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Review

Selecting Suitable Battery Technologies for Untethered Robot

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Abstract: Untethered robots carry their own power supply in the form of a battery pack, which has a crucial impact on the robot's performance. Although battery technologies are richly studied and optimized for applications such as electric vehicles, computers and smartphones, they are often a mere afterthought in the design process of a robot system. This tutorial paper proposes criteria to evaluate the suitability of different battery technologies for robotic applications. Taking into consideration the requirements of different applications, the capabilities of relevant battery technologies are evaluated and compared. The tutorial also discusses current limitations and new technological developments, pointing out opportunities for interdisciplinary research between the battery technology and robotics communities.

Keywords: batteries; robotics; design engineering; mobile robots; space robots; unmanned aerial vehicles; unmanned underwater vehicles

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1. Introduction

Energy storage is one of the major barriers to achieve long-duration autonomy in robots. A large amount of research has therefore been dedicated to improving the energy efficiency of robots through, e.g., control [1] and mechanical design [2]. Despite these efforts, an energy source will always be required to overcome the losses inherent to any mechanical system. Potential energy storage modalities for robots include gasoline (used in some legged robots [3] and exoskeletons [4], autonomous vehicles or drones), fuel cells and batteries. Although gasoline has a very high energy density, around 20 times higher than batteries, combustion engines operate efficiently in only a narrow operating range, cannot deliver torque at zero speeds, and are ill-suited for use indoors due to the heat and fumes they produce [5]. Moreover, internal combustion engines based on conventional technology are ill-suited for smaller robots, although a hybrid generator/battery architecture would be a viable solution for intermediate robot sizes [6]. Lithium-ion batteries and fuel cells have similar ranges of specific energy, but the batteries are capable of much higher specific power [7]. Therefore, batteries remain the logical choice for powering untethered robots. While a vast amount of research has been dedicated to the development and selection of suitable battery technologies for electric vehicles [8–10] and consumer electronics [11], battery selection for robotics has attracted much less attention. This is somewhat surprising, considering the particularly demanding and specific battery requirements of robots.

In this survey paper, we discuss the selection and design of battery systems for mobile (untethered) robotics. The paper starts with a discussion on commonly used battery technologies (Section 2). We then match the general requirements of different categories of mobile robots with the general capabilities of different battery chemistries, identifying general trends, technology gaps and trade-offs in battery selection (Section 3).

Technical solutions such as battery management systems, hybrid architectures and charging stations, which can be used to overcome some of the intrinsic limitations of the batteries, are discussed in Section 4. Finally, we provide an outlook on future developments and opportunities for further research (Section 5). Section 6 concludes the paper.

2. Current Battery Technologies

There are various types of rechargeable batteries such as lead-acid, nickel-cadmium, nickel-metal hydride and Lithium-ion batteries. An overview of some common battery chemistries and their abbreviations is given in Table 1. Lead-acid batteries are the most mature rechargeable battery technology, however, in comparison with Lithium-ion technology, are more suitable for mobile applications due to the high energy density properties, enabling lighter battery packs but with a higher cost.

Table 1. Abbreviations of battery chemistries.

LCO	Lithium Cobalt Oxide ($LiCO_2$)
LFP	Lithium Iron Phosphate ($LiFePO_4$)
LMO	Lithium Manganese Oxide ($LiMn_2O_4$)
LiPo	Lithium-ion Polymer
NCA	Lithium Nickel-Cobalt-Aluminum Oxide ($LiNiCoAlO_2$)
NMC	Lithium Nickel-Manganese-Cobalt Oxide ($LiNiMnCoO_2$)
LiS	Lithium Sulphur
LTO	Lithium Titanate (Li_2TiO_3)
Ni-MH	Nickel-Metal-Hydride

Lithium-ion batteries have been in the market for three decades since Sony first launched them in 1991 [12,13]. Since then, many new chemistries have been developed with significantly improved properties [14,15]. Today there is a large group of mature technologies. The most common technologies in the market are LCO, NCA, NMC, LFP, LMO, LTO, LiS, etc. [10]. From these technologies, some advanced Lithium-ion technologies such as Nickel-Manganese-Cobalt Oxide (NMC) are still under further development. In addition, hybridization of the different technologies is being explored. Lithium-ion polymer (LiPo) battery technology, in which a polymer electrolyte instead of a liquid electrolyte is used, is widely used in applications in which the weight is a critical parameter [16]. LiPo batteries have been around for decades; however, cost and lifespan have prevented their large-scale deployment in, e.g., EVs, but the technology is heavily used in consumer products and robots.

The gravimetric energy density (crucial for weighing critical applications) and the volumetric energy density (crucial for volume critical applications) of current commercial batteries are shown in Figure 1. Although energy density is an important criterion for many applications, there are many more battery properties to consider, including safety, cost, lifetime, energy and power. The available Lithium-ion battery technologies in the present market offer characteristics that vary strongly in all these regards. The application plays an important role when selecting the most adequate storage technology [17,18], and may cause any of these aspects to be prioritized. Table 2 lists the typical parameters of the most common Li-ion battery technologies. In this paper, we focus specifically on robotics as an application.

