistribution was early disregarded as the complexity of such systems drastically increased compared to a passive system where excess energy is burned of in resistors. Some evaluated chips had integrated control units but the disadvantage of such systems is the difficulty to program them. The final decision became the BQ76925 [3], an analog front end that relies on an external microcontroller for control. The chip has integrated amplifiers to read individual cell voltages and built in transistors for balancing. The maximum balancing current was $50\,\mathrm{mA}$. It communicates over I^2C and voltage reading is done through an analog pin on the microcontroller. The chip also includes functionalities for current and temperature sensing, available for future improvements.

An STM32 Nucleo development board of type L474RG was used to run software on. Code was developed and uploaded using the manufactures STM32CubeIDE software. The first test was to run a "blinky" program to confirm code could be uploaded and the STM32 would execute it properly. Thereafter the next hurdle was to configure I^2C communication. To confirm the I^2C peripheral was setup correctly, an AHT20 temperature sensor development module was used.

A. Software

Peripherals were initialized using the STM32CubeIDE visual interface. Required peripherals for the program are I^2C and ADC. Additionally, UART was also used for debugging the code by printing in the computer terminal. UART will not be required for the final program implemented in the aircraft but some way of storing cell voltages on a memory card would be a recommended improvement of the program. The program consists of two files *bms.c* and the accompanying header files *bms.h*, the header file holds global variables such as register addresses and also the maximum allowed voltage. Through *main.c* the functions of bms.c were called. For the final implementation a BMS task would have to be created to run the program in conjunction with the code for boost converters. All functions of *bms.c* are described in Table I. The only functions that need to be called by the main program are *BMS_Init* and *Master_Balance*. *BMS_Init* needs to be called in the setup part of the program and *Master_Balance* should be scheduled during charging to prevent overcharging cells, it is not necessary to run the function when the battery is discharging unless it is used for recording cell voltages for data logging. However, code to store cell voltages is currently not developed but should be a straightforward task as Y. Obreykov [2] has shown how data can be stored on SD-Card.

A major part of code development have been calibrating ADC readings. Correction factors for each cell and the on-chip voltage reference have been saved in non-volatile memory on the BQ76925. Reading the factors is done through I^2C and fixed point operations are used to calculate the corrected voltage. The concatenation-of-bits equations have been taken from the Texas Instruments supplied code[1]. These equations take up the majority of the function *Offset_n_Gain*. For improved reliability, the internal ADC voltage reference can be calibrated using the BQ76925's voltage reference, it is supposed to be a stable reference according to the datasheet [3]. The reference is routed to the same ADC pin used for cell voltage readings, this allows the BMS system to only use one ADC pin on the microcontroller unit (MCU).

[1]"SLUC581 - bq76925 Example Code" available at https://www.ti.com/product/BQ76925 under "Software development".

TABLE I
THE DIFFERENT FUNCTIONS OF *bms.c* AND THEIR PURPOSE

Name	Purpose
Cell_Read	Does analog read and calculates actual cell voltage.
Start_Balance_Cell	Opens the transistor for Cell_n to drain energy.
write_UART	Takes cell number and cell voltage to input and writes it over UART to a computer
BMS_Init	Initialize function to turn on required peripherals on the BQ76925.
Master_Balance	Master function that should be scheduled during charging. It calls Cell_Read and Start_Balance_Cell.
Offset_n_Gain	Part of initialization and called by BMS_Init. Only needs to run once on power up.

B. BQ76925

The BQ76925 is an analog front-end BMS integrated circuit (IC). It requires a microcontroller to run a balancing algorithm. It communicates with the microcontroller through I^2C and cell voltages are read through an analog pin. To perform actions on the chip, data is written to the BQ76925 registers using the I^2C bus. The chip has a unique addressing method as each register has its own I^2C address. That means that a read and write to any register can be performed through a single transaction on the bus, making for a faster system. The drawback is that the module uses more address' compared to the traditional way where one chip has a single I^2C address.

Another feature of the chip is the $3\,\mathrm{V}$ reference voltage. It is said by the manufacturer to be stable but it has not been verified in different environment conditions.

C. Circuit Board

The BQ76925 comes in a TSSOP (20) package and a Printed Circuit Board (PCB) was designed following the general application circuit diagram provided in the datasheet [3]. The final schematic can be seen in Fig 1. The board was manufactured using a PCB mill and components soldered using a standard soldering iron. Connectors used are called JST_GH, they are the same kind used on the Orange Cube flight controller. Parts and crimp tool were readily available. Fig. 2 illustrates the resulting layout.

