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INTELLIGENT ENERGY MANAGEMENT OF UNMANNED GROUND VEHICLE

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Abstract: *Operator of an Unmanned Ground Vehicle (UGV) often needs to know, when point of no return (PNR) capability limit is being reached. Predicting PNR is not a trivial task as energy consumption often changes when driving the same path backwards. Intelligent Energy Management (IEM) is proposed to give UGV operator a capability to manage on-board energy resources and operating modes regarding to mission priorities.*

Key words: Energy Management, Battery Monitoring, Reconfigurable Chain Structure, Point of No Return, Robot, UGV, Vehicle, Unmanned

1. INTRODUCTION

The vast majority of modern portable or unmanned devices have rather sophisticated energy management to protect their rechargeable batteries from overcharging and overdischarging. Energy management is one of the most challenging tasks in Unmanned Ground Vehicle (UGV) usage due to complicated characteristics of commonly used Li-ion batteries and versatile usage scenarios. Still, adding sensors or using more advanced electronics does not influence the total product cost as much. UGV operator needs highly flexible energy management system to use available energy resources in the best possible way, according to the mission priorities. Monitoring every cell individually is required to detect situations where current dissipation peaks should be limited or battery chain structure should be changed. Ignoring too low voltage (usually below 2.5V) of a cell easily leads to non-reversible cell damage. In routine tasks (like training) the top priority should usually involve keeping Li-ion battery pack in the best health condition possible. Part of IEM uses a set of latching relays to achieve the ability to remotely overcome many severe main battery pack defects without the need for on-board service. Once implemented, virtually the same hardware can have many uses. Few of the proposed uses are investigated using partly practical experience gained from the design and usage of 4-wheeled UGV built in TUT Department of Mechatronics in 2008. The behaviour of Intelligent Motion Control Layer (IMCL) has been modelled in Matlab and Simulink. When UGV drives to the operation area, a lot of information can be gathered about the terrain. The return scenario can be simulated using gathered empirical data and advanced battery modelling [2] algorithms to find out whether returning by the same path would be theoretically possible. This information cannot be very precise but it helps to prevent energy and power shortcomings and an unexpected interruption of a critical mission.

2. MANAGING BATTERY PACKS

The UGV energy management system handles two separate battery packs. The first one is named B1. It is a 24V battery with limited capacity (about 20 Ah) to power UGV control electronics and it is unconfigurable. The second one is named B2. It contains about 10 high-capacity high-current Li-ion cells and it has a configurable chain structure. B2 is mostly being used for powering the UGV motion servos. Servos may load the B2 battery with short, heavy current spikes, when high torqueses are needed. In case the chain of B2 has one cell with high internal resistance or too low voltage, high current peaks should be avoided not to cause further damage to the cell. Specific and expensive hardware is needed to change B2 chain structure but without the reconfigurability of the B2 battery pack, the UGV would be very sensitive to the commonly known cell failures. However, when operating in low temperature environment and all cells in B2 battery pack cool down evenly, all cells feature temporarily increased internal resistance [3]. Changing chain configuration in this case would not help. Discharge rate should be limited. Carefully powering dedicated battery heater would allow restoring the limitation to the default level, after a while. Increased internal resistance of a cell limits the recommended discharge rate but the cell may still have retained the original energy capacitance.

2.1 The "Limp Home" Mode

In portable devices, failure of one cell in a Li-ion battery pack often renders an entire battery useless. Electrical vehicles may have a special emergency mode called "limp home", which allows current to bypass the damaged section containing the damaged cell. New connections must be made to substitute removed section with direct connection. This mode adds flexibility to the battery pack but it is too limited for using it in the UGV energy management. However, using similar idea, two remotely selectable chain configurations could be defined for the main chain. Using two rather simple configurations may have an advantage when UGV mission can be divided into concrete high-power and low-power operation sections. When low-power mode is applied, all cells will be connected in series. The main chain has then almost maximum voltage output and the current can be drawn from all the cells. In high-power mode, only healthy cells are included in the main chain. Output voltage of the chain is reduced but as long as the voltage does not drop below operating voltages of servo amplifiers, UGV battery pack should again tolerate relatively high current surges. This type of solution requires at least one additional battery pack (B1) for control logic. Servo amplifiers with separated logic supply and servo supply would be preferred as less error prone to the voltage peaks while the main chain configuration is being changed.