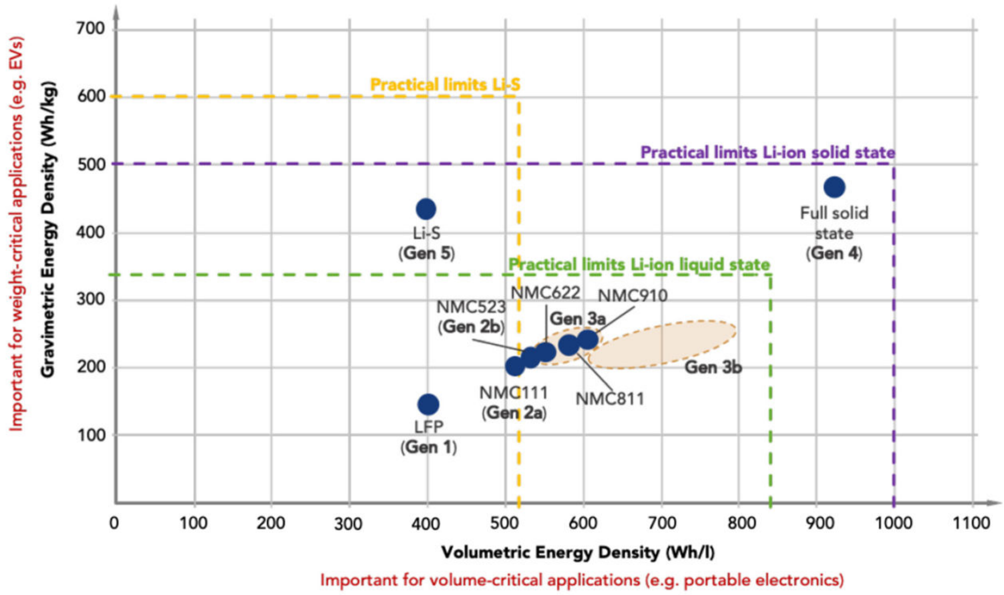

Figure 1. Characteristics and market potential of Lithium-ion technologies [19].

Table 2. Average parameters of popular battery technologies reproduced from [20].

	LCO	LFP	LMO	NCA	NMC	LTO
Nominal voltage (V)	3.6	3.2–3.3	3.6–3.7	3.6	3.6–3.7	2.3
Gravimetric energy (Wh/kg)	160–200	120–140	140–160	200–260	150–220	50–80
Charge/ discharge rate (continuous)	0.7–1C/1C	1C/1C	0.7–1C/1C	0.7C/1C	1C/1C	1C/10C
Cycle life (full equivalent cycles)	500–1000	>2000	300–700	500	1000–2000	3000–7000
Thermal runaway	150 °C	270 °C	250 °C	150 °C	210 °C	280 °C
Advantages	High specific energy, thermally stable	High power, safe, low cost	Comparatively safer, high power	High energy capability	High capacity, leading system	Very safe, long life, fast charging
Disadvantages	Limited specific power, presence of Cobalt	Low capacity, lower discharge performance	Less specific energy, limited growth potential	Higher C-rates concerns	High C-rates can reduce lifetime	High cost, low specific energy
Typical applications	Consumer electronics	EV, portable and stationary applications	EV, power tools, medical devices	EV, industrial, medical devices	EV, industrial, medical devices	EV, UPS, solar-powered lights

3. Capability Analysis of Battery Technologies for Robotic Applications

3.1. Methodology

In order to define the requirements for batteries, we will consider the following main categories of robots (Figure 2):

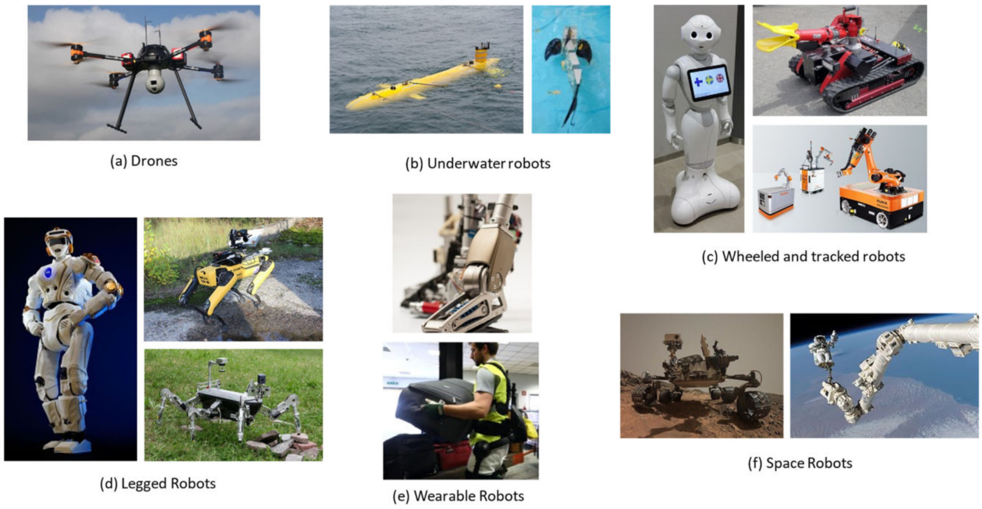

Figure 2. Categories of robots considered in this work, each requiring dedicated requirements from battery technologies. All of the images reprinted in this figure are in the public domain [21–26].

(1) **Space robots**: the two main types of robots present in space missions are orbital and planetary robots, both having the possibility to carry robotic arms for manipulation [27].
(2) **Drones**: these are typically fixed-wing and multi-rotor drones.
(3) **Underwater robots**, more specifically Autonomous Underwater Vehicles (AUVs): These have electric motors on board to actuate their control surfaces (rudders and sterns), actuators for manipulation (robotic arms), in some cases, the thruster. Less conventional, non-commercial solutions such as snake robots, jellyfish robots or swimming (fish-like) robots are also usually actuated by electric motors [28].
(4) **Wheeled and tracked mobile robots**: Most unmanned ground vehicles (UGVs) fall under this category, but many other mobile robots also fit this description. The well-known humanoid robot Pepper, for example, can also be classified as a wheeled robot [29].
(5) **Legged robots**: Another type of UGV, where a large number of actuators—typically electric motors [30,31] are used to drive the joints of two or more robotic legs [32]. These robots can also be equipped with robotic arms to manipulate payloads.
(6) **Wearable robots**: This category includes powered prostheses and active exoskeletons, which exist for both upper and lower limbs. Exoskeletons can fulfill different functions: they can assist the wearer or augment his/her capabilities, at home or in industrial settings, or they can be used for rehabilitation purposes [33].