While the board was a good way to start testing the IC, a few drawbacks were discovered when using it. First, it did not break out a few of the pins. They were originally deemed unnecessary for this application where only the core functionality was to be tested, but some (like VREF) were useful in debugging. They could have been broken out to test-points at the least. The same goes for the current sense output. While there was no intention of using it in this project, it would not have hurt to make it available.

Second, because the VREF pin was deemed unnecessary, its external $1\,\mu\mathrm{F}$ capacitor was also omitted. It later turned out that it is necessary for making the reference voltage stable, even

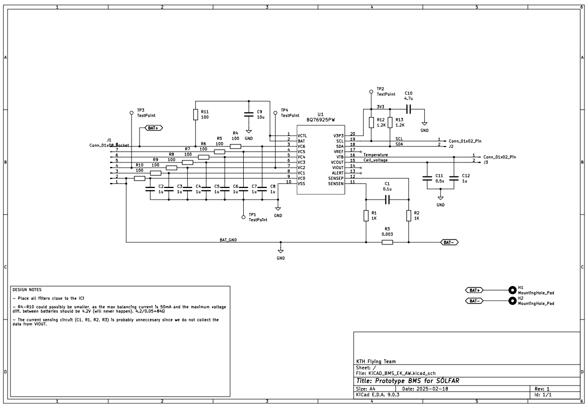

Fig. 1. Schematic of the designed development board for the BQ76925 IC.

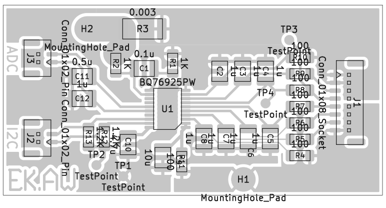

Fig. 2. Layout of the test board.

internally. A THT capacitor was soldered on later to mitigate this oversight.

Additionally, the series resistors for balancing where initially chosen to $100\,\Omega$ each resulting in a total $200\,\Omega$ resistor to burn off excess charge. Maximum cell voltage $4.2\,\mathrm{V}$, would result in $21\,\mathrm{mA}$ balancing current. Only utilizing roughly half of the maximum allowed $50\,\mathrm{mA}$ current. To further improve balancing performance the series resistors were exchanged to $50\,\Omega$, which results in $42\,\mathrm{mA}$ balancing current. This was achieved by soldering another $100\,\Omega$ surface mount resistor on top of the already existing resistor, resulting in a parallel connection of the two.

D. Pinout

The produced test board had three connectors. One for the ADC measurements, one for I^2C and one for the battery. The board can be seen in Fig. 3, where the large connector on the right is the battery connector. ADC and I^2C are on the upper- and lower left respectively. The blue line on the I^2C cable is the clock- and the green is the data line. For the ADC, the blue carries the VCOUT (voltage reading) pin from the IC and the green is the temperature reading.

The battery connector has eight pins. The first two (from the top in Fig. 2 and 3) are both ground. Next is the positive of battery cell one and the negative of battery cell two. This is the pattern for the remaining pins. If the system is used with fewer than six cells, the topmost (unused) cables should all be connected to the positive of the top cell in the battery. In this project, the top two pins on the connector were soldered to the positive of cell five, as only five cells were used.

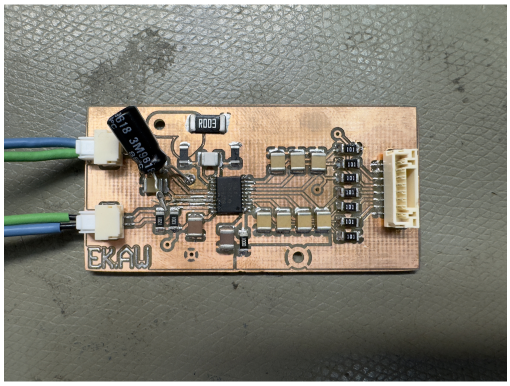

Fig. 3. Image of the produced test board.

IV. Results

Measurements were performed on the battery pack at three levels of charge. The test was aimed at testing the BMS measurement accuracy. The results can be seen in table II, with the difference visualized in Fig. 4.

TABLE II
Reading from multimeter (actual) and system (ADC) at different voltage values.

