Chapter 8

Batteries

Batteries are components that usually limit a lot the autonomy of a mobile robot, besides representing a significant part of its weight. Usually, batteries are the heaviest component of a mobile robot. Humanoid robots, for instance, have reached an impressive level of sophistication in the last 20 years. Powerful motors were miniaturized, high performance computational systems became even more compact, however the components that less evolved until now were batteries. In 2000, the most sophisticated humanoid robots needed to be recharged every 30 minutes, even though their batteries accounted for a significant portion of their weight, about 15%. But recent advances in lithium battery technologies, such as the development of A123 batteries, are starting to change this.

Fortunately, combat robots only need an autonomy of about 3 minutes. Combots still need about 15% of their weight in batteries, similar to several humanoid robots, however it is possible to extract from them a much higher power during this short period. But most batteries were designed to be slowly discharged, in 20 hours, in 1 hour, not in 3 minutes. Therefore, it is necessary to know the advantages and disadvantages of each type.

The main battery types are: lead-acid (Sealed Lead Acid, SLA), nickel-cadmium (NiCd), nickel-metal hydride (NiMH), alkaline, and lithium, presented next.

8.1. Battery Types

8.1.1. Sealed Lead Acid (SLA)

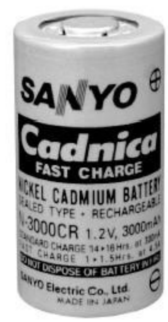
SLA batteries have lead-based electrodes, and electrolyte composed of sulfuric acid. Each electrode inside the battery contributes with about 2V, therefore a typical 12V battery has 6 cells connected in series. The SLA types usually used in automobiles cannot be used in combat, because the acid can spill if they are flipped over or perforated by an opponent’s weapon.

Competitions only allow SLA batteries in which the electrolyte is immobilized, which could work upside down without risk of spilling. The most common technologies to immobilize the electrolyte are gel, where silica is added to generate a semi-solid gel, and AGM (Absorbed Glass Matte), where a fibrous and porous material absorbs the acid and keeps it suspended.

SLAs are usually available in up to 12V, therefore it is necessary to use at least 2 of them connected in series to reach usual combot voltages of 24V or more. They are the cheapest type of battery, however they are the heaviest ones, therefore it is usually better to replace them for NiCd, NiMH, or lithium batteries, which will be discussed next. Another disadvantage is that most of them take several hours to charge.

8.1.2. Nickel-Cadmium (NiCd)

NiCd batteries use nickel as cathode, and cadmium as anode. They supply high currents without significant voltage drops, and because of that they are an excellent choice to power the robots’ weapons. They are more expensive than SLAs, however they can last several years if properly handled, returning their investment. Each cell (pictured to the right) provides about 1.2V. The cells are usually soldered in series to form battery packs (also pictured to the right), with voltages that are a multiple of 1.2V. The packs used in combat usually have 12V, 18V, 24V and 36V, with respectively 10, 15, 20 and 30 cells.



8.1.3. Nickel-Metal Hydride (NiMH)

NiMH batteries also use nickel as cathode, however the anode is composed by a metallic alloy capable to absorb hydrates, replacing cadmium, which is poisonous. NiMH batteries store 30% more energy per weight than NiCd, however they can consistently supply about half the peak currents of a NiCd with same capacity. They are a good choice for the robot's drive system, resulting in a high capacity to avoid having a slow robot at the end of a match (drive systems usually don’t require very high current peaks due to wheel slip). A significant problem is that these batteries lose naturally about 30% of their charge every month (self-discharge), therefore they are not appropriate for applications with sporadic use, such as TV remote controls. Even if the remote is not used, in about 2 months the battery would probably need to be recharged again.

8.1.4. Alkaline

Alkaline batteries are the most common, storing a great amount of energy. They don't suffer as much from the self-discharge problem as NiMH batteries, therefore they are the best option for sporadic use (although they are prone to suffer long term corrosion, which may cause cell rupture and electrolyte leakage – this is why they should be removed if not used for several months). The problem with alkaline batteries is that they are not able to supply high currents, and because of that they are not used in combat. Besides, they are not rechargeable, and therefore it would be very expensive to use new batteries in every match. There is a rechargeable version, called RAM (Rechargeable Alkaline Manganese, pictured to the right), however it doesn't supply high currents as well, and the number of recharge cycles is relatively low.

8.1.5. Lithium

Very used in cellular phones, portable computers and several other gadgets, lithium batteries (pictured to the right) currently are the ones with the highest charge capacity with lowest weight. However, they are more expensive and, sometimes, dangerous.

The lithium-ion type is the oldest one, and it suffers risk of explosion if perforated and exposed to oxygen, shorted out, or improperly charged, hence it is not recommended for combat robots. This risk is reduced in the lithium-ion-polymer type (a.k.a. LiPo or lithium-polymer), due to its polymeric layer, but it still exists. Newer lithium battery chemistries, such as lithium-manganese and lithium-iron-phosphate, are much safer, although great care and attention is needed when handling this kind of battery, as discussed in section 8.3.

In addition to safety issues, the models that are capable to supply high currents are still expensive, and they require some electronic system in the robot to guarantee that they won't be discharged below a critical voltage, to avoid permanent damage. But the cost-benefit is still very good. The main lithium technologies for use in combat are described next.