Each of these categories imposes a set of requirements on the selected battery technology. We have compiled a list of seven requirements that are relevant for a large number of robotic applications: specific energy, current variation, specific power, temperature sensitivity, lifespan, safety and cost. Each requirement receives a score on a scale of 1–5 based on its importance for a category of robots. These scores, summarized in Table 3, are merely intended to reflect the global characteristics of these categories; requirements will of course vary for the diverse applications and robot designs that exist within a category. In Appendix A, we provide a motivation for these scores.

In similar fashion, we have rated eight of the most common Lithium battery chemistries in terms of their performance in the seven requirements listed above. These scores are shown in Table 4. A motivation for the scores can be found in Appendix B.

Table 3. Relative importance of the requirements for the considered categories of robots. The scores are expressed on a scale from 1 to 5. The higher the score, the more important the requirement.

	Drones	**Underwater Robots**	**Wheeled Robots**	**Legged Robots**	**Wearable Robots**	**Space Robots**
Specific energy	5	4	3	3	5	5
Current variation	5	1	2	5	5	2
Specific power	4	2	3	4	5	2
Temperature sensitivity	2	1	3	3	3	5
Lifespan	1	4	1	1	2	5
Safety	3	1	2	2	5	1
Low-cost	4	2	3	2	4	1
Total score	**24**	**15**	**17**	**20**	**29**	**21**

Table 4. Relative performance of the considered battery technologies. The scores are expressed on a scale from 1 to 5. The higher the score, the better the battery technology performs.

	LCO	**LMO**	**NMC**	**LFP**	**NCA**	**LiS**	**LTO**	**LiPo**
Specific energy	3	2	3	2	3	5	1	3
Current variation	1	3	3	4	4	1	5	5
Specific power	2	3	3	5	3	1	4	4
Temperature sensitivity	2	3	3	4	4	1	5	3
Lifespan	2	3	4	5	4	1	5	2
Safety	1	3	3	4	2	1	5	5
Low-cost	4	4	4	4	3	1	2	2
Total score	**15**	**21**	**23**	**28**	**23**	**11**	**27**	**24**

Finally, we calculate the suitability of different battery technologies for the considered categories of robots, based on the scores assigned in Tables 3 and 4. To calculate these scores, we propose the following formula:

$$f_{br} = \frac{\sum_i f_b^i f_r^i}{\sum_i f_r^i} \quad (1)$$

where f_r^i and f_b^i stand for the score assigned to the robot categories and the battery technologies, respectively, for each ith requirement. This weighted average ensures that a battery technology scores better if it serves the most important needs of a robot category. As the denominator cancels out the influence of more demanding robot categories (higher f_r^i on average), the scores can be compared across different battery technologies as well. The scores are represented in Table 5.

Table 5. Relative Suitability of different battery technologies for the considered categories of robots.

	Drones	**Underwater Robots**	**Wheeled Robots**	**Legged Robots**	**Wearable Robots**	**Space Robots**
LCO	2.2	2.4	2.3	2.0	2.1	2.2
LMO	3.0	2.9	3.0	3.0	3.0	2.8
NMC	3.2	3.4	3.2	3.2	3.2	3.3
LFP	3.8	3.9	3.9	4.0	3.9	3.9
NCA	3.2	3.3	3.2	3.4	3.2	3.5
LiS	1.8	2.1	1.7	1.6	1.7	2.0
LTO	3.5	3.4	3.6	3.9	3.7	3.8
LiPo	3.6	3.0	3.4	3.8	3.7	3.1

3.2. Analysis and Discussion

Table 5 indicates that LFP and LTO present a good match for most robot categories. This is not a surprise, since these were also the highest-scoring battery technologies in Table 4. LFP emerges as the best-suited battery for all considered applications. An important disadvantage of the chemistry, however, is its self-discharge, which might trouble the balancing of the battery system [34]. LiPo presents an excellent alternative for drones, legged robots, wearable robots and wheeled robots thanks to its safety and its ability to deal with current variations. Moreover, the use of gel electrolytes instead of liquid electrolytes makes LiPo batteries safer and lighter by providing flexibility in packaging. LCO and LMO score poorly overall as these mature technologies are being overtaken by other technologies. In contrast, the emerging LiS technology still needs considerable improvements to become competitive. Finally, NMC and NCA turn out as suitable chemistries for specific applications.

It is important to note that tailor-made solutions and specificities of the chemistries can have an impact on the choice of specific chemistry. For example, although Table 5 recommends the selection of LFP for drones, the lighter packaging of LiPo batteries makes them the cell of choice for most commercial electronic devices [11]. High-rate LFP chemistry is used in only a small number of drones for shorter missions, due to its good high-current discharge abilities. NMC technology is utilized for longer missions where energy demand (specific energy) dominates the selection process.

In the case of underwater robots, the pressure tolerance of the battery is an additional consideration that guides the Lithium-ion chemistry choice [35]. The present Lithium-ion technologies are replacing the usually used lead-acid and Ni-MH batteries providing more energy and lifespan [36]. Despite their low score in Table 5, LiPo batteries are considered a suitable choice since their packaging can be designed to resist pressure in deep water. Table 5 also suggests NMC, LTO and NCA as good alternatives for underwater robots due to their lifespan. Overall, there is no clear preference in the present battery selection for underwater robots [36].

In commercial wheeled and tracked robots, a variety of Lithium-ion batteries are used, including LFP and LiPo batteries. LFP technology indeed ranks first in the battery selection for this category of robots, which are very balanced in terms of requirements. LiPo batteries—the third choice after LTO—can bring light packaging and flexibility as additional advantages.

For legged robots, LTO and LiPo batteries are rated similarly to LFP. The limited commercial availability of LTO batteries makes LFP and LiPo technologies, which dominate the market share [37–40] the preferred choice. LiPo batteries are more common as the polymer electrolytes endow them with the ability to support the high current pulses typical of legged robots.

LiPo technology is an excellent choice for wearable robots, as it fits most of the requirements for current variation, specific power and safety. LiPo battery packs have indeed been used in several exoskeletons, although newer exoskeletons increasingly rely on Lithium-ion chemistries [41,42]. Specifics about the battery chemistry of wearable robots are, however, rarely reported. Table 5 suggests LFP and LTO as the most suitable technologies.