2.2 Primary and Secondary Chain

More flexible solution proposes using two separate cell chains named primary chain and secondary chain. Reduced schematic of the concept is presented on Figure 1. It has a capability to switch any cell from primary chain into a secondary chain or to entirely isolate the cell from the system.

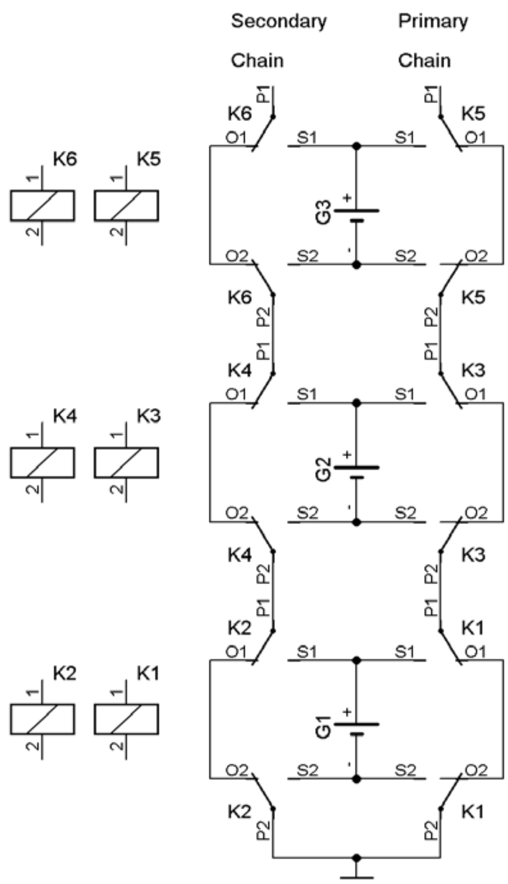

Fig. 1. Reconfigurable (B2) battery pack

This solution requires one high-current 2-pole latching relay and one low-current 2-pole latching relay per every cell. For example, switching “ON” all high-current relays K1, K3 and K5 connects G1, G2 and G3 to the primary chain. In case G3 will be classified as “weak”, K5 will be switched “OFF” and low-current K6 will be switched “ON”. In case, the cell later appears to be classified as “dead”, turning K6 “OFF” isolates the cell from both of the chains. This solution enables the cells with increased internal resistance to be used for powering low-power devices through secondary chain while the strong cells are still operating in high-current mode using the primary chain. In case any chain contains a cell which cannot or should not be used any more, it can be isolated from both of the chains. All cells are isolated in Figure 1. to demonstrate the “Initial” or “Panic” configuration of B2.

The number of weak cells in a battery pack cannot be predicted. Therefore, standard voltage (24V) can be achieved using wide input voltage range DC/DC converter. As soon as secondary chain fails to supply the needed amount of energy, power should be drawn from dedicated low-current battery pack B1. This is done by primitive Uninterruptible Power Supply (UPS) on Figure 2.

