SIZE & COST-OPTIMIZED POWER SOLUTIONS
for Non-tethered Applications

Modern advancements in power supplies and powered solutions are transforming the “inconvenient necessity” of the system into highly-enabling features that are driving a global transformation into a wireless world.

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SWAP FACTORS & THEIR IMPORTANCE IN POWER SOLUTIONS

In the world of electronics, power solutions (i.e., power supplies, power conversion devices, energy storage, safety components, and related interconnects/boards/cables, etc.) are commonly perceived as an inconvenient necessity. Obviously, nothing runs without power, but conversely, most designers and engineers would rather focus on optimizing their systems for the application and the overhead to keep the system running.

As luck would have it, there is the additional annoyance of power solutions quite often driving the majority of system size/weight, bill-of-materials (BOM) costs, and even bottlenecking the overall, system development schedule. One can always drill deeper into headaches associated with power solutions (such as those related to supply chain and manufacturing), but that is neither the focus nor the goal of this white paper. As a matter of fact, it is our hope that the contents of this document and the additional resources referenced may help to actually reverse these negative perceptions of yesteryear and bring one optimistically into a more sustainable future.

Some of the most common figures of merit (FOM) for a system are its size, weight, and power (a.k.a., SWaP factors) characteristics. When combined with a cost metric, this can also be referred to as SWaP-C factors. Given the point above about power solutions being famous for dominating these FOMs in the overall system design, it naturally makes sense that these characteristics are under a microscope, specifically regarding the system components that make up and/or are closely related to the power subsystem. Power density is typically a function of the total available power versus overall solution volume, and it is the reason why component size tends to have an inverse relationship with power density. The power density metric is taken a step further when combined with overall solution mass (typically translated to weight on Earth), which can be a critical FOM in non-tethered applications, as is reviewed from many perspectives in the content that follows.

In terms of the components comprising power solutions, the primary ones driving SWaP (and sometimes –C) factors are the filter components in the form of magnetics (i.e., transformers, inductors, toroids, chokes, etc.) and capacitors (i.e., bulk/electrolytic caps, safety caps, etc.). These often enable compliance with safety and other standards, such as those for critical requirements of electromagnetic compatibility (EMC) and protection against dangerous voltage and/or energy surge levels, in addition to power conditioning. Given how significant filter components can be to driving SWaP factors in undesired directions for what may outwardly appear to be "benign circuits" to the core application, it cannot hurt to regularly remind oneself as to why they exist and why the motivations for meeting such requirements go beyond clearing off some regulatory checklist item.

It should also be noted that while filter components can look fairly rudimentary from a circuit schematic/diagram perspective, the construction and implementation of such devices can be deceptively complex, particularly when it comes to both meeting compliance targets and optimizing SWaP-C factors.

This is where it can behighly beneficial to utilize commercial products for filtering and protection , which are designed by experienced professionals.

Even though commonly disaggregated throughout a system, components related to interconnects (i.e., wires, cable assemblies, connectors, etc.) can contribute significantly to SWaP-related challenges, especially in transportation modalities. A modern vehicle can easily contain over a mile's worth of wiring and therefore, also contribute considerably to the overall weight. This is only trending up and to the right of the curve in the rush to electrify drive trains and bring sensor-based intelligence, advanced computing, and wireless communications to mobility applications.

While the application space of electronics can be a very wide spectrum, thermal mitigation techniques can be quite significant contributors to a system's size and weight. Heatsinks can become very bulky, particularly in passively-cooled or conductively-cooled use cases. In forced-air solutions, fans may not only occupy a significant amount of overall system volume but may also require a non-negligible amount of power themselves, thus compounding the overall, SWaP-related challenges. This should also serve as a reminder for the perpetual quest for improving power supply efficiency, which translates to the reduction of dissipated power and facilitating the mitigation of nearly every design challenge stated here related to SWaP-C factors and beyond [1].

Some applications may have extensive requirements for packaging that can offer be more significant contributions to size and weight, such as an enclosure/chassis and even potting material [2] used to encapsulate the electronics. System requirements driving these SWaP contributors can range from reliability, such as in the case of environmental protections from external factors such as temperature, humidity, dust, conductive particles (a.k.a., foreign airborne metallics), and even hermetic sealing for waterproofing and/or safety reasons. Non-engineering motivations can also come into play here, such as the need for security from prying eyes and reverse engineering.

So far, all the components and solutions described here have been in the context of SWaP factors, but just about any system or application will have a sharp focus on cost and lead to a SWaP-C analysis. It would be irresponsible to dictate highly-generalized rules of thumb in terms of component versus cost tradeoffs because of the wide spectrum of solutions for each component type/class and an even wider spectrum of application spaces. A perfect example of this is the frequently used, yet misguided and oversimplified metric of dollars per watt ($/W). To understand the point, see the figure below, which makes a direct comparison of five different 300 W power supply solutions covering a range of applications, form factors, and therefore size/weight/density FOMs. It is thus important to identify the critical design requirements/targets for a power solution, then assess those against a prioritized list of what is truly driving the SWaP-C factors. Of course, your mileage may vary.