Due to their excellent properties in terms of current variation and lifespan, LFP and LTO technologies are suggested as the technologies of preference for space robots, with NCA—the battery chemistry that was selected for the Mars Rover—as a close third. However, due to high self-discharge (important for long missions) and lack of commercial availability, LFP and LTO technologies are not commonly used. In recent missions, robots have typically been equipped with NCO technology batteries, which are similar in terms of chemistry to NCA but lack the presence of aluminum [43]. NCA is found to be the key technology of interest in NASA's future consideration as they are closely studying various market-available NCA batteries [44]. Although it ranks poorly in Table 5, and is rarely used in other space applications, LCO is often used in NASA missions. The possible reasons for this may include a customized battery cell, maturity of the technology, optimized anode resisting lithium-plating at low temperature, better stability, etc. [45]. For satellite missions, both LiPo and Lithium-ion cells are being considered depending on the features of interest [46,47].

Although Table 5 presents a general view of the applicability of battery technologies for different categories of robots, its contents should be interpreted with scrutiny. Firstly, aspects such as lifecycle cost, material availability, environmental impact and recycling have been left out of the scope of requirements to be assessed but may also be of interest for battery selection. Secondly, all requirements have received equal weights in the calculation of the final score; a weighting of the different requirement categories may produce a more targeted selection. Finally, and perhaps most importantly, the scores do not reflect the specifics of a particular robot application, nor do they capture all the available technological solutions to tailor battery cells to the application. We discuss these in the following section.

4. Additional Technologies for Improved Performance

Several additional technologies can be added to overcome the inherent limitations of batteries, albeit often at the cost of extra weight, complexity and cost. Below, we give an overview of common solutions (depicted in Figure 3).

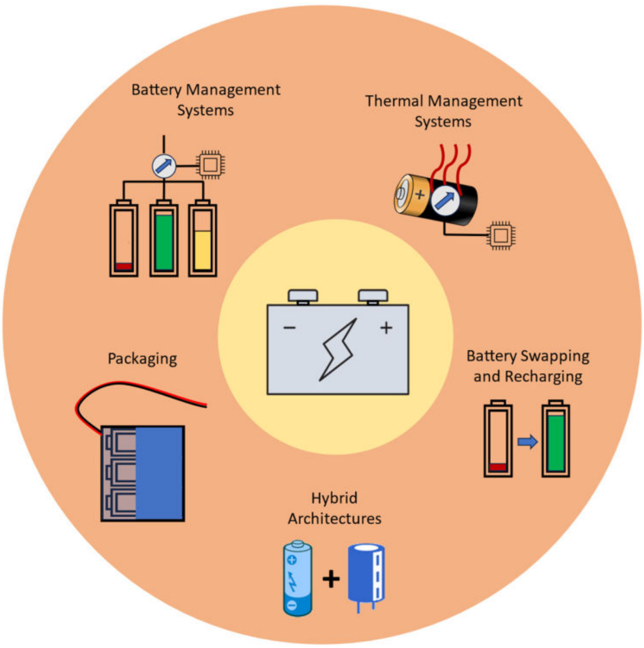

Figure 3. Additional technologies that can improve the performance of a battery.

4.1. Battery Management Systems

The Battery Management System (BMS) ensures that the battery is operated within the Safe Operating Area (SoA) and helps prevent accelerated degradation of the battery [48]. It can therefore be considered a safety-critical component. The main functions of the BMS are (1) monitoring the voltage, current and temperature; (2) diagnosis of the battery by estimating the state of the battery; (3) cell balancing by keeping the cell voltage at the same level; (4) management of the battery system, both electrical and thermal; and (5) communications. Advanced BMS with wireless communication systems and advanced sensor technologies could improve battery monitoring [49,50]. Hence, next-generation models for battery performance and aging (SoH and RUL) monitoring can upgrade BMS functionalities [51–55].

BMS units are commercially available, and off-the-shelf devices often present the most convenient solution. However, for robotic applications, these may end up being less cheap, less safe, and less sustainable in the longer term compared to customized solutions. Customized BMS have been developed for rescue robots [56] and underwater robots [57].

4.2. Thermal Management Systems

Achieving high battery performance under safe conditions is a challenge that is addressed by the design of appropriate battery thermal management systems (BTMS). Accurate 1D–3D thermal models are indispensable for predicting the thermal behavior of the battery to improve its design and shorten the development process [58]. Robotic applications may require a tailor-made BTMS to fit their specific needs, the development of which may be driven by space limitations and the movement of the robot. There is a need for scientific research in this domain.

In addition to the thermal management of the BMS, active cooling (based on air or liquid [59]) and passive cooling (phase change materials and heat pipes [60]) can be introduced to keep the battery's temperature in check. Thermal management is, of course, not limited to the batteries: the performance of actuators and power electronics is also directly affected by temperature, which is why they often have their own thermal management systems. An overview of thermal management systems for robotic systems can be found in [61].

4.3. Recharging and Battery Swapping

The need for high energy densities can be reduced by frequent recharging. Various charging methods have been developed, often optimized for the working conditions of the robot. In many cases, the robot is idle or has limited capabilities while it is being charged; therefore, a high charging speed is desired. Here, the BMS plays an important role in controlling the charging speed, resisting overcharging if safety is compromised [62], and optimizing the charging strategy, which supports the energy management of the battery [63,64]. In terms of battery selection, the fast-charging capabilities of battery technologies such as LFP, LTO, NCA and LiPo puts them ahead of others when charging speed is a priority.

To enable easy charging, docking stations are now utilized for many commercial robots such as vacuum cleaners, grass-mowing robots and mobile social robots [27]. Moreover, for electric vehicles, especially for the upcoming driverless cars, robotic EV chargers, both stationary [65] and mobile [66], are under development. These approaches are being transferred to untethered robots [67,68], although they present some application-specific challenges. Docking stations for underwater robots that utilize contact-based wet-mate connector technology require high-precision docking and are prone to corrosion and electrical safety issues [35]. To overcome these limitations, wireless recharging techniques are being investigated [69]. Inductive and capacitive power transfers are also possible at the cost of lower charging speed and higher losses [70,71].