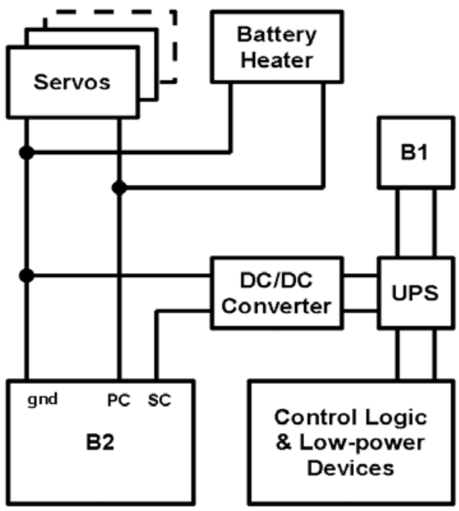

Fig. 2. Main Connections of UGV

Primary chain output and secondary chain output are marked “PC” and “SC” respectively. Some UGV operations may require long term low-power surveillance. Although it is preferable to use weaker cells first in secondary chain, to support powering low-current devices, it may be later necessary to use the energy resources of healthy cells. In this situation it is probably not the best idea to sacrifice good cells one by one, loosing several volts of primary chain voltage every time. Instead, extra current should be drawn from cells with higher SoC. This can be done by connecting the cells with higher voltage reading to both of the chains. After some time, cell conditions may change and switching to another configuration may become preferred. Retrieving energy while balancing the cells, keeps the primary chain of battery B2 at the best possible condition for high-current servo related to operations which may follow. The energy of the original low-current battery B1 (originally dedicated for control and low power devices) can then be reserved for later use. Spending energy needed for independent return would be acceptable only if battery-powered return capability of the UGV is not required.

2.3 Cell Classification

All Li-ion cells of B2 can be either connected to one of the chains (primary or secondary) or disconnected. In normal mode, IEM module monitors all cells and advises the operator to apply changes to the chain configuration and the usage of the secondary chain. Classifying cells as “healthy”, “weak” and “dead” is based on cell internal resistance, temperature and open-circuited voltage. Changing IMCL maximum current limit may have an effect on the distribution of the cells into these categories. Recommended charge rate is provided by the supplier of the battery. As soon as regenerative braking is beginning to produce too high charge current to the primary chain cells, complementary electromechanical breaking devices should be progressively activated to limit the velocity. While the battery temperature is lower than desirable, the dangerous voltage peaks may be suppressed by applying an automatically regulated heater's load to the primary chain. This protection is vital only in extremely low temperatures, where Li-ion cells should not be charged at all. Using traditional dynamic braking would simply convert the extra energy to heat in servo amplifiers and servo coils.

2.4 Charging Options

Having an additional low-power energy source (like a solar panel) on-board, would enable the second chain to be used for charging cells with low SoC. When UGV is in service, the primary chain should be used for charging the healthy cells. Latching relays enable to exclude the cells which have achieved a full SoC one by one. Low rate charging can be made through the secondary chain, as needed.

2.5 Reservoir Capacitors

Servo amplifiers usually contain reservoir capacitors, which when directly connected to the battery output, may cause a high current peak due to rapid capacitor charge. This current peak is not desirable as it may damage some of the capacitors. This problem is usually solved by connecting a resistor in series with the capacitors before enabling direct connection with the battery. Adding resistor R1 to the primary chain as in Figure 3 or replacing R1 with current limiting device helps to prevent capacitor damage.

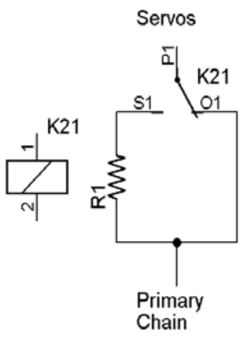

Fig. 3. Capacitor Protection Circuit

One additional 1-pole high-current latching relay is needed for this capability. Using the proposed reconfigurable battery chain structure, it is possible to include cells to the primary chain one by one raising chain output voltage progressively. In case the reservoir capacitors need to be completely discharged, cells could be excluded from the primary chain one by one, progressively lowering the primary chain voltage. Any chain configuration change of B2 should be performed only when R1 is connected in series with the capacitors. Any servo activity must be disabled during the balancing procedures. Compared to conventional balancing, progressive balancing is expected to generate less heat per charge/discharge as R1 would never have higher voltage drop than one cell voltage. Automatic progressive balancing needs real-time input about the voltage of reservoir capacitors and open circuit voltages of all cells for optimal control. In case the reservoir capacitors hold a remarkable amount of energy and the battery pack configuration needs to be changed often, R1 should be replaced with switching current regulator to achieve even better efficiency. Balancing, however, may introduce noticeable time requirements to the configuration change operations when using reservoir capacitors with extremely high capacity and excessively limiting balancing current.