Lithium-Ion-Polymer

Most lithium-ion-polymer batteries have discharge rates higher than 20C, in other words, it is possible to completely discharge them in less than 1/20 of an hour, which is exactly the 3 minutes that we need during a combot match. For 2 minute matches, common in insect classes, a discharge rate of 30C or higher would be better.

The nominal lithium-polymer cell voltage is 3.7V, but when fully charged it provides up to 4.2V per cell. It is not recommended to let the battery voltage drop bellow 3.0V per cell. If this happens, the pack can swell and become permanently damaged, which is also known as puffing or ballooning. This is why it is a good idea to use LiPo battery sets with at least twice the capacity you might think your robot will need during a match, making sure they'll not be completely drained.

Similarly to other battery types, more than one cell is usually needed to power a combat robot. Most manufacturers use the number of cells connected in series or in parallel to describe their products. For instance, if each cell has a nominal voltage of 3.7V and a 500mAh capacity, then a 3S LiPo pack would stand for three cells in series, resulting in 11.1V and 500mAh, and a 3S2P pack would stand for two parallel arrays of three cells in series, resulting in 11.1V and 1,000mAh.

An inconvenience of LiPo batteries is that, despite their short discharge time, usually the charge time is much longer, up to 2 hours in the oldest models, which can be critical between combats. However, newer models can be safely charged at a 1C rate (in other words, in 1 hour), while a few vendors state that their packs can handle a 2C charge rate (charged in 30 minutes). The use of an adequate charger is mandatory, never charge lithium-polymer batteries on lead-acid, NiCd or NiMH chargers, otherwise it will ignite on a strong fire, releasing toxic fumes.

As it can be seen in the picture to the right, LiPo batteries usually have two sets of wires. The twisted pair cable, with black and red wires, is the main power cable. The other cable, with five wires and a white connector in this case, is used for cell-balancing. This process consists of equalizing the cells after charging. There's some controversy on that, because a few manufacturers claim that their battery packs don't need to be balanced, while others recommend to balance the cells regularly. As a rule of thumb, cell balancing is only needed when a fully charged pack presents significant disparities between cell voltages. This can be checked using a voltmeter between the black (negative) and the other wires of the balancing connector. Most vendors recommend balancing if there's a difference higher than 0.1V.

LiPo batteries are mostly used in combat in the lightest (up to 3lb) weight classes, however new technologies are emerging to allow their widespread use. Lithium batteries have a great potential to become the best choice even for the heaviest classes. Nowadays, there are quite a few heavier robots that use this kind of battery, such as all our hobbyweights and featherweight combots, as well as Kevin Barker's lightweight vertical spinner K2, which uses two LiPo 6S1P 5,000mAh packs.

Lithium-Manganese

Lithium-manganese batteries (LiMn, pictured to the right), developed in 2005 by Apogee High Performance Lithium Polymer Technology, use a safer chemistry that can sustain perforation without exploding.

Since the voltage of each cell is 3.7V, these batteries are entirely compatible with lithium-polymer chargers. They can provide the same peak currents of NiCd and the same capacity of NiMH with about half the weight. In addition, they can be charged at a 2C rate. Apogee states that their batteries don't need balancing, due to their cell matching process.

An interesting feature of these batteries is their polycarbonate shielding, which can minimize cell damage during rough handling in combat.

Super Charge ion Battery

Toshiba started shipping in 2008 its Super Charge ion Battery (SCiB, pictured to the right), which can be recharged to 90% of its capacity in only 5 minutes, with a life span of over 10 years.

SCiB Cell

Charging can be performed with currents as high as 50A, which is a real breakthrough. This battery can sustain more than 3,000 rapid charge cycles, with less than 10% capacity loss. It adopts a new negative-electrode material technology that is safer and more stable, being virtually resistant to punctures and short-circuits.

Unfortunately, SCiB batteries are currently only available to industrial markets, in either 2.4V/4.2Ah/0.150kg or 24V/4.2Ah/2.0kg versions.

Lithium-Iron-Phosphate

One of the most promising battery technologies is the lithium-iron-phosphate ($LiFePO_4$ or LFP), discovered in 1996 at the University of Texas. In addition to its high peak currents (over 100C pulsed discharge rates) and high capacity, it is a safe technology: it will not catch fire or explode with overcharge. Its charge time is very low compared to other lithium battery types, sometimes as low as 15 minutes. It is also environmentally friendly.

The most famous brand of $LiFePO_4$ battery is A123. Originally, only the M1 cell model (pictured to the right) was available, but now A123 is also producing other models with higher capacity, such as the M1HD and M1Ultra cells. A123 cells are also sold assembled in battle-ready packs, as pictured to the right, available in several configurations at www.battlepack.com.

Nominal voltage varies amoung manufactures, from 3.0V (K2) to 3.3V (A123) per cell, but when fully charged the cells can provide up to 3.6V. To avoid damaging them, these batteries must not be discharged below 2.8V per cell.

Note that $LiFePO_4$ batteries must be charged with a specific charger, such as the Astroflight 109 A123, iCharger 1010B+, or Robbe Power / MegaPower Infinity SR. There are also adapters, such as the Dapter123, which allows the use of most NiCd chargers.

8.2. Battery Properties

Several battery characteristics need to be considered: price, weight, voltage, shelf life, number of recharge cycles, charge time, self-discharge, discharge curve, internal resistance (which determines the peak current and voltage drop), capacity, de-rating factor and discharge rate, described next.

8.2.1. Price

Price is the first factor in the choice of batteries. SLAs are the cheapest, followed by alkaline, NiCd, NiMH, and finally the lithium batteries. Prices vary a lot depending on the technology, manufacturer, quality and capacity.

