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Digital Hydraulic Technology: Applications, Challenges, and Future Direction

Francesco Sciatti[1*], Paolo Tamburrano[1], Elia Distaso[1] and Riccardo Amirante[1]

[1] Department of Mechanics, Mathematics and Management (DMMM), Polytechnic University of Bari, Bari, Italy;

*Francesco.sciatti@poliba.it

Abstract. Digital hydraulic technology has emerged as a promising alternative to conventional hydraulic systems, offering several advantages such as improved energy efficiency, more precise control, and reduced complexity. In recent years, digital hydraulic technology applications have been widely researched in various engineering sectors, including aerospace, biomedical and industrial. The aim of this paper is to provide an overview of the recent advancements in digital hydraulic technology, focusing on the various applications and their benefits. The paper begins by introducing the two different branches of this innovative technology. Subsequently, it presents an overview of digital hydraulic technology applications, highlighting their specific advantages, particularly in biomedical, industrial and aeronautical sectors, when compared to conventional hydraulic technology. Finally, the paper addresses the challenges and limitations associated with digital hydraulic technology and discusses potential areas for future research and development.

1. Introduction

Conventional hydraulic systems are highly prevalent in a wide range of industries and applications where there is a need for robust power transmission, precise control, and substantial force capabilities [1]. These systems operate by using pressurized fluid to transmit energy and generate force or motion. The remarkable power density they offer is a major factor contributing to their widespread adoption, as they can deliver ten times the power of electric systems occupying the same size and space [2].

Despite these great advantages, there are certain challenges that need to be addressed. The high cost of hydraulic components, as revealed by a study conducted by Achten, is not aligned with the direction of industrial development. These components can be three times more expensive than their mechanical counterparts, with costs ranging from 40 to 80 pounds per kilogram [3]. Additionally, conventional hydraulic systems suffer from low energy efficiency due to notable energy losses that occurs as the pressurized fluid circulates through the hydraulic circuit and its components. This is evident in excavator hydraulic systems, where up to 80% of the energy is dissipated [4].

Among the hydraulic components, the control-ones mainly impact the overall efficiency of the entire hydraulic system. In conventional hydraulic systems, high-bandwidth spool valves, including proportional and servovalves, are commonly employed to regulate the hydraulic power transmitted to actuators [5]–[7]. While these valves offer excellent accuracy, precise control, and fast response times, their spool design leads to significant energy losses. This is because the pressurized fluid encounters high pressure drops as it flows through the narrow passages created by the spool during valve actuation [5], [6]. In [8], a medium-sized four-way three-position 4/3 spool valve was analyzed for power dissipation. When the two metering chambers were opened together (P→A and B→T for main spool right displacement, or P→B and A→T for main spool left displacement), the valve experienced a pressure drop of 30 bar and a flow rate of 60 L/min. The analysis considered a pump efficiency of 80%, and it was found that the valve dissipated approximately 7 kW of power.

In order to maintain the relevance of hydraulic technology across industries and applications, it is crucial to focus on reducing costs and enhancing efficiency in hydraulic systems. The remarkable success of digital concepts in information, communication, and power electronics, combined with the similarities between electrical and hydraulic systems, clearly indicates that integrating digital concepts into hydraulic technology can effectively tackle these challenges and enable intelligent control [9], [10].

The term "digital hydraulic technology" was introduced by Matti Linjama more than a decade ago [11]. However, Linjama's definition of digital hydraulic technology only partially captured its characteristics [12]. It highlighted two characteristics: discrete control and active control. Discrete control is intrinsic to digital hydraulic technology as it uses discrete digital signals to control hydraulic components. On the other hand, the notion of active control only partially captured the essence of digital hydraulic technology, as it does not encompass intelligent control. It was not until 2020 that a standardized definition emerged, describing digital hydraulic technology as a system that utilizes modulated, discrete, digital signals to achieve both active and intelligent control of the system output [13]. According to this definition, hydraulic components capable of discretizing fluid flow or control signals are referred to as digital hydraulic components, while hydraulic systems composed of such components are known as digital hydraulic systems.