2.6 Pulsed Discharge

Some battery cell producers claim that their Li-ion cells perform better on pulsed discharge. Researchers have been able to prolong a battery lifetime even by a factor of two [[4]]. Introducing rest periods to a constant load enables the electrolyte to drift a lot in a battery cell. Therefore, more of the electrolyte can be efficiently included in the electrochemical reaction. Pulsed discharge also is claimed to reduce internal resistance of a cell raising the overall efficiency of a battery pack further. Although the best timing of load and rest intervals is not yet known for our B2 battery pack, further research and experiments with UGV intelligent energy management would benefit from the pulsed discharge capability as an option.

Pulsed discharge for B2 battery pack can be made possible with redesigned switching current regulator in the primary chain (replacing R1 in Figure 3) and keeping K21 in balancing mode even in operating mode. To use the full potential of the positive effects of pulsed discharge, the regulator must be modified according to optimal battery-dependent values of load and rest. It may be necessary to add few cells to the primary chain to compensate for the resting intervals. There are also higher requirements for balancer circuit components, with long-term high-current operation capability. As soon as the rest intervals become insignificantly short due to high current consumption and regulation, K21 can be switched back to the original state bypassing the balancer circuit which has lost its usefulness.

3. POINT OF NO RETURN

Intelligent Motion Control Layer [1] was designed to constrain UGV motion (acceleration and jerk) by finding and rejecting two disturbance components in real time. The first one is caused by friction and has velocity-dependant sign. The second one is caused by gravity and ground reaction forces of the ramps. After every main cycle (100 s^{-1}) IMCL produces a set of disturbance values. Taking into account the sign change of gravitational component, rough estimation can be made about the potential energy consumption in every passed terrain section when theoretically returning exactly by the same trajectory later. Summing of all the energy portions gives an estimated energy needed to drive the same path backwards or a different path if the energy estimate for this path is known. Keeping all the values in an array would enable IEM of the UGV to occasionally simulate the returning scenario, based on that array and virtual battery models. To start the simulation all initial parameters of all the cells and the chain configurations must be according to the real situation. Simulations help to discover dangerous voltage drops at the sections, which require very high servo power. Estimations do suffer from inadequacy when UGV wheels dig deep into a soft ground on steep ascents. Driving the identical terrain section downhill would probably not cause that severe terrain deformations and actual power consumption would be less. However, passing previously deformed soft terrain is not suggested as estimations may differ even more from real-life and there is a greater chance to get stuck in softened ground or old tracks. Therefore, UGV operator must not entirely rely on IMCL and IEM estimations.

4. CONCLUSION

Battery control and specially Li-ion batteries can be made more reliable by introducing latching relays into the system. Splitting the battery into two chains gives multiple options to cope with cells with very different states of charge and stages of health. Although the latching relays only need to endure nominal current statically, the price range of currently available latching relays is high. Using solid-state relays has been avoided so far because of their higher voltage drop and lack of mechanical memory. Balancing the primary chain of battery pack B2 and the reservoir capacitors of servo amplifiers require a dedicated balancer circuit to protect the capacitors from excessive current peaks. Virtually the same circuitry can be used for implementing a pulsed discharge, which is expected to give positive effect on battery efficiency. Fully automatic battery reconfigurability functions are considered to be useful for less advanced UGV operators. Using a set of common modes may cover most of the scenarios. Further development is needed to test the proposed concepts though the problems presented and investigated are vital for mission critical UGV usages.

5. ACKNOWLEDGMENTS

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