What is the difference between these 300 W AC/DC power supplies?

Figure 1: A Comparison Between Multiple Versions of 300W AC/DC Power Solutions with $/W Metric [3]

OPTIMIZING SWAP FACTORS FOR NON-TETHERED APPLICATIONS

This focus on SWaP factors will never be more salient than in non-tethered applications, where a system's performance, range, and reliability are all at the whim of the available power (though at the end of the day, everything in the world of electronics kind of is, right?). Non-tethered applications are the ones in which the system is not required to be connected to a fixed power source, such as AC power from a wall outlet (a.k.a., offline power source). Examples include anything mobile (from phones to vehicles), most forms of transportation (terrestrial or aerospace), tiny things (wearables and wireless sensor networks), and even the most untethered applications you can possibly find (space-based applications).

The amount of available power to a non-tethered system may be characterized in a number of different ways, but will invariably come down to a balance between power sources and the loads that consume them. As described in the first section, SWaP factors become so important in this application space because of the constant battle between allocating power for functionality (i.e., movement, data analysis, communication, etc.) and supporting the overhead of the system itself (i.e., larger mass consumes greater amount of the power budget). Such characterizations of power utilization will ultimately be the constraining, operational factor, whether it be called fuel (hydrocarbon-based combustion), battery-life, range, or flight time. The table below outlines many application-dependent considerations and their impact on SWaP-C factors.

CONSIDERATIONS FOR SPECIALIZED DESIGN/SUPPORT SWaP-C IMPACTS ON SOME EXAMPLE APPLICATIONS	
MIL-AEROSPACE [4]	■ Numerous governmental standards (DO, MIL-STD, etc.) to meet in addition to standard power supply and system qualification requirements (UL, ISO). ■ Highest targets for SWaP factors concurrent with highest reliability factors. Every gram of power solution translates directly to fuel/energy costs. Also consider if a soldier must carry. ■ Extremes of environmental performance (temperature, humidity, shock, elevation, corrosion/in-gress, etc.). ■ Supporting redundant power/system implementations.
TRANSPORT/ RAILWAY [5]	■ Very stringent shock/vibe and other environmental specs to meet (see EN 50155, AEC-Q100 for example). ■ "Functional failures" can mean catastrophic damage and loss of life. ■ Regardless of safety/filtering component size, space occupied by riders must still be functionally and aesthetically pleasing (i.e., comfortable storage space, embedded entertainment, power charging ports, etc.). ■ Very long development cycles increase the value of leverage/reuse.
MEDICAL EQUIPMENT [6]	■ Very stringent leakage currents limits requiring higher-quality parts ($$$). ■ Can be very high voltages (kVs), so one must deal with wide spacing requirements and necessita-ting stricter ■ safety limits and larger safety components. ■ Lower acceptable electromagnetic interference (EMI) limits can lead to bulkier filter components. ■ Systems can be modalities with very sensitive data signals, which may also be susceptible to thermal as well as electrical interferences.
WIRELESS NETWORKING/INTERNET OF THINGS (IoT)/INDUSTRIAL IoT (IIoT)/WIRELESS SENSOR NETWORKS (WSN) [7] [8]	■ Extreme temperature/humidity/contaminant environments may require conduction cooling and/ or hermetically-sealed enclosures. ■ "Set & Forget" system deployments may require long battery lives, perhaps supplemented with energy harvesting [9] solutions requiring "forever power." [10] ■ Frequent recharging may be unacceptable to the end user. ■ Devices and sensor network battery life can be a tradeoff between data quality, quantity, and frequency of wireless communication. ■ High dynamic ratio between active and sleep states, thus complicating the steady-state consump-tion modeling.

Table 1: Simple Summary of Specialized Requirements Driving SWaP-C for Some Key, Non-tethered Applications

An excellent strategy for optimizing system tradeoffs for SWaP-C factors is to take advantage of a family of components with a common footprint. This can allow for many advantages from flexibility in design to accommodate unexpected load deviations (i.e., accommodate higher power than expected or reduce cost for lower power than expected) to future-proofing a product roadmap that takes advantage of the best of leverage/reuse of qualified developments and technology advancements. Industry-standard power solution footprints, such as the "brick" format that brings commonality to power form factors and pinouts are very common example of this. A list of brick-format solutions for comparison can be found here.

Design cycles and development costs can be reduced through the leverage of qualified systems and pre-qualified power solutions.

The tremendous growth in breadth and depth of power needs in the automotive sector (and supporting markets) is a continually-evolving landscape of requirements for a variety of input/output voltage levels combined with a persistent demand for increased power density.

This is one of the most brutal application spaces in which the constant pursuit of cost cutting is convolved with rigorous quality and reliability standards. Modular product lines providing dense power solutions that can support a number of input/output voltage combinations, output current levels, and those pre-qualified for automotive standards are critical enablers. RECOM's RPX series of DC/DC converters for automotive applications are a prime example of this as shown here.