8.2.2. Weight

The weight of the battery is crucial in robot combat. More specifically, it is important to know the power-to-weight, energy-to-weight, and capacity-to-weight ratios of each type, the higher the better. SLAs are the worst ones in this requirement, they store less energy per pound than any other type. NiCd and NiMH are much better, while lithium is the best, see sections 8.2.10 and 8.2.12.

8.2.3. Voltage

Battery voltage depends on the number of cells and the electrode chemistry. SLA electrodes nominally supply 2V, usually combined to provide 12V. Alkaline electrodes supply 1.5V, while each NiCd or NiMH cell provides 1.2V. The nominal voltage of lithium batteries depends on their type: lithium-ion-polymer (LiPo) and lithium-manganese (LiMn) provide 3.7V per cell, lithium-ion (Li-Ion) 3.6V, and lithium-iron-phosphate ($LiFePO_4$ / A123) between 3.0 and 3.3V.

Note that the values above are nominal voltages. In practice, the voltage is usually higher than this value, when the battery fully charged, or it can be lower, if it is supplying very high currents, which lead to significant voltage drops due to their internal resistance.

8.2.4. Shelf Life

Shelf life depends a lot on the use and mainly on the storage temperature. In a few cases the batteries can last more than 20 years without significant capacity loss, such as in the case of NiCd stored at 40°F (about 5°C) in a refrigerator. If stored at 100°F (about 38°C), these same batteries would last less than 2 years.

8.2.5. Number of Recharge Cycles

The number of recharge cycles during the useful life of a battery goes from zero (alkaline), up to 300-800 (SLA and NiMH), 500-1200 (lithium-ion), 1500-2000 (NiCd), 5000 (SCiB), and even up to 10,000 recharge cycles in a few special lithium batteries. Note that, as the technology develops, these numbers can be outdated, however they are a good reference for comparison purposes. Forum posts and manufacturer websites are a good source of information to find out more accurate values.

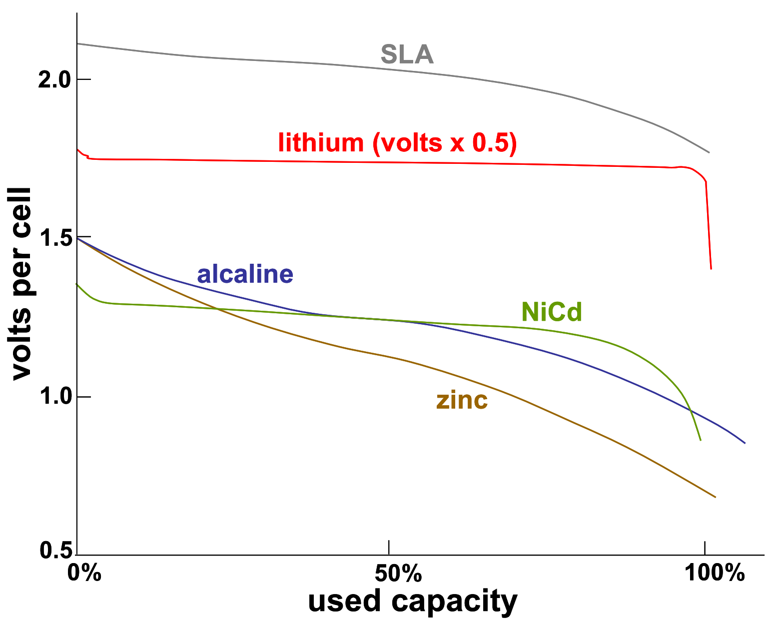
8.2.6. Charge Time

Charge time is another important factor, it determines the minimum time necessary to fully charge a battery without damaging it. The longer it is, the higher will be the number of spare battery sets you will need in a competition. SLAs are the worst ones in that sense, they usually need several hours to fully charge. The Li-Ion and LiPo types usually need at least 1 hour (1C charge rate), however a few of the newer technologies may charge must faster than this, such as A123 (in 15 minutes, with a 4C charge rate) and SCiB (in 5 minutes, 12C). The NiCd is one of the best types, it takes much less than 1 hour to fully charge, in a few cases in only 15 minutes, without permanent damage. Some newer NiMH batteries are reaching similar charge times as NiCd.

8.2.7. Self-Discharge

Self-discharge quantifies which percentage of its capacity a battery naturally loses per month (or per day). Lithium batteries lose about 5% of their capacity per month. NiCd and SLA batteries, if stored at room temperature, may lose about 10% of their capacity per month, while NiMH may lose about 30% per month. Therefore, if you use NiMH batteries in a combat robot, always recharge them again at the day of the competition, to compensate for this loss. This is also a good idea for the other types.

8.2.8. Discharge Curve



The discharge curve of a battery shows its voltage level as it drops off during use. For instance, the graph to the right shows that each electrode (cell) of a SLA battery supplies about 2.1V (up to 2.2V) when fully charged, a value that is gradually reduced until reaching about 1.7V. Therefore, a SLA battery with nominal voltage 12V (with 6 lead electrodes) would have up to 6 × 2.2V = 13.2V when fully charged, and 6 × 1.7V = 10.2V when discharged. This noticeable drop has only one advantage, it could be used to indirectly measure the remaining capacity of the battery. But this voltage drop, on the other hand, will make the system lose power and become slower. Also, robot combat judges would be able to tell that the batteries where dying from this sluggishness, awarding damage points to the opponent. This significant voltage drop happens not only with SLA, but also with (disposable) zinc and alkaline batteries, as seen in the graph above.