An advantage of wireless technologies is that they can be deployed for continuous charging [72,73], which is an interesting option if the downtime associated with recharging is considered prohibitively long. However, the cost of continuous wireless charging infrastructure can turn out to be high, and the resonating coils that are typically used may produce high values of stray magnetic fields [74,75]. Power transfer through sliding contacts (so-called "powered floors") can be a more cost-effective alternative [76]. For mobile robots that are not in contact with the ground, recharging during the mission is made possible by photovoltaic cells [77] and electromagnetic field (EMF)-based alternatives such as charging from high-voltage power lines [78]. Alternative approaches include laser beam and battery dumping.

Another method to reduce the downtime is battery exchange or battery swapping. In [79], a change/recharge station is presented that swaps the depleted battery of a UAV with a fully charged one. A queue of batteries, which are continuously being recharged, is available at all times. Barrett et al. developed a mobile ground robot for the battery exchange of small-scale UAVs [80].

4.4. Hybrid Architectures

High charge and discharge currents at very short pulse lengths are challenging for many battery chemistries. Hybrid architectures (battery + battery or battery + capacitor) could present a solution for robots that perform cyclic tasks, but require additional attention to factors such as cost, self-discharge and temperature effects [81–83]. Capacitors, for example, generally exhibit higher self-discharge rates than batteries. A capacitor will thus drain energy from the battery in a battery–capacitor hybrid, decreasing the autonomy of the robot. Temperature effects are another important consideration for hybrid battery structures. They affect some battery technologies more than others, which is why they should be considered when designing a hybrid battery structure for a robot expected to operate at a wide range of temperatures. This is the case for, e.g., field robots and wearable robots. The hybrid use of battery technologies would also require advanced control strategies to efficiently optimize the power and energy demand, for example, shown in [84]. Finally, the mixed-use of coupled batteries may challenge the sizing requirements in robotic applications [85,86].

4.5. Packaging

The performance and safety of a battery can be affected by the working conditions, in particular, moisture, vibrations and shock loads. Many untethered robots are deployed in such harsh conditions. A robust packaging protects against these conditions, but adds around 15% to the volume and mass of the battery [87]. Typical shapes of Lithium-ion batteries (cylindrical, pouch and prismatic) provide benefits in packaging density, but this comes at the cost of more complex thermal management [88].

The impact of shock and vibration on battery performance is, however, a poorly investigated topic [89]. Standard shock and vibration tests found in the literature report no effect on the battery capacity [90]. However, an external shock due to accidents, improper packaging, pressure and operational thrust can have a detrimental effect on the battery characteristics triggering sudden failure [90,91]. A robust mechanical design considering the thermal protection, egressing outlet, vibration isolation, crashworthiness, packaging material, and concept not only improves the battery reliability but also positively impacts performance [88,92].

On a robot level, shock-absorbing materials, airbags [93], compliant actuators [94], fall and impact detection techniques [95] with prevention strategies and constraint handling control techniques [96] can be used to mitigate the damaging effects of shock loads. A robust battery packaging can further protect against these conditions, improving mechanical stability but also enhancing safety [92]. There is however a packaging penalty in terms of the mass and volume of the battery packs. A good rule of thumb is to deduct 15 percent from the cell performance figures [7,89]. Typical shapes of Lithium-ion batteries (cylindrical, pouch and prismatic) provide benefits in packaging density, but this comes at the cost of more complex thermal management [88].

Batteries are usually subject to standards and passed through quality control before being used in an application that already certifies safe handling during regular and irregular shocks [90]. Errors in the system design can, however, also trigger mechanical failure or damage and, consequently, battery performance. In this case, the LiPo battery is often considered a better choice due to its flexible shape and size.

5. New Solutions

Finally, we provide an outlook on new solutions that can help push battery technology beyond its current boundaries and open up new possibilities within the field of robotics. A graphical depiction of these solutions can be found in Figure 4.

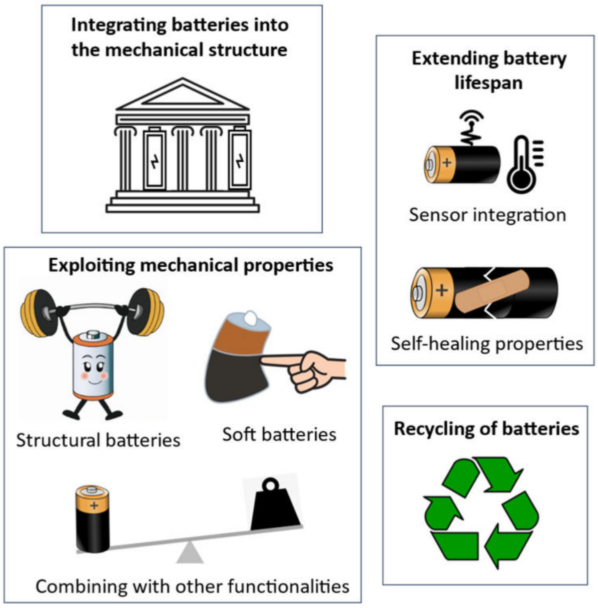

Figure 4. New solutions and directions for future research.

5.1. Extending Battery Lifespan

The research community is trying to discover new ways to detect battery degradation and to slow down the ageing phenomena in batteries. We consider sensor integration and self-healing as two promising concepts for battery life extension.

5.1.1. Sensor Integration

Novel sensors can be used to monitor the mechanical properties of the cells, such as the internal pressure in the battery cell, and utilize those for both State of Charge (SoC) and State of Health (SoH) estimations [97]. In recent studies, ultrasonic acoustic sensors and non-destructive testing probes with high frequency [87] have been explored for SoX estimation (X = charge, health, energy, power and safety) [98]. Electrochemical and chemical reactions can also be monitored, allowing thermal runaway or any other side reaction to be diagnosed and a failure predicted. Optical fiber sensor technology is able to track chemical events such as solid electrolyte interphase formation and structural evolution, which can be correlated to SoH estimation but also detect cell temperature gradients [99].