When products can have extensive and costly qualification cycles, yet when they also need to support a product roadmap containing a variety of features and options for a customer to choose from, the management of designs and components can quickly grow to become unmanageable from a logistics and/or cost perspective. This is where future-proofing with a pipeline of SWaP-C-optimized power solutions can be imperative to implementing a modular, yet pragmatic product line. Predictable form factors combined with room to grow in terms of input/output voltage ranges and regular power density improvement is a recipe for success here.

One does not have to be a power electronics expert to optimize SWaP factors in order to take advantage of the state of the art (SOTA) in power solutions. As detailed above, non-tethered applications have an inherent ability to motivate the optimization of SWaP factors due to the limited fuel supply (again, fuel can mean anything from gasoline to battery life in this context). Systems sourcing their power from offline sources tend to only be limited by the current-handling capability of the wiring and circuit breakers of the electrical infrastructure, which may still flow "indefinitely" from a system's perspective. This can actually complicate system design tradeoffs because designers and users are not forced to make the difficult choices that come with a very constrained power budget. So, what areas should a designer focus on when looking at the SOTA?

While optimization of system budgets can take on many strategies, an excellent and comprehensive one is to start at the loads, then work your way back. In other words, consider the end application and associated power draws from these loads, then work your way back up through the power subsystem until you get to the most upstream power source (i.e., battery, charging station, fuel tank, power plant, etc.). Consider the factors that impact the power footprint at each stage and evaluate the options that provide the most impact to that footprint in both operation (e.g., usage models) and intrinsic design. For the latter, examples of SOTA design may be taking advantage of the latest semiconductor node (e.g., Moore's Law) or an integrated sensor utilizing microelectromechanical systems (MEMS).

Once you get up the power distribution system and the power solutions themselves, there are also the regular technological advancements to take advantage of. Wide input and higher-conversion-ratio switching power converters can enable an increase in the voltage of main distribution conductors, thus allowing for lower currents to deliver higher amounts of available power while also reducing distribution (V=IR) and thermal losses ($P=I^2R$) due to conductor resistance. There are even considerations upstream of the power electronics with the intelligent utilization of energy storage [11] devices (typically batteries or supercapacitors) that can use peak shaving techniques to service infrequent peak power demand with local energy storage, while enabling the overall system design and infrastructure to be optimized for a much lower steady-state power budget instead.

If really looking to go lower-level into the power conversion blocks, which can be helpful when looking to optimize the full SWaP-C factors, then consideration of discrete power solutions may come into play. There is a wide variety of directions to head in this regard, which are highly dependent on the experience and comfort level of the designer. A good example of this is the use of wide bandgap (WBG) power semiconductors (i.e., gallium nitride or GaN, silicon carbide or SiC, etc.) that are at the forefront of optimizing SWaP factors in power supplies [12] but may also come with a steep learning curve that complements their improved power density FOMs. While out of the scope of this white paper, it should be noted that even just the gate driver circuits for WBG devices can be far more complex due to increased switching speeds and transients that are a departure from the design rules for traditional silicon power semiconductors. An excellent overview and reference to such challenges can be found here.

Lastly, be sure to check out the major advancements in the area of three-dimensional power packaging (3DPP[R]), particularly for lower-voltage DC/DC power converters. Advanced packaging techniques have facilitated power conversion and power management solutions with the ability to take advantage of many of the SOTA technologies tabled above and integrate them into highly dense, integrated components. 3DPP allows for the best of these technologies to contribute to SWaP optimization, while still taking advantage of the access to commercial, off-the-shelf (COTS) solutions. RECOM provides an excellent overview of the value propositions and the latest offerings in this regard [13].

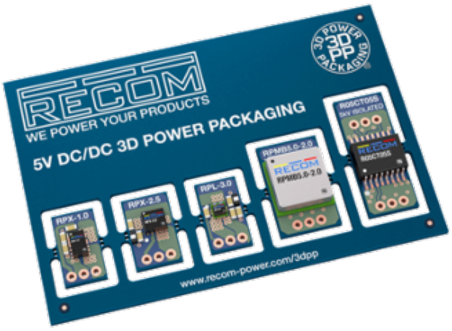

Figure 2: Examples of DC/DC Solutions Taking Advantage of SOTA 3D Power Packaging [13]

The hard work put into optimizing system design for SWaP-C factors can pay dividends in numerous ways as teased in the content of this white paper. Hopefully, it also becomes clear how the benefits can be multiplicative when considering system design and utilization with a multidimensional approach. For instance, a higher-voltage battery enables reduced distribution currents or WBG semiconductors may improve power conversion efficiencies, all of which reduce the amount of total dissipated power.

When performance and/or functionality is not sacrificed even after reducing the overall system power budget, then that can be a huge win in the perpetual fight to optimize SWaP-C factors. A reduction in thermal mitigation needs and EMI filters can have tremendous impacts on SWaP-C.

SWaP(-C) factors are important to most applications, but CRITICAL to most non-tethered applications. System weight (including the weight of the power subsystem itself) and battery life tend to be the bottlenecks in the ability to maximize performance, range, time to recharge, or whatever FOM(s) are considered the highest priority for a given use case. As many examples and opportunities for SWaP-C factor improvement have been outlined above, designers can take advantage of the SOTA ***WHILE STILL*** taking advantage of COTS solutions.

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