Lithium and NiCd cells have an almost horizontal discharge curve, keeping constant their voltage level during the entire combat (except during voltage drops due to high currents). The (rather abrupt) voltage drop is only noticeable towards the end of the battery capacity. NiMH curves are not as horizontal as in NiCd, they are slightly sloped, however not nearly as much as in SLA.

8.2.9. Internal Resistance

The internal resistance of a battery is added to the total resistance of your electronic system. Therefore, the smaller the resistance, the larger will be the current peaks that the battery can deliver. SLA and NiCd batteries have very low internal resistance, allowing them to generate very high currents. The problem with SLA is that those current peaks reduce a lot the battery capacity, due to the de-rating factor, which will be discussed later. NiMH batteries have larger resistance than NiCd, and therefore they are not able to deliver such high current peaks (if compared to NiCd batteries with same capacity, of course). The first lithium batteries had high internal resistance, however in the most recent versions, such as the A123, this value is much lower.

The internal resistance is also related with the voltage drop in the battery caused by very high currents. This is simply due to the energy loss caused by the resistance, which is significant under high currents. This energy is converted into heat, which can also cause thermal failure of the battery due to overheating. A123 batteries, due to their very low internal resistance, can deliver very high currents without significant increase in their temperature.

8.2.10. Capacity

Capacity measures the total amount of current that a battery can deliver until it is fully discharged. It is measured in A·h, calculated from the product between the total discharge time and the average delivered current (if the current isn't constant, then it is calculated integrating it along the discharge time). For instance, a 3.6A·h battery would theoretically supply a current of 3.6A, continually, during 1 hour, or 36A for 1/10 hour (6 minutes). Note that if two identical batteries are connected in parallel, the total capacity is doubled.

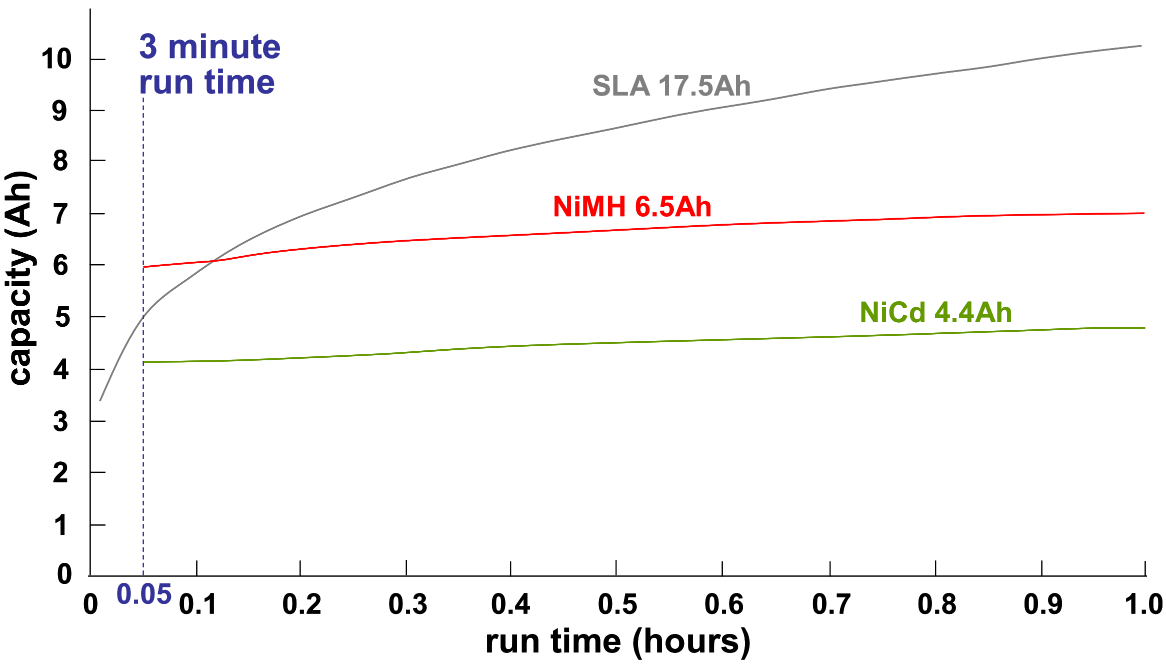
In theory, the capacity of a 24V SLA battery would be about 1.25A·h per kilogram (about 0.57A·h per pound). This is a relatively low capacity, leading to a low energy density of about 24V × 1.25A·h = 30V·A·h/kg = 30W·h/kg. A 24V NiCd pack would have from 1.7 to 2.5A·h/kg (0.77 to 1.13A·h/lb, with energy density between 40 and 60W·h/kg), a good quality NiMH would have 2.5 to 3.3A·h/kg (1.13 to 1.5A·h/lb, with energy density between 60 and 80W·h/kg), and finally lithium batteries would go beyond 4.2A·h/kg (1.9A·h/lb, with energy densities between 100 and 200W·h/kg).

Regarding energy per volume, which is also relevant if you want to build a compact robot, then SLAs only have between 60 and 75 W·h per liter, while NiCd between 50 and 150, NiMH between 140 and 300, lithium-ion about 270, and LiPo around 300W·h/liter.

But those capacity and energy numbers are theoretical, because in practice it is not so simple, the effect of the de-rating factor must be considered, as discussed next.