5.1.2. Self-Healing Properties

We expect self-healing properties to play a key role in the coming battery technologies, as they can drastically improve the sustainability of the robot [100]. Self-healing characteristics are directly linked to the battery materials in use. The use of silicon for battery cell development is very promising because of its high energy density, but degradation poses several problems that currently stand in the way of developing safe and durable batteries. In recent research, lifetime and thermal instability problems have been tackled by developing self-healing polymer systems and technologies for the synthesis of novel polymerized ionic liquids, self-healing surface layer-protected silicon anodes, and advanced core/shell-structured NMC nanoparticles [101].

5.2. Integrating Batteries into the Mechanical Structure

Fat, which is one of the main sources of energy in the human diet alongside carbohydrates and proteins, can be considered the human counterpart of batteries. It can be stored in fat tissue, which is spread over the entire human body. Mobile robots may also benefit from the integration of batteries in their structure, since their battery packs—which are usually structured in a rectangular shape—currently take up a lot of space. Car manufacturers have already picked up on this idea. Volvo was one of the first to develop experimental car panels with integrated batteries [102], and recently, Tesla has announced that their new Model Y will have batteries integrated into the structure of its chassis [103]. Although damage-tolerant battery packs have recently been demonstrated for use in electric vehicles [104], the potential outbreak of fire or the occurrence of an explosion in the event of an impact or structural failure remains a major safety hazard [105]. Since weight reduction is of great importance for many battery-driven robots, we anticipate that structural integration of batteries will also gain traction in robotics.

5.3. Exploiting Mechanical Properties

Aside from its function as energy storage, body fat also serves as an insulator and as a shock absorber, helping the body sustain a normal core temperature and keeping organs safe from mechanical impacts. Similarly, one can exploit the mechanical properties of batteries. There are two main options: using the battery as a structural component, taking advantage of its material strength, or exploiting its elastic or damping characteristics (soft batteries).

5.3.1. Structural Batteries

Structural batteries combine electrical energy storage and mechanical load-bearing functions. As such, they can reduce the cost of transport of vehicles, mobile robots or any self-propelling machine. Structural batteries have been suggested for implementation in electric vehicles, aircraft (including drones [106] but also robotic birds [107]) and spacecraft [108].

Structural batteries are often designed as composites where the reinforcement elements double as electrodes, while the polymeric matrix acts as the electrolyte and as a structural binder for the fibers, creating what is, in essence, a Lithium-ion battery [109]. A disadvantage of these structural battery composites is that they often present a trade-off between mechanical and electrochemical performance, although some promising improvements have been presented in recent years [110–112].

An alternative to structural battery composites is Zn-air batteries. These hold great promise due to their safety properties and high theoretical specific energy. Nevertheless, they have some downsides, such as a low operating voltage window, corrosion issues, and the need to use metal catalysis, which normally is quite expensive. Those limitations have slowed down the introduction of this technology into the market [113].

5.3.2. Soft Batteries

Soft robots are typically constructed out of soft materials that have a stiffness similar to materials found in living organisms (104–109 Pa) [114]. To enable the integration of batteries into their structure, flexible rechargeable batteries would be required. Their development has received a considerable amount of attention from the academic and research communities in recent years. The battery's flexibility would enable it to be bent, folded, twisted, and deformed in many other ways, opening up new possibilities for end-user applications. Lithium-ion, Li-sulfur, Li-air, Zn-ion and Zn-air technologies have already been shown to be suitable candidate technologies. However, frequent mechanical deformations lead to a deterioration of the electrochemical functions, accelerating the ageing process of the battery [11].

5.3.3. Combining Other Functionalities

In [115], a robotic fish was presented with a synthetic vascular system consisting of redox flow batteries. It combined the functions of hydraulic force transmission, actuation and energy storage into a single integrated design. In the Kangarobo, the battery pack is intentionally located on the tail, using it as a counterweight to assist jumping motion and help achieve a stable landing [116].

5.4. Recycling of Batteries

Battery materials have a profound impact on the environment when not properly disposed of. Moreover, the materials from which they are composed are rare. There is thus a strong need for economically useful and ecologically appropriate ways of dealing with devices at the end of their lifespan. Ideally, batteries would be re-used. For example, Nissan re-uses the batteries from the Leaf car in factory-automated guided vehicles [117]. Recycling is however more common and is therefore becoming a very important topic in the battery landscape. Novel battery technologies, manufacturing techniques and battery management systems should thus be conceived while bearing in mind end-of-life management and recycling.

6. Conclusions

Although batteries are widely used in robotics, engineers typically only consider battery selection at the end of the design process of a robot's actuation system. Design optimizations often stop at the actuator, while achieving high performance and autonomy requires the whole system—including batteries and peripherals—to be taken into consideration. In this paper, we discussed the key criteria that guide the choice of battery technology for different robotic applications, taking into account additional technologies that can be used to overcome their inherent limitations, and discussed novel solutions that are currently under development. It is clear that gaps still exist between the requirements of robots and the capabilities of battery technology. We hope that this paper will bring the battery research field and the robotics community closer together, allowing us to close these gaps and fulfill the promise of battery-operated robots with unprecedented levels of performance and autonomy.

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Appendix A. Battery Requirements of Robots

In this appendix, the battery requirements for different categories of robots are discussed. This appendix also serves as a motivation for the scores assigned in Table 3.

Appendix A.1. Specific Energy

Specific energy is defined as the amount of energy that can be stored in a battery divided by the mass of the battery. In our applications, the required amount of energy corresponds to the desired amount of autonomy for the robot (running time), which is specified by the designer. The specific energy requirement is therefore equivalent to the need for a lightweight battery pack.

