Foreword

A Prospective on the Future of Fluid Power Technology in Off-Road Applications

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1. Introduction.

The market of vehicles for construction, agricultural and mining applications has been facing a revolution for the sake of sustainability and lower carbon emissions. Following the same technology progress path of on-road vehicles, electric- and hydrogen- based prime movers are now considered as an alternative to the combustion engine (CE), with implications affecting the whole vehicle actuation system. Differently from their on-road counterpart, off-road vehicles (ORVs) always require working functions (both rotary and linear functions) in addition to the propulsion. Therefore, an overwhelming topic for both academia and industry pertains to finding the right technology choice for generating and distributing power in the next generation of ORVs. Will Fluid Power (FP) remain the technology of choice for future vehicles? Or should industry focus switch to fully electro-mechanical actuation? The answer is not straightforward, and it should consider multiple factors. The following sections further elaborate the author's experience and perspective on this topic. As a warning to the reader, it should be considered that author spent his entire professional career in FP topics, and inevitably there will be some bias towards the merit of FP actuation. Nevertheless, it is the author's belief that that most of the following considerations will be of inspiring interest and will align to future development of ORV technology.

2. Prime mover technologies for future off-road vehicles.

Different scenarios for the actuation technology of current and future ORVs can be defined based on the prime mover choice: CE (either conventional diesel or based on alternative fuels such as hydrogen, biofuels, etc.), battery electric (BE) or hybrid CE/BE. Similarly to on-road applications, all these technologies have merits/demerits pertaining to the infrastructure required for supplying energy to the tank (or battery); the well to wheel energy efficiency and CO_2 impact; prime mover costs. Several sources (like [1, 2]) indicate that electric vehicles will soon dominate the low-power and short-usage applications, while the other prime mover technologies will lead the heavy-duty applications. This scenario is shown in Fig. 1, for the case of loaders.

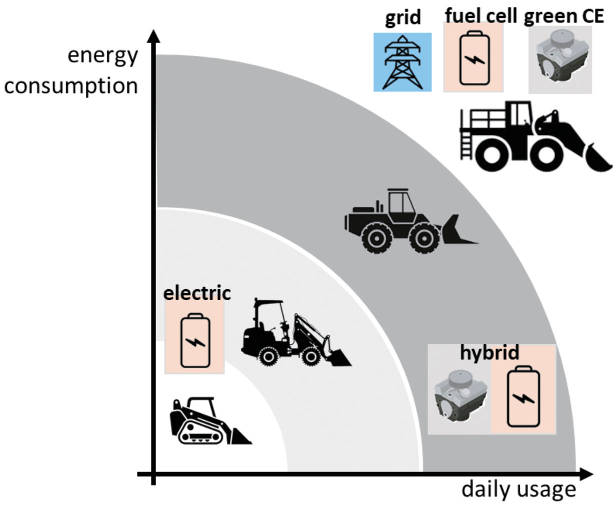

Figure 1 Most suitable prime mover technology depending on vehicle size (example of loaders)

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3. Technologies for the working functions.

Besides the propulsion that can be performed through a purely mechanical system, the working functions of an ORV require an electro-mechanical and/or a FP system. The favorable power to weight ratio, low cost, and robustness have made FP the go-to technology for conventional diesel ORVs over the last decades. However, the low energy efficiency of their FP actuation (an average of about 30 % across different ORVs was found by a US Dept. of Energy study [3]), poses severe questions on the usage of conventional FP technology for future ORVs. It is not only a matter of a more rationale usage of energy resources; in fact, future ORVs will have more stringent energy storage limitations than today's vehicles - at least for BEs and hydrogen-based vehicles - affecting their up-time between refueling or recharging events. Additionally, the unitary cost of energy is expected to be significantly higher than current diesel cost, for most of the alternative fuels. From these considerations it is clear how the *total cost of ownership* (TCO) of future ORVs will be more linked to the energy efficiency of the transmission system than in today's vehicles. Consequently, one can reach the straightforward conclusion that electromechanical actuation, often associated to much higher energy efficiency than FP, will dominate the future of ORVs. Indeed, electromechanical technology is readily available for both rotary and linear actuators, meeting the size and power requirements of many ORVs. Few fully electric ORVs also appeared (or soon to be) on the market, taking advantage of such actuators. Notwithstanding, it is still unclear which actuation technology is best among FP and electromechanical, as their potential is not yet fully exploited. This potential should be considered by looking at all the prime mover scenarios as shown in Fig. 2.

Future ORVs using green CEs (hydrogen or alternative fuels) will meet cost effectiveness by retaining FP actuation to avoid the added cost of a high-power electric actuation system. However, technology progresses to increase energy efficiency of FP system are required to achieve competitive TCO.