8.2.11. De-Rating Factor

The total capacity of a battery depends on the discharge time. The nominal capacity that is written on SLA batteries, for instance, is related to a discharge time of 20 hours. Therefore, if you discharge a 17.5A·h SLA with a constant current of only 17.5/20 = 0.875A, it will really last 20 hours. But if you discharge it at 17.5A, it won't last 1 hour. This is because the real capacity of this battery in 1 hour would be only about 10A·h, see the graph below. Therefore, the correct value for a 1 hour discharge would be 10A instead of 17.5A. As it is discharged faster, its capacity decreases. That same battery would only supply 5.8A·h if totally discharged in 6 minutes (0.1 hours), and less than 5A·h during a 3 minute combat (0.05 hours). Those values, obtained experimentally, are represented in the graph below.



Note in the graph that the capacity of the SLA battery depends a lot on the total discharge time (run time). The value that must be multiplied to the nominal capacity to generate the actual battery capacity is called de-rating factor, a number that is usually between 0 and 1. For instance, the de-rating factor of a SLA battery that is required to be discharged in only 6 minutes (0.1h) is worth 0.33, which would give 0.33 × 17.5 = 5.8A·h for the 17.5A·h SLA, which agrees with the graph above, delivering continuous 5.8A·h / 0.1h = 58A.

If you still need more current than that, to the point of fully discharging the battery during a 3 minute combat (0.05h), the de-rating factor will be even lower, about 0.28. In this case, the capacity would be 0.28 × 17.5 = 4.9A·h for the 17.5A·h SLA, which also agrees with the graph above, delivering continuous 4.9A·h / 0.05h = 98A.

The special SLA Hawker-Odyssey (also known as Hawker-Genesis, pictured to the right) has higher de-rating factors than regular SLA batteries, reaching values between 0.4 and 0.5 for the 6 minute run time (instead of 0.33).

One of the greatest advantages of NiCd and NiMH batteries is that their capacity is almost insensitive to the total discharge time (run time). This can be seen in the previous graph, which shows NiCd and NiMH capacity curves that are almost horizontal. Note that their nominal capacity is measured in a 1 hour discharge time, instead of 20 hours as with SLA (lithium batteries are also measured in 1 hour). Even so, there is a de-rating factor for NiCd and NiMH, which is about 0.9 for run times between 3 and 6 minutes. That de-rating factor is 3 times better than the one from regular SLA, and almost 2 times better than in Hawker-Odyssey.

Therefore, for instance, 2 regular SLA batteries with 12V and 18A·h each, when in series, are able to supply 24V with a combined weight of 6.2kg × 2 = 12.4kg (27.3lb). If their desired run time is 3 minutes (in practice it is safer to design your robot with run times of at least 4 minutes, so it can safely endure a 3 minute combat), their actual capacity is 0.28 × 18 = 5A·h. On the other hand, two 24V NiCd packs with 3A·h each, when in parallel, can supply the same 24V with a nominal capacity of 3A·h × 2 = 6A·h. Their actual capacity in 3 minutes is 0.9 × 6 = 5.4A·h, larger than the one from the SLA, and with a total weight of only 1.8kg × 2 = 3.6kg (7.9lb). This is less than a third of the weight of the SLA set, with an equivalent capacity!

The performance of SLA batteries only approaches NiCd when at least 10A·h is needed by the robot, such as in heavyweights and super heavyweights. Even so, this only happens for special batteries such as Hawker-Odyssey. For instance, two 12V Hawker-Odyssey batteries with 26A·h each, when in series, supply 24V, with a combined weight of 6.1kg × 2 = 12.2kg (26.9lb), with an actual capacity of 0.42 × 26 = 10.9A·h (the 0.42 de-rating factor was experimentally measured). It would be necessary to use four 24V NiCd packs, with 3A·h each, in parallel, to achieve those values, resulting in a combined weight of 7.2kg (15.9lb). The NiCd packs would still be lighter, however the weight difference decreased to 5kg (11lb), a small value if compared to the total weight of a heavyweight or super heavyweight. The advantages of using special SLA batteries are their price (about one third the price of equivalent NiCd) and the achievable peak currents, which would be about 800A for this NiCd arrangement (with high discharge cells) but almost 2400A for the Hawker-Odyssey (watch out not to burn your motors and electronics!).

The previous calculation always assumed that the discharge current was constant, which is certainly not true during combat. To estimate with better accuracy the capacity of a SLA battery, you need to use different values of the de-rating factor. For instance, consider the 17.5A·h SLA battery from the previous graph, and assume that your robot needs about 15A to drive around with the weapon turned off, and 100A when it is on. How many minutes would it last with that battery, assuming that it spends 80% of its time with the weapon powered? The answer is obtained calculating the capacity considering the different values of the de-rating factor. From the previous graph, a run time of 0.6 hours (36 minutes) would result in 9A·h, with a continuous current of 9A·h/0.6h = 15A. But a run time of 0.05 hours (3 minutes) would result in only 5A·h, with a continuous current of 5A·h/0.05h = 100A. If the number of minutes to be calculated is t, then the robot spends 0.8·t minutes drawing 100A (3 minute run time), and 0.2·t minutes drawing 15A (36 minute run time), so to completely discharge the battery we would have (0.2·t)/36 + (0.8·t)/3 = 1, thus t = 3.67 minutes.