The reduction in mass is one of the primary goals in the design of untethered robots, since it contributes directly to their cost of transport, and thus their energy consumption. An avalanche effect comes into play here: bringing down the energy consumption will reduce the size of the battery pack for the same autonomy requirement, further driving down the cost of transport. Moreover, a reduced mass can also introduce an increase in maximum speed, payload capabilities, maneuverability and safety [118].

Based on this reasoning, we assign a score of three for legged robots and UGVs. Underwater robots (2) receive a lower score because underwater drag forces are higher and therefore responsible for a relatively larger portion of the robot's energy consumption.

In space missions, every gram counts, so space robots (5) top the list when it comes to prioritizing mass reduction. UAVs (5) also receive a high score, since their battery presents a large proportion of the total weight of the device and will therefore have a strong impact on the UAV's range [119]. The final category to receive the top score is wearable robots (5). Except for rehabilitation platforms and a small number of exoskeletons intended for human augmentation, most wearable robots are not continuously in contact with the ground. This means that their mass is carried by the wearer, which comes at a metabolic cost. For this reason, mass reduction is one of the main goals of exoskeleton designers.

Appendix A.2. Current Variation

What sets robotics apart from other common machines such as fans, pumps, etc., is that their actuators do not operate at constant speeds, nor do they deliver constant torques. Instead, accelerations of the motors and variations in load torque result in variable currents drawn from the battery.

Wearable robots and legged robots (5) encounter very high current variations, which are inherent to the way humans move. During the stance phase of gait, the legs bear the entire weight of the robot, leading to high motor torques and therefore high motors currents. When the foot is lifted from the ground (swing phase), however, this weight is removed, and the required motor torque drops drastically [120]. Similar considerations apply to the upper limbs, which sometimes carry high payloads. Moreover, the accelerations of human motions are typically high, and a transparent actuator should be able to follow these [121].

The motors of drones (5) face high accelerations, which lead to considerable current peaks, making discharge rate one of the main design criteria for drones. Accelerations tend to be lower for UGVs (2) and underwater robots (1), where the dynamics are damped by friction from the environment, and for space robots (2), where accelerations can be kept low by spreading the task out over time.

Appendix A.3. Specific Power

Specific power is defined as the peak power of the battery divided by its mass. As a consequence of the varying torques and speeds encountered in robotics, there is a large variation in the power consumed by the actuators. Large power peaks are very common in many applications. In intermittent operation, it is the peak power rather than the average power that determines the capacity of the battery [122].

Wearable robots (5) face the strongest variations in power demand. An ankle prosthesis, for example, must produce around 250 W of peak power during normal walking [123]. A typical full lower limb exoskeleton may produce over 2 kW of peak power [124], and a full-body suit will have even higher requirements, especially if it is intended for human augmentation. Legged robots (4) encounter similar peak powers, but wearable robots receive a higher score because mass reduction is more of a concern for this category of robots.

Power profiles of UAVs (4) also exhibit high power peaks due to their rapid ability to change direction. UGVs and underwater robots (2) encounter less variation in the power profile and, as explained earlier, can afford to carry more battery mass. Specific power is also less of a concern for space robots (2) since their tasks can be spread out over time to decrease power peaks.

Appendix A.4. Temperature Range

The external temperature will have an impact on the performance of the battery, and therefore needs to be considered in the design. Though modern Lithium-ion technologies can operate at low temperatures such as 30 °C, a warmer zone is required to obtain the best performance.

Space robots (5) are exposed to the most extreme ranges of temperatures. The average temperature on Mars, for example, is around −55 °C with regular temperature swings of around 100 °C within each day. On the Mars Curiosity Rover, a dedicated heating system is used to bring the lower limit up to −20 °C, but the rest of the difference has to be handled by the battery itself [125].

The other categories of robots are often deployed outdoors, where they have to deal with the temperature variations inherent to the earth's climate—which are much more moderate than those encountered in space. Still, these robots will need to operate at temperatures below 0 °C in wintertime, while during the summertime, the overall temperature inside the robot casing can reach up to 50 °C. UAVs (2) and, to a lesser extent, legged robots, UGVs and wearable robots (3), enjoy the benefit of forced convection, which aids heat transfer. Underwater robots (1) have the additional benefit of not being exposed to atmospheric conditions but rather to the moderate temperature variations of water.

Appendix A.5. Lifespan and Reliability

Usable battery lifetime and reliability are key criteria for robots that operate in remote locations, where replacement of the battery is difficult or even impossible. It is a primary concern for space robots (5) that perform long missions and for which failure of the battery unit is catastrophic. Untethered underwater robots (3) are also often sent on remote missions, but these are often more limited in duration, and the economic consequences of a potential failure of the robot are less serious. The batteries of UAVs, UGVs, legged robots (1) and wearable robots can be replaced on a regular basis; wearable robots (2) however demand a higher cycle life because they are likely to be used more frequently (i.e., on a daily basis).

Appendix A.6. Safety

From a battery perspective, safety hazards may arise from potential explosions or the release of excessive amounts of heat. Wearable robots (5) are particularly sensitive to these safety aspects since their batteries are worn in close proximity to the human body. In contrast, space robots (1), most underwater robots (1) and, in many cases, also legged robots (2) and UGVs (2) operate in remote areas with no humans in the vicinity. UAVs (3) also typically spend most of their time operating at a large distance from humans, but a malfunction of the power supply could present a safety hazard as the device becomes an uncontrolled projectile.

Appendix A.7. Cost

Low cost is, in the first place, important for consumer robots. Wearable robots (4) typically fall into this category, although a higher cost can be justified for some types of wearable robots, e.g., rehabilitation robots. UAVs (3) for the consumer market are also widely available, although some are intended for a professional market, which is why they receive a lower score. Legged robots, UGVs and underwater robots (2) are more likely to be deployed by corporate than by private customers. For space robots (1) the cost of the robot and its components is usually negligible in comparison with the total cost of the mission.

Appendix B. Capability Analysis of Battery Technologies

In this appendix, the performance of different battery chemistries is discussed for the considered categories of performance. This appendix also serves as a motivation for the scores assigned in Table 4.

Appendix B.1. Specific Energy

The gravimetric energy density is the stored energy per weight ratio. In this category, LiS (5) scores the highest due to the use of light atomic-weight materials. However, this immature technology faces many challenges before it can enter the competitive market. On the contrary, Ni-based chemistries (NMC, NCA) are the most used in the market providing decent specific energy. The polymer-based LiPo batteries and other chemistries such as LCO and LMO also offer a moderate range of specific energy. Among the cathode chemistries, LFP (2) and LTO (1) score the least due to their lower inherent voltage, which leads to a lower Wh/kg.

Appendix B.2. Current Variation

Demanding charge and discharge currents at a very short pulse length is a challenging criterion for many lithium chemistries. The scoring focus here is more in the discharge direction. Among the compared chemistries, the LTO and LiPo batteries obtain the highest score (5) due to their safe and rechargeable properties. The LFP and NCA battery technologies can also offer higher current rates that are suitable for the applications concerned. The charge–discharge rates of the LMO and NMC chemistries are restricted due to the mix of energy (Ni) and power (Mn) optimization; thus, they receive a score of three in Table 4. The other chemistries of LCO and LiS score the least (1) in current handling, comparatively, due to the absence of manganese, which reduces the internal resistance.

Appendix B.3. Specific Power

The specific power of lithium technologies refers to the power output per kilogram of weight. This property is driven by the battery designs and their ability to discharge high currents in a short time. LFP chemistry comes out on top (5) in this category due to its low resistance and electro-chemical suitability. The LiPo batteries with polymer electrolyte and LTO-anode-based batteries can be categorized at level 4 due to their high discharge current capability. The LMO chemistry (3) has a flexible design that can be optimized for high-power, NCA (3) receives the same score despite providing greater stability and power, and NMC batteries (3) can also be power-optimized. LiS (1), due to its immaturity, and LCO (2), due to its limited load capabilities, are rated the lowest in this category.

Appendix B.4. Temperature Sensitivity

Lithium batteries are in general prone to temperature differences. Low and elevated temperatures result in a performance decline. However, the continuous battery development process has enabled batteries to withstand this crucial challenge. The common lithium battery technologies are scored comparatively in this section.

The LTO gains the top performance overall as it eliminates Li-plating at low temperature having better thermal stability at higher temperatures. The LFP (4) scores higher for its better stability, and so does the NCA (4) due to the presence of aluminum. LCO (1) has low thermal stability, while manganese spinel provides good thermal balance to LMO and NMC (3). LiPo (3) scores similarly for its gel polymer electrolyte. The LiS chemistry (1) faces chemical challenges that seriously impact the performance when operated over room temperature.

Appendix B.5. Lifespan and Reliability

The right selection of Lithium-ion battery technology considering its long life may require less frequent replacements, thus benefiting the total cost of ownership [126]. The LTO chemistry (5) is well-known for its long life that could potentially reach tens of thousands of cycles. The LFP (5) also scores highly, although it has a high self-discharge rate. Continuous improvement of the chemistries has given the Nickel-based cells of NMC and NCA (4) an edge compared to others in terms of the life cycle. The LMO (3), cobalt-based LCO (2) and LiPo (2) technologies score lower in a lifetime. LiS (1), as a newcomer in the battery market, is still far away from the expected performance [127].

Appendix B.6. Safety

The liquid-electrolyte-based Lithium-ion batteries always raise the question of safety concerns, paving the way for safer solid-state batteries in the market. The use of toxic active materials and flammable electrolytes, thermal instability in sudden failures, etc., all pose a threat to the safety aspects. Nevertheless, the available lithium technologies score better than the concerning level. The LTO (5) battery is considered the safest among the compared technologies offering no solid electrolyte interface (SEI) and no Li-plating plus higher thermal stability. LiPo (5) battery technology also stands on the top due to its safer polymer electrolyte. LFP (4) offers a very good rating due to its electrochemical performance and low resistance. Similarly, having the resistance in check by Manganese, NMC (3) and LMO (3) also provides good safety. However, the presence of cobalt in NCA (2) and LCO (1) makes the batteries less interesting in terms of safety because of low thermal stability. LiS (1) scores the lowest because of the limited operating window and electrochemical challenges.

Appendix B.7. Cost

Depending on the active material cost, the price of a battery system may vary. Figure A1 shows the cost breakdown of an NMC (6,2,2) cathode battery, using standard binders, conductive agents and a graphite anode [34]. This research study shows that the two most costly components are the positive and the negative electrode. Additionally, the active material within the negative electrode, in this specific case the graphite, is the most expensive component of a battery cell.

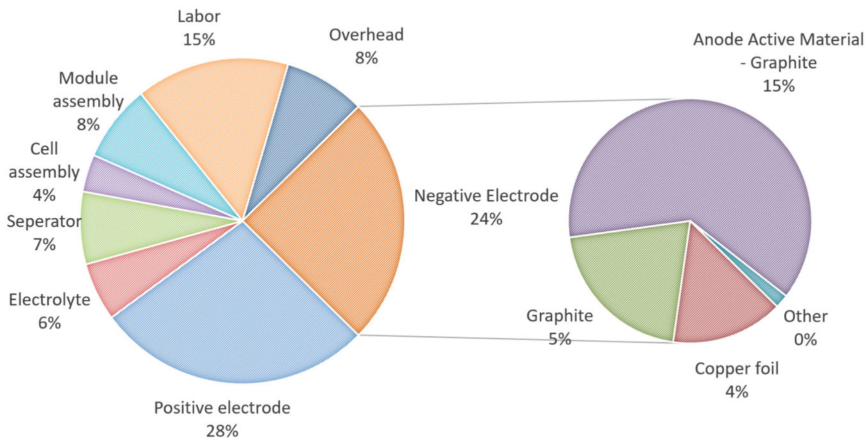

Figure A1. Categories of robots considered in this work, each requiring dedicated requirements from battery technologies.

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