BEs, fuel cell, and hybrid BE/CE can instead adopt both FP and electromechanical technologies, and the choice of the best system should factor:

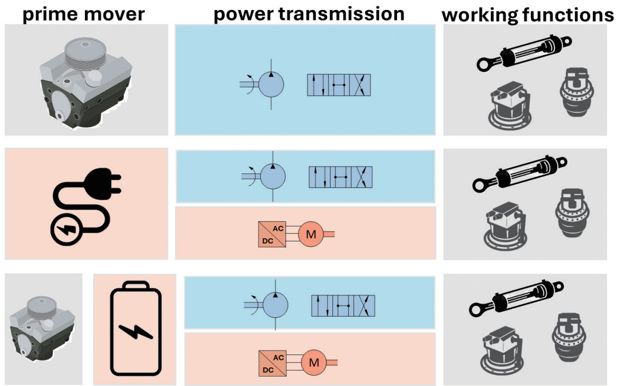

Figure 2 FP vs. electromechanical actuation in ORVs

- cost
- productivity
- energy efficiency
- space claim
- robustness
- space claim
- damping
- resistance to shock
- tolerance to contamination
- leakage potential
- cooling needs
- noise and vibration
- prime mover limitations
- installed power

With a compromise that highly depends on each specific ORV type and size. For example, ORVs with functions seldom utilized in their typical utilization cycles will prioritize installation cost over energy efficiency, while the opposite will occur for functions affecting ORV's productivity.

Some general considerations can be made while comparing electromechanical vs. FP actuation with respect to the previous bullet point list:

Cost. Electric components in the power range suitable for ORV application are currently more expensive than FP components. However, there is a price reduction tendency for electric components (batteries, electric motors, power electronics) that might soon bring their cost to a competitive level, particularly for <100 kW ORVs, where synergies with mass production capabilities developed for on-road application are possible. To remain competitive, FP must evolve in the direction of "smart components" able to perform multiple functions through electronic/software integration. For example, a smart electronic-controlled pump can reduce the current variety of hydraulic- controlled pumps, so that pump variants can be reduced along with their production cost.

Energy efficiency. For rotary functions, electric machines are simply more efficient than hydraulic motors. Consequently, for productivity functions such as propulsion, it is expected to see more and more adoption of electric technology. However, for linear functions, there is not a clear winner among the two technologies. State-of-art linear electromechanical actuators require a mechanical gearbox to convert the high-speed rotary motion of the electric machine into a linear motion, with detrimental effects in terms of efficiency, backdrive ability, and resistance to shocks. If compared to an electro-hydraulic actuator that use an electric prime mover for each linear function, the energy efficiency is only slightly favorable for electromechanical actuators in resistive mode [4], although in overrunning conditions the electro-hydraulic actuation can have advantages [5], as it will be also discussed in section 5. It is also important to note that the energy efficiency of FP system depends on the chosen layout architecture of the hydraulic system, and numerous options are available among primary-controlled, secondary-controlled and metering-controlled architectures [6]. Very often, the selected architecture for an ORV is not the one that maximizes energy efficiency. Further considerations on this point will follow.

Space claim. FP has the notorious advantage of power to weight ratio over electromechanical technology. This can be immediately deducted by comparing the mass of same-power electric vs. hydraulic, as shown in Fig. 3. The figure points out a difference in mass quantifiable in about one order of magnitude.

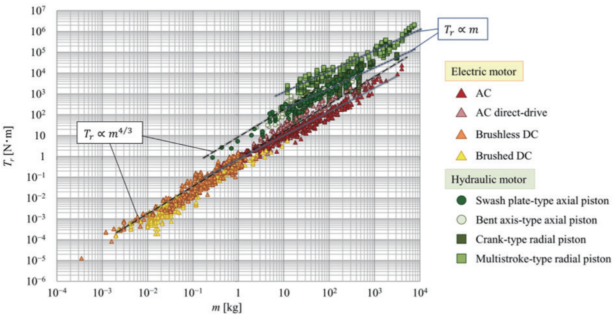

Figure 3 Mass vs. Power for commercially available electric and hydraulic machines [7]

However, the above comparison alone, does not outline all the space claim potentials given by FP technology, even when used with electric prime movers, which can be summarized with the opportunity of *grouping functions* (centralized systems) and *integrated electric-hydraulic solutions* (*ePumps*).

Grouping functions refer to the ease of combining multiple actuators to the same prime mover which is arguably one of the main prerogatives of FP systems over electric actuation technology. While each electric actuator requires a prime mover, a FP system can be equipped with proper hydraulic control valves to independently control multiple functions with a single hydraulic power source. Among other advantages, grouping functions allows reducing the number of prime movers, and therefore the overall space claims of the actuation system.