Let's check the calculations: during the 0.2·t = 0.734 minutes at 15A the robot drains 0.734min/36min = 2% of the battery capacity, and during the remaining 0.8·t = 2.936 minutes at 100A it drains the other 2.936min/3min = 98%. These more sophisticated calculations are not necessary for nickel or lithium batteries, because their de-rating factor varies very little, between 0.9 and 1.0.

8.2.12. Discharge Rate

Finally, the last relevant battery property is the discharge rate, which measures how much current can be continually drawn from the battery without letting it become significantly hot. It is represented by a number followed by the letter C. For instance, 8C means that the battery tolerates without problems a current of 8 times its measured capacity (C, hence the name 8C) in A·h. For instance, a 3.6A·h battery with 8C tolerates continuous 8 × 3.6 = 28.8A without overheating. This is the same as to say that it can be fully discharged in 1/8 of an hour (because 28.8A × 1/8 h = 3.6A·h), which is equivalent to 7.5 minutes.

In practice, most NiCd batteries can withstand more than twice the calculated current from their discharge rate, however they will significantly warm up (but not necessarily overheat, in special if the cells are spaced inside the pack to keep down their temperature). In other words, a NiCd 8C battery could be continuously discharged in only 3.75 minutes, compatible with the duration of a typical combat. Avoid using NiCd batteries rated below 8C, they will very likely overheat during combat.

A few lithium batteries, such as the Polyquest (LiPo) and A123 ($LiFePO_4$), can continuously deliver over 30C and sustain 50C (or higher) peaks without overheating. But, different from NiCd packs, lithium batteries usually do not tolerate current peaks that are more than twice the calculated value from the discharge rate.

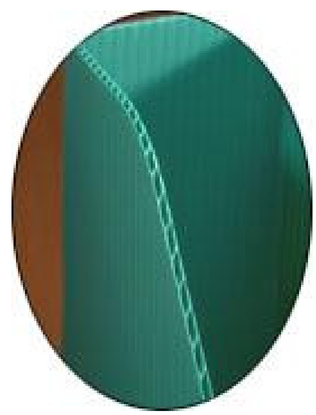
Another way to evaluate discharge capacity is through the power-to-weight ratio of a battery, in W/kg. It evaluates the power that a battery can continuously deliver divided by its weight. SLAs can only deliver about 180W/kg, while nickel batteries between 150 and 1,000W/kg, lithium-ion about 1,800W/kg, and LiPo beyond 2,800W/kg.

8.3. Battery Care and Tips

To make your batteries last longer, it is important to follow several procedures, described next.

8.3.1. Shock Mounting

Make sure that the batteries are very well mounted inside your robot, with some cushioning to avoid impact damages. For instance, the instantaneous accelerations that a robot might suffer during an impact from a violent spinner can reach up to 800G, in other words, 800 times the acceleration of gravity. Only for reference, at 10G a person would faint, and at 100G one's brain would detach from the skull, causing instantaneous death. Therefore, 800G is somewhat frightening, even considering that this acceleration lasts only a small fraction of a second. Quick calculations show that a 4.4lb (2kg) battery would suffer an equivalent inertial force of 2kg × 800 = 3,520lb in its support. Of course this would be an extreme case, but even for much smaller impacts it is evident that zip ties are not appropriate (unless it is a very light pack such as the ones used in receivers). Besides, zip ties might also melt due to the high temperatures that the batteries can reach.



Good materials to shock mount your batteries are hook-and-loops and neoprene. Corrugated plastic, cut from file cases or other office supplies, is also an inexpensive and effective shock mounting material, as pictured to the right.

Be careful not to cause short-circuits, you must isolate very well any metal parts that get in touch with the battery. And you must guarantee in your robot design that the batteries can be quickly replaced, to speed up pitstops.

Note that LiPo batteries expand almost 10% in size during use, so make sure that there's extra room inside your robot not to let them get squeezed too much. Using very compliant shock mounts is a good way to accomplish that.

8.3.2. Recharging

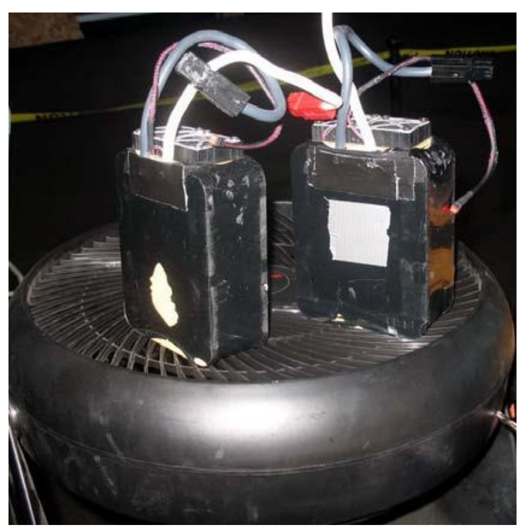
To recharge batteries, especially the nickel and lithium types, you must use an electronic charger. They are an indispensable investment. Without them, the chances of damaging batteries are very high. Triton 2 (pictured to the right) is one of the best and easiest chargers to use. It automatically charges or discharges most battery types, with several programming options. It eliminates the infamous "memory effect" that happens when NiCd batteries are not properly charged. It costs a little over US$100 in the US. It is really worth investing in an electronic charger such as Triton 2, or several famous others such as Astroflight, Thunderpower or Dynamite models. It only takes one damaged 24V NiCd pack to set you back more than the price of the charger.

Due to lithium batteries being prone to ignite when mishandled, they need a lot of attention when charged. They need an intelligent charger to charge them following the correct algorithm. This kind of battery cannot be overcharged under any circumstances. In addition, to prevent damages to your robot (and people), always remove the batteries from the robot and charge them inside a fireproof container, such as LP-Guard or LipoSack. The picture to the right shows a LipoSack and the ignited battery that it withstood inside.

If your robot uses more than one pack, you might want to have more than one charger, to be able to charge the entire set of batteries at the same time, in time for the next match. We’ve built a wooden box, which is a good electric insulator, to mount 4 Triton chargers (pictured to the right), together with 12V power supplies taken from old personal computers. The box also carries our battery packs, which is a practical solution for ground transport and use in Brazilian competitions. For international competitions, which require air travel, we have a more compact version of the charger box, shock-mounted inside a suitcase.

Always have at least 2 sets of batteries for your robot. Nickel and lithium batteries can take up to 1 hour to fully charge, however the pit time between rounds can be as low as 20 minutes. If you can afford it, get 3 or more battery sets. Besides solving the charging time problem between rounds, having a third (or fourth) set is an additional insurance in case a pack gets damaged or shorted out during combat. If you use regular SLA batteries, you might need up to 6 or 7 sets during a competition, because they charge very slowly, sometimes taking several hours.

Another important tip is: never charge hot packs. Its useful life would be very much reduced if charged while still hot after a match. As soon as a combat ends, immediately remove the battery packs and put them over a large fan to cool down (as pictured to the right). Only begin to charge them after they get close to room temperature.



8.3.3. Battery Storage

Always store SLA batteries fully charged. If they are stored discharged for a long time, they can be damaged. Completely recharge SLA batteries every 6 months if they're stored.

Unlike SLA, NiCd and NiMH batteries should be stored fully discharged. Be careful not to discharge them too much, nickel batteries should never get below 0.9V per cell. Lithium-polymer and lithium-manganese batteries must never get below 3.0V per cell, while $LiFePO_4$ should never be allowed to drop below 2.8V per cell.

Also, have in mind that heat kills: even if properly discharged, nickel batteries can last less than 2 years if stored at 100°F (38°C). At 77°F (25°C) they usually last 5 years, at 59°F (15°C) they can reach 10 years, and at 41°F (5°C) up to 20 years. Therefore, store NiCd and NiMH batteries inside a refrigerator, fully discharged. Put them inside a sealed plastic bag to protect them from moisture. Never freeze the batteries. Every 6 months or less, make sure to fully charge and discharge them, and put them back in the refrigerator.

To store lithium batteries, first place the packs into a LiPo sack or equivalent, then charge (or discharge) them to 40%~60% of their capacity (LiPo: 3.8~3.9V per cell; $LiFePO_4$: 3.2~3.3V per cell). If your charger does not support terminal voltage configuration, then fully charge the battery and then discharge it monitoring the voltage value with a voltmeter. Finally, isolate the connectors with tape, place the batteries into separate sealed plastic bags, and store them in the refrigerator at about 41°F (5°C). Once a month, check the voltage of your lithium batteries and, if needed, recharge to keep them between 40% and 60% of their capacity.

Be very careful not to short-circuit your batteries, especially the lithium ones. Be attentive when handling screws near the pack, they can fall inside and cause a short-circuit that can permanently damage the battery. There is also the risk of metal debris entering your pack during combat. This may result in the famous "magic smoke" (pictured to the right), which will either disable your robot or result in damage points to your opponent. Some people say that magic smoke is the robot's soul leaving its metal body.

To avoid this problem, you can wrap up each battery in the pack with Kapton tape, a polymer that resists high temperatures, up to 750°F (400°C), besides being a good electric insulator.

If your pack is getting too hot, an option is to install one or two fans to blow air inside it, helping it cool down. There are a few ready solutions in the market. One of the best NiCd and NiMH packs in the market are the ones from Robotic Power Solutions (www.battlepack.com), they sell both the traditional battlepacks and the intercooled ones (pictured to the right).

8.3.4. Assembling Your Own Pack

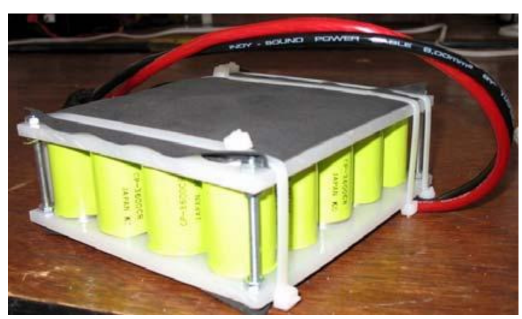
NiCd and NiMH packs are not cheap, so it is possible to save some money if you assemble them yourself. First, buy individual cells, making sure that their discharge capacity is at least 8C, and wrap each of them with Kapton to avoid shorts.

To assemble the pack, weld the cells using flexible copper braids. Rigid connections can break during combat. At the RoboGames 2006 semi-finals, one of the two 24V battery packs from our middleweight drumbot Touro stopped working right after the first impact against the tough rammer Ice Cube. Touro had to fight the entire 3 minutes with only one pack, which made it slow down near the end of the match. This counted as damage, which was decisive in our split decision loss by 17-16. Back in the pits, we've realized that a rigid connection had broken off inside the battery. The pack was cold, indicating that it had broken in the beginning of the match, with almost full charge. This was confirmed from the 2 minutes it later took to be recharged, after the solder was fixed. Since then, we've only used copper braid connections in our batteries.

Use very fine sandpaper on the battery contacts to remove oxidation, which would compromise the mechanical and electrical resistance of the solder. Use a high power solder iron, with at least 100W. Tin as much as possible the battery contacts and the wire, and weld them quickly to avoid heating up and damaging the cell. An important tip is, before welding, to put o-ring spacers among the cells, as pictured to the right. These spacers can be, for instance, cardboard rings held together with shoemaker's glue. By doing so, you will leave gaps among the cells that will allow air to flow, making the heat exchange much more efficient, avoiding overheating them.

After having soldered all the cells using copper braid, weld the connector and its wires. The connector can be, for instance, a Deans Ultra or the Anderson Powerpole. Remember that the battery should always use the female connector, never the male, to avoid any chances of short-circuit if the connector accidentally touches some metallic part.

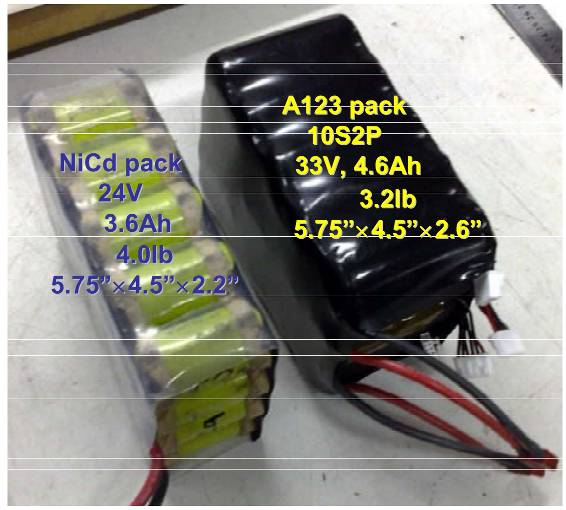
Optionally, you can use nylon plates (or some other insulating and resistant material) covering the top and bottom of the pack, as pictured to the right. It will be necessary to use a mill to carve slots in the nylon to accommodate each of the cells. You can then secure the nylon plates with long screws, as shown in the picture.



With or without nylon plates, it is advisable to protect the pack with shrink-wrap. If you don't have shrink-wrap, a very cheap alternative is to fit the pack inside a cut Coke bottle, and use a heat blower to shrink it to hold the pack with a snug fit. Using a hot soldering iron, you can make a few openings in the shrink wrap (or Coke bottle) at the spaces between the cells, to improve cooling.

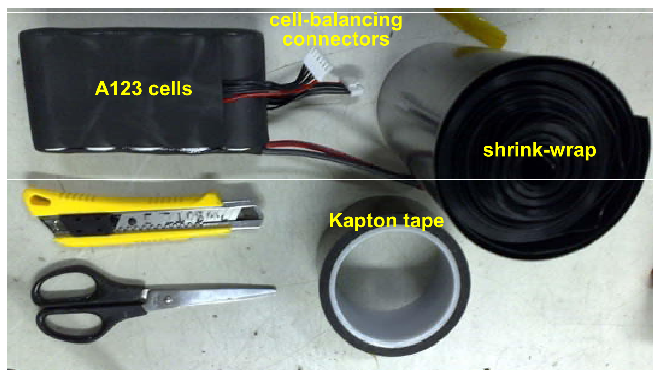
A very similar process can be used to assemble packs made out of A123 packs, which also have a cylindrical shape. But don't forget to solder separate cables and connectors for cell-balancing.

The pictures to the right show a 20-cell 10S2P A123 pack including cell-balancing connectors. The 10S2P configuration features 2 parallel arrays of 10 A123 cells each in series, resulting in a nominal capacity of 2 × 2.3Ah = 4.6Ah and a nominal voltage of 10 × 3.3V = 33V.



This pack resulted in the exact same width 4.5" and length 5.75" of a 24V 3.6Ah NiCd battlepack (including o-ring spacers, as pictured to the right), which allows both to be interchanged without having to modify existing robots to fit them.

The height of the A123 pack, however, is a little higher: 2.6" instead of 2.2" from the NiCd pack. But the A123 pack is actually lighter, because its 20 cells weigh 20 × 70g = 1.4kg, instead of 20 × 88g = 1.76kg from the NiCd CP-3600CR cells. In addition, this A123 pack has higher nominal voltage and capacity than the equivalent sized NiCd battlepack, 33V and 4.6Ah instead of 24V and 3.6Ah. Not to mention the improved properties of A123 cells over NiCd.



An important advice: you should only assemble your own pack if you know what you’re doing. It is not difficult to damage cells by overheating them while they’re soldered. It pays off to have them professionally assembled, for instance, at www.battlepack.com.

8.3.5. Billy Moon’s Rules for LiPo

Finally, a battery care section would not be complete without the rules from famous builder Billy Moon for handling LiPo batteries:

1. NEVER, NEVER, NEVER charge in your robot;
2. NEVER, NEVER, NEVER charge them hot;
3. always charge them in a LiPo sack or steel tool box;
4. check balance on your batteries before each charge;
5. charge them as slow as you can afford to;
6. never short their leads (if you do, toss them out);
7. never remove them from your bot by the leads;
8. allow extra room for them to expand by 10% in all dimensions while in use;
9. never fully discharge them: plan for at least 50% more capacity than you need;
10. bring or arrange to have a 'class D' fire extinguisher on hand.