The main components of digital hydraulic systems are digital hydraulic valves. These valves are typically designed as On/Off valves, which means they do not require a spool for flow adjustment. Instead, they can have a similar structure to poppet valves. Poppet valves offer several advantages over conventional spool valves, including lower cost, increased robustness, absence of leakage, and the ability to perform multiple working cycles with reduced pressure drops. This is achieved by designing the flow area of the valves larger, allowing for improved flow control. As a result, the power dissipated by these valves is minimized, leading to enhanced overall system efficiency [14].

Over time, digital hydraulic technology has gained significant attention and interest from researchers, and engineers, due to its potential to revolutionize hydraulic systems. In fact, compared to conventional hydraulic systems, digital hydraulic technology offers several benefits. These include enhanced reliability, reduced energy consumption, precise control of machine movements, minimized production losses, decreased downtime, standardized components, and lower initial investment and maintenance costs [14], [15].

In this scenario, the aim of this paper is to provide an overview of the recent advancements in digital hydraulic technology and its applications. It begins by introducing the two different branches of this innovative technology. Subsequently, an examination of digital hydraulic applications is presented, underscoring the advantages it brings, particularly in biomedical, industrial, and aeronautical sectors, in contrast to conventional hydraulic technology. Finally, the paper addresses the challenges and limitations of digital hydraulic technology and explores potential avenues for future research in the field.

2. Digital Hydraulic Technology Branches

Digital hydraulic technology can be divided into two main branches: parallel digital hydraulic systems and high frequency switching digital hydraulic systems [12].

Parallel digital hydraulic systems achieve intelligent control of the system output, by using a parallel connection of digital hydraulic components. The different state combinations of these components, which are controlled using modulated discrete digital signals, allow for the achievement of a fixed number of discrete output values. This eliminates the requirement for frequent on/off switching of components.

In contrast, high frequency switching digital hydraulic systems employ rapid and continuous switching components to achieve intelligent control of the system output. These components use pulse modulation techniques to switch at high frequencies, resulting in the flow rate exhibiting different discrete values as the output. While theoretically, the system output can have any value within a certain range, it remains a discrete quantity due to the switching frequency of the components.

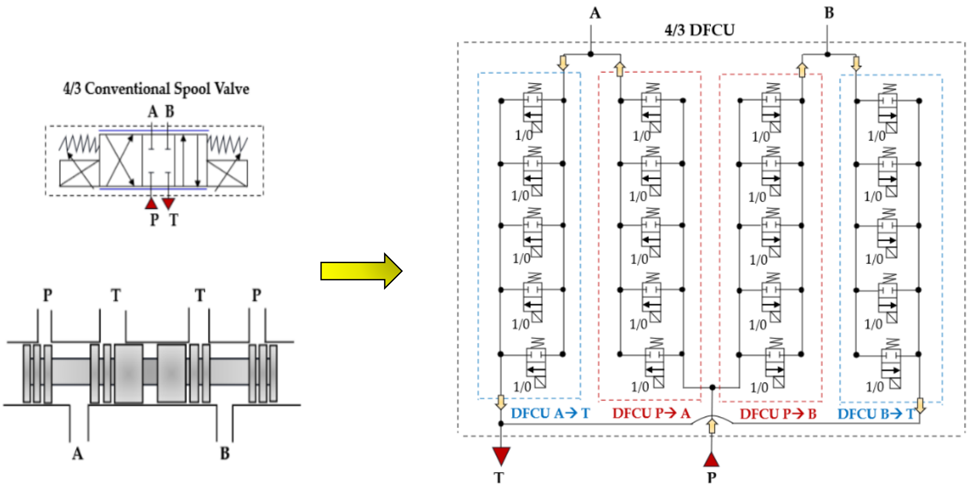
2.1 Parallel Digital Hydraulic Systems

The core component in parallel digital hydraulic systems is the parallel digital hydraulic valve, known as the Digital Flow Control Unit (DFCU). It is composed of multiple On/Off valves that are interconnected in parallel, enabling accurate flow control. To achieve intelligent control of the system output, three distinct digital control approaches can be employed to determine the flow capacity of each On/Off valve within the DFCU. These approaches can be summarized as follows [11]:

- Pulse Number Modulation (PNM): All On/Off valves have the same size and thus the same flow capacity (1:1:1:1 etc.);
- Pulse Code Modulation (PCM): The orifices following the valves enable the flow capacities of different valves to be set according to a binary series (1:2:4:8:16 etc);
- Fibonacci Numbers (FN): The orifices after the valves allow the flow capacities of the different valves to follow a Fibonacci series (1:1:2:3:5:8:13 etc).

Regardless of the specific coding method used, a DFCU has a total of 2^N possible combinations, where N represents the number of parallel-connected switching valves. These combinations are referred to as the states of the DFCU. By selectively turning the valves "on" and "off," the individual valve flows are combined, resulting in the creation of different discrete flow rates corresponding to different states of the DFCU. One notable advantage of the DFCU is that valve switching is only required when transitioning between states, reducing unnecessary valve operation [12].

Independent DFCUs offer a viable alternative to mechanically control edges in achieving the same functionality of a conventional four-way three-position (4/3) spool valve [13]. Figure 1 shows the hydraulic circuit of a four-way three-position (4/3) DFCU. This configuration includes four DFCUs (P→A, A→T, P →B, B→T), each composed of five On/Off valves.



a) **b**)

Figure 1. Comparison of Two Types of Four-Way Three-Position Valves: **a**) Conventional 4/3 Spool Valve; **b**) 4/3 DFCU, adapted from [13].

As shown in Figure 1b, the On/Off valve utilized in each DFCU is a two-way two-position (2/2) On/Off valve that operates in a normally closed configuration. In the unactuated position (0), the valve blocks the flow, while in the actuated position (1), it allows the flow to pass through. The number of On/Off valves required in each DFCU depends on the desired flow rate precision. A more precise flow rate necessitates the use of more On/Off valves [14].

To achieve a comparable controllability to that of a conventional 4/3 spool valve, the maximum flow rate provided by a DFCU should be approximately 200xQ. This can be accomplished by employing about 200 On/Off valves of equal size using Pulse Number Modulation (PNM) coding (resulting in a maximum flow rate of 200xQ), 11 On/Off valves with Fibonacci Numbers (FN) coding (resulting in a maximum flow rate of 232xQ), or 8 On/Off valves with Pulse Code Modulation (PCM) coding (resulting in a maximum flow rate of 255xQ) [11]. It is important to note that the total number of states provided by the DFCU, based on the chosen coding scheme, varies significantly, ranging from 256 (PCM) to 2048 (FN) and up to around $1.6 \cdot 10^{60}$ (PNM).

The previous findings indicate that PCM coding has the advantage of high resolution, which refers to the ratio of the maximum flow rate provided by a DFCU to the largest step between two consecutive flow steps [16]. However, PCM coding is prone to pressure peaks caused by non-uniform On/Off valve switching times, which can impact the system performance [17].

On the other hand, PNM coding offers the best fault-tolerance performance and has the potential to eliminate the pressure peak issue [12], [18]. However, its main drawback lies in the requirement for a large number of On/Off valves to achieve a good resolution. This can pose challenges in practical applications, especially when considering the space limitations of the DFCU.

To balance the advantages of PCM and PNM, the Fibonacci Numbers (FN) control approach is used as a compromise. It offers a more effective solution for limiting pressure peaks compared to binary coding, while requiring fewer valves than the PNM approach [19].

By employing the digital control approach mentioned earlier, On/Off valves can also be utilized to actively and intelligently modify: the displacement (V_{ToT}), the force (F), and the torque (T_q) produced by parallel digital hydraulic pumps, cylinders, and motors [12].

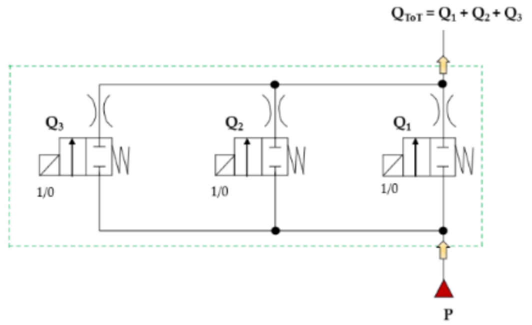
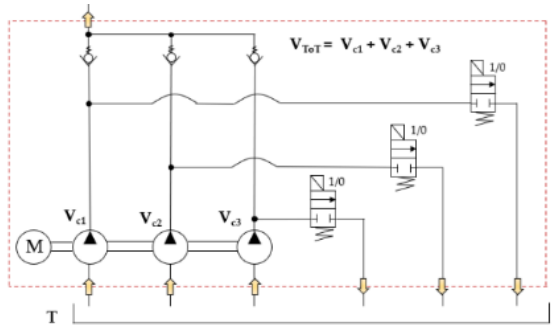
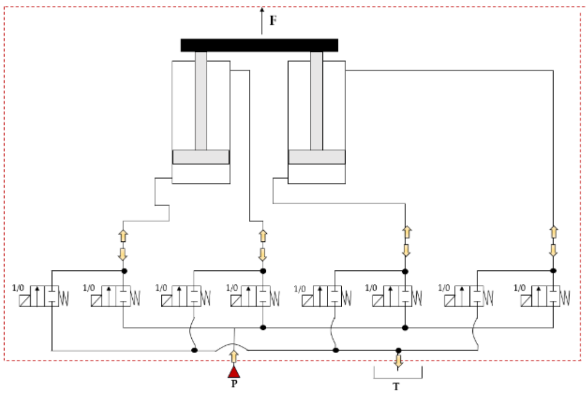
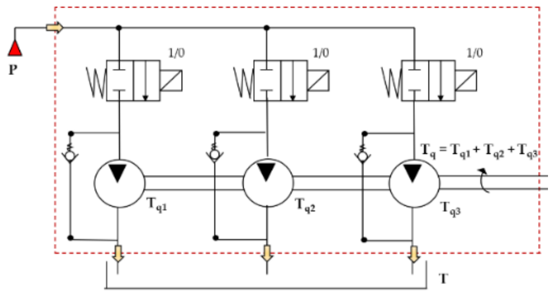
A parallel digital hydraulic pump consists of multiple volumetric pumps arranged in parallel and coaxially. Each pump is individually controlled at its outlet by an On/Off valve. The maximum displacement (V_{ToT}) produced by this parallel digital hydraulic system is obtained by summing up the displacements of all the volumetric pumps, while the minimum displacement is determined by the volumetric pump with the smallest displacement. The range between the highest and lowest displacement values depends on the coding scheme of the switching valves (i.e. PNM, PCM or FN coding scheme). Regardless of the digital approach used for the switching valves' control, the system offers 2^K displacement options, where K is the number of pumps operating in parallel [13].

A parallel digital hydraulic cylinder offers multiple implementation options, with one of the simplest being the parallel connection of several hydraulic cylinders. In this system, the force (F) generated is controlled by adjusting the flow rate supplied to the different cylinders through several On/Off valves. However, this setup can be inconvenient due to the need for numerous On/Off valves, resulting in a large installation space requirement [13].

A parallel digital hydraulic motor consists of multiple coaxial hydraulic motors operating in parallel. Each motor is controlled individually using an On/Off valve. In this system, the maximum torque (T_q) is obtained by adding up the torques produced by all the motors operating in parallel. Conversely, the minimum torque is determined by the torque obtained by the motor with the smallest displacement. The range of torque between the highest and lowest values is determined by the switching valves' coding scheme (namely PNM, PCM or FM coding). Independently of the valves' digital control approach, the parallel digital hydraulic motor offers a total of 2^M torque options, where M represents the number of hydraulic motors operating in parallel [13].