Integrated electro-hydraulic solutions refer to the design merge of electric and hydraulic components to pursue physical advantages, one of these being the reduced space claim. Examples of this ongoing effort include the ePumps developed at various institutions (in Fig. 4 the examples from the author's research center). By maximizing the usage of the inert space inside an electric machine, where a hydraulic unit can be fitter, and by leveraging better cooling strategies (such as adopting immerse cooling strategies), it is possible to achieve significant (>30%) space reduction.

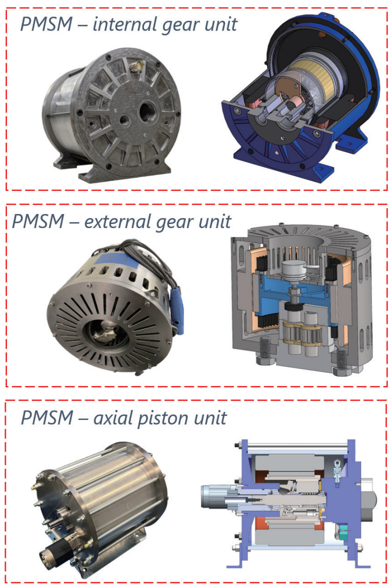

Figure 4 Design integration for implementing electric and hydraulic machines capable to generate or recover hydraulic energy [8-10]

Installed power. This feature refers to the overall power of the prime movers present in the vehicle, and it can be suitable to outline a significant difference between a fully electric ORV compared to an FP-actuated ORV. With electromechanical technology, each actuator needs a dedicated prime mover matching its peak power demand. This means that a fully electric vehicle might end up having an installed power several times higher than its conventional FP technology equivalent [11], which usually benefits from the function grouping explained in the previous paragraph. This feature of electromechanical actuation is sometimes interpreted positively, as an increased potential for higher productivity. However, it also highlights the inherent design limitation of electromechanical systems, which cannot avoid increasing the installed power, compared to what is strictly necessary to perform the required ORV specific mission profiles. This negatively reflects on the usage of electric material (including rare minerals), which is against the basic sustainability concepts.

Cooling needs. Being often more energy efficient than FP systems, electromechanical actuation systems tend to have less heat dissipation, thus less cooling need. However, this consideration does not reflect the challenges associated with the implementation of cooling solutions. Ease of cooling is a key advantage of FP technology: the hydraulic fluid is not only an energy vector, but thanks to its favorable thermal properties it is also a good heat carrier. Despite being inefficient – thus with high cooling needs – today's FP systems allow a convenient placing of heat exchangers. Instead, electric technology requires cooling solutions able to locally the components where the power transformations occur. Consequently, the thermal conditioning system for a fully electric ORV is a critical, sometime challenging design aspect, particularly for heavy duty ORVs. Design integration of FP and electric components (like in Fig. 4) can be promising in EVs for leveraging both advantages of electric technology (i.e. high efficiency) and of hydraulic technology (i.e. ease of cooling), so that all the cooling requirements can be concentrated into the FP circuit.

4. Research on energy-efficient hydraulic actuation.

The recent push towards sustainable, low TCO, ORVs has brought an unprecedented interest in the development of more energy-efficient FP technology. The most energy-efficient concept is the *decentralized hydraulic*, which consists in implementing a dedicated flow supply for each working function. It is currently adopted for the propulsion of several ORVs (*hydrostatic transmissions*), but it can be implemented for the working functions as well. Two concepts are available, depending on how the flow-on-demand regulation is performed: *displacement control* (i.e. one variable displacement pump for each function) or prime mover control, or *electro-hydraulic actuator* (i.e. one variable speed electric motor for each function). Both solutions have experimentally proven capabilities of doubling the energy efficiency of the transmission systems [5, 12]. The displacement control concept is particularly attractive as it also allows reducing the installed power and the number of prime movers [11].

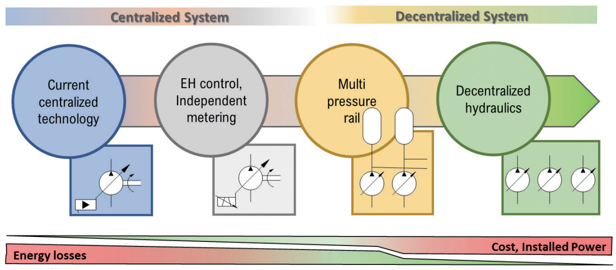

Figure 5 Portfolio of FP solutions for future ORVs

The practicality of the decentralized hydraulic concept in ORVs is however under question, as it increases component cost. Therefore, it can be justified only for reducing energy consumption of the actuators with high utilization cycles. For this reason, combinations of conventional (and inefficient) *centralized hydraulic* solutions with decentralized solutions are more likely to occur.