	Actual [mV]			ADC [mV]		
Cell	Low	Mid	High	Low	Mid	High
1	2954	3523	4145	2978	3540	4228
2	3122	3554	3964	3143	3596	4038
3	3173	3554	3958	3208	3600	4036
4	3054	3537	3965	3091	3590	4050
5	2975	3533	3963	3015	3590	4055

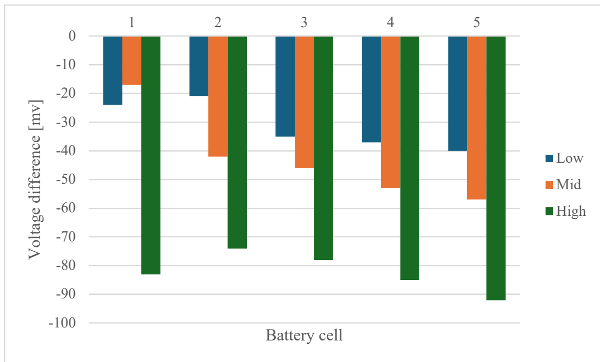

Fig. 4. Difference in voltage between actual voltage of the battery cell and the voltage measured by the system at low, mid and high cell voltages.

The figure shows that the precision is within $100\,\mathrm{mV}$ for all measurements.

The balancing capability was tested for all cells, the discharge rate was measured over one of $50\,\Omega$ series resistances. Using a multimeter the voltage over the resistor showed a discharge current flow.

An attempt was made to improve measurement precision by calculating the ADC offset and gain using the $1.8\,\mathrm{V}$ and $3\,\mathrm{V}$ reference, produced by the BQ76925. After compensation the precision was worse, which led to scrapping of that code.

V. Discussion

The system shows solid measurement capabilities of the individual cells of a 5S battery package. To achieve even better precision the ADC of the STM32 needs to be offset and gain compensated. From Fig. 4 it can be seen that the error seems to be a linear gain error in the ADC on the microcontroller, this measurement error could most likely be reduced. For further refinement, the voltage references from the BQ76925 could be used to get a potentially more environmentally stable ADC reference. As presented in section IV, an attempt using this method was made but ultimately worsened performance. The exact cause of failure is unclear but is believed to have been caused by errors in calculation method.

The design proves that the system in theory is capable of detecting when any cell reach maximum voltage. It also proves that slow discharging can be performed to balance the cells. A short-coming of this BMS is that two adjacent cells can not be discharged at the same time. The inability to balance adjacent cells simultaneously may not be critical for minor imbalances, but it could limit safe charging in long term operation. In a scenario where both cell 1 and 2 are charged to $4.2\,\mathrm{V}$ and cells 3, 4 and 5 are charged to $4\,\mathrm{V}$, this system could not continue to charge as we are not able to keep both cell 1 and 2 from charging beyond $4.2\,\mathrm{V}$. In such a scenario it is advised to remove the battery from the aircraft and instead use a commercial LiPo charger to balance the cells.

A. *Future work*

The first step in the continuation process will be to transfer the system onto the Data-hub from the development board and verify functionality. Afterwards, a decision of where the BMS module should be placed, it can both be part of the main PCB with DC-DC regulators or it can be it's own board communicating over two I^2C pins and one analog pin. Keep in mind that the BMS and microcontroller require a common ground to communicate over I^2C.

The next milestone will be to integrate the BMS with the system constructed by Y. Obreykov [2]. Develop code that uses that BMS voltage readouts to determine if the battery can be charged at full speed or if the charging needs be reduced. Thereafter, testing under real charging/discharging cycles is of interest.

Also useful for the aircraft will be logging of the cell voltages. Using the Data-hub, data should be able to be written to the onboard Micro-SD card.

VI. Conclusion

This work presented the development and testing of a basic Battery Management System (BMS) for a 5S LiPo battery pack. The system was shown to provide cell voltage measurements with a precision of better than $100\,\mathrm{mV}$, which is sufficient for basic protection functions. Cell balancing was successfully demonstrated, although simultaneous balancing of adjacent cells is not supported, which may limit function in long term operations.

An attempt at ADC offset and gain calibration using the BQ76925's internal references did not improve measurement accuracy, suggesting that further refinement in software is required. Despite these limitations, the prototype confirms the feasibility of implementing battery monitoring and balancing suitable for integration into the target SÓLFAR platform.

Future work should focus on implementing a balancing strategy and integrating the BMS with the aircraft's electronics system. Overall, the system demonstrates sufficient accuracy to protect cells from over voltage and and provides hardware support for in flight monitoring and logging of individual cell voltages.

References

[1] K. Klarin and H. Jonzon, "Design of a Power Management System Utilizing Photovoltaic Cells and Batteries for a UAV." Bachelor's thesis, KTH Royal Institute of Technology, 2024.

[2] Y. Obreykov, "Design and Implementation of a Power Management System for the SÓLFAR Hybrid UAV," Master's thesis, KTH Royal Institute of Technology, 2025.

[3] Texas Instruments, *BQ76925 3-Series to 6-Series Cell Li-Ion and Li-Phosphate Battery Monitor (Analog Front End).* Texas Instruments, Rev. E ed., Apr. 2020. Datasheet No. SLUSAM9E.