Table 1 presents the hydraulic schematic of the four primary hydraulic systems, using International Organization for Standardization (ISO) symbols. The table provides a clear visual representation of the configuration and components of each system.

Table 1. Hydraulic Schematic of Parallel Digital Hydraulic Systems, adapted from [12].

Parallel Digital Hydraulic Valves / DFCUs	Parallel Digital Hydraulic Pumps
	
Parallel Digital Hydraulic Cylinders	**Parallel Digital Hydraulic Motors**
	

Parallel digital hydraulic pumps, cylinders, and motors have been proven to improve system efficiency, as evidenced by various scientific publications [20]–[22]. One important example is the sizing press drive, which combines analogue primary pump control with a parallel digital hydraulic cylinder system [23]. This integration of technologies enhances the overall performance and efficiency of the system.

2.2 High Frequency Switching Digital Hydraulic Systems

The key component in high frequency switching digital hydraulic systems is the high frequency switching digital hydraulic valve (HFSV). The HFSV employs Pulse Width Modulation (PWM) techniques for control. This involves sending a digital pulse signal with a range of 0 to 1 to the HFSV, where flow modulation (Q) is achieved by adjusting the amplitude and duty cycle of the signal. The controllability of the valve is influenced by the switching frequency: a lower frequency allows for better control but increases pressure pulsation. To minimize noise and ensure a smoother flow rate, accumulators and inertance tubes are commonly employed [24], [25].

The functionality of a conventional 4/3 spool valve, with two control edges opened simultaneously, can be achieved by using four 2/2 HFSVs. This setup results in the realization of a 4/3 HFSV, which hydraulic circuit is shown in Figure 2[13].

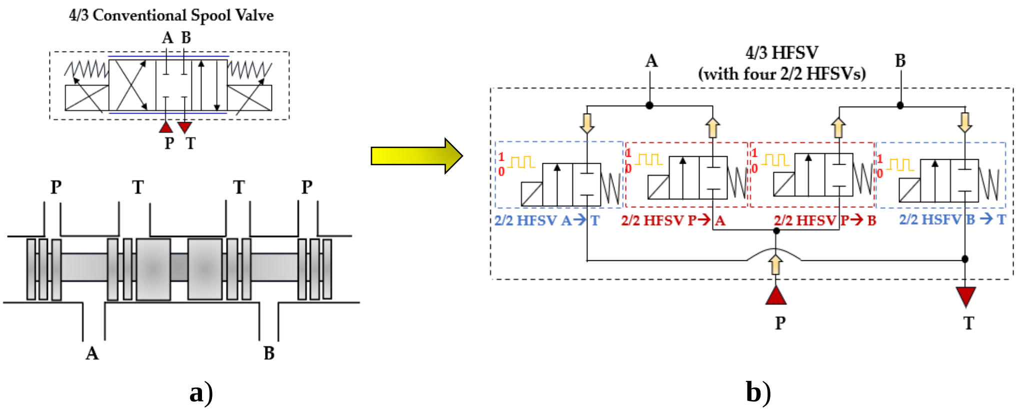


Figure 2. Comparison of Two Types of Four-Way Three-Position Valves: **a**) Conventional 4/3 Spool Valve; **b**) 4/3 HFSV with four 2/2, adapted from [13].

A comparison between the 4/3 HFSV and the 4/3 DFCU reveals notable differences. The On/Off valves used in the former system are larger, more robust, and faster. This is because the HFSV needs to switch between open and closed positions rapidly, within a very short period (e.g., less than 5 ms), and is tasked with performing these switching cycles numerous times per day [12]. Additionally, the 4/3 HFSV is a preferred option by virtue of the lower number of On/Off valves required. This reduction in the number of valves contributes to a simpler circuit design and potentially lower costs. To further simplify the system and reduce costs, the 4/3 HFSV can be realized by using two four-way two-position (4/2) HFSVs instead of four two-way two-position (2/2) HFSVs, as shown in Figure 3.