Several R&D institutions focused on alternatives for cost effective and practical FP solutions for the working functions of future ORVs. The most relevant effort can be summarized with the alternatives illustrated in Fig. 5. At the extreme left of the figure, there is the state-of-art centralized hydraulic technology, typically based on hydromechanical, valve-controlled systems (mainly open center and load sensing systems [6]), which has been optimized to meet the requirements of conventional diesel based ORVs. At the extreme right, there are the mentioned decentralized solutions, which bring the maximum energy efficiency benefit at the price of a higher installation cost. In the middle, there are other promising solutions that are expected to grow in commercial ORVs. First, there is the category of intelligent components based on advanced electro-hydraulic (EH) control, as opposed to conventional hydraulic pilot control. This includes smart components, such as smart pumps and smart valves, whose operation can adapt to the instantaneous requirement of the work function. These solutions, already appearing in the market, can bring to moderate /good reductions of energy consumption.

The other category of solutions is the pressure-controlled systems, either *constant pressure rail* (CPR) or *multiple pressure rail* (MPR). The CPR solution is the most elegant one: it is based on a single pressurized rail that serves all the working functions, each one with a local regulation (secondary control). Conventional hydraulic cylinders cannot be used, as they do not offer any internal regulation, and for this reason multiple chamber cylinders have been proposed [13] and have reached a level close to commercialization. Another concept for CPR is achieved by using a hydraulic transformer for each function to eliminate throttling losses [14]. Despite several efforts in developing hydraulic transformers [15], no commercial solution is yet available, although there are certainly promising solutions such as the one in [16].

MPR systems are a surrogate of the CPR concept that allow direct implementation through commercially available components. Several prototypes ORVs have shown remarkable energy efficiency gains (up to double efficiency) in both construction and agricultural fields [17, 18].

5. Energy Recovery solutions for ORVs.

The working functions of several ORVs, particularly in the construction sector, offer opportunities for energy recovery during overrunning loads. For example, in the typical use of an excavator, there is the opportunity to recover about 15% of energy associated with overrunning loads. When using electromechanical actuation, this energy amount might not be high enough to justify the added hardware complexity which is required for a successful recovery. In fact, actuators with backdrive capability are required; moreover, there are several energy transfers processes (each one associated with a component efficiency) to recover/reuse the energy from/to the actuator to/from the electric battery. Additionally, it must be considered that energy recovery process might bring to detrimental charging/discharging rates to the electric battery.

When using FP solutions, multiple options are available to handle energy recovery. The possible options are conceptually shown in Fig 6.

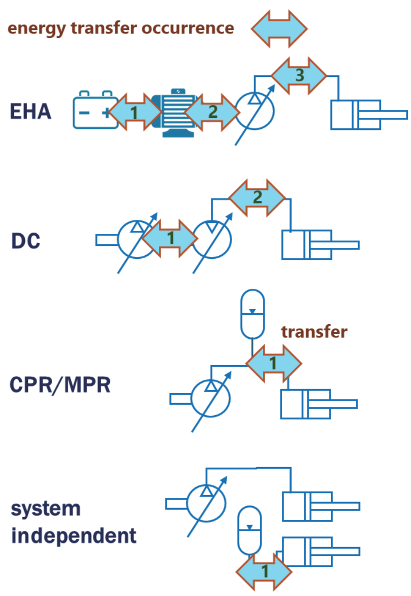

Figure 6 Solutions for energy recovery using FP

The two distributed hydraulic options (displacement control, DC and electro-hydraulic actuator, EHA) engage different mechanisms for energy recovery. Similarly to electromechanical actuators, EHA involves several energy conversion steps, and might be not appealing for ORVs. However, fewer conversion steps occur in other FP solutions: DC can engage internal energy recirculation without involving the prime mover; CPR and MPR offer a smooth energy recovery through energy accumulation in the pressure rails. There are also stand-alone solutions that have been proposed to isolate the energy recovery function from the actuator control function, which can apply for any type of hydraulic system and offer the minimum energy conversion loss. Significant is the example reported in [19].

6. Conclusion.

This paper discussed how the inherent advantages in term of power to weight ratio, layout flexibility, and ease of cooling, should collocate FP technology at least at the same level, if not superior, to electromechanical technology for the development of future ORVs, including BE, CE, or hybrid solutions. However, it is clear that conventional FP solutions do not meet TCO requirements associated with the use of novel prime mover technologies (electric and hybrid vehicles, fuel cells, combustion engines with alternative fuels) and therefore investment and research effort is required.

An adverse factor to the deployment of novel FP solutions is the complexity of hydraulic control systems that conflicts with the chronic lack of educated FP engineers, which – if no action is taken – will slowly determine the decline of the FP technology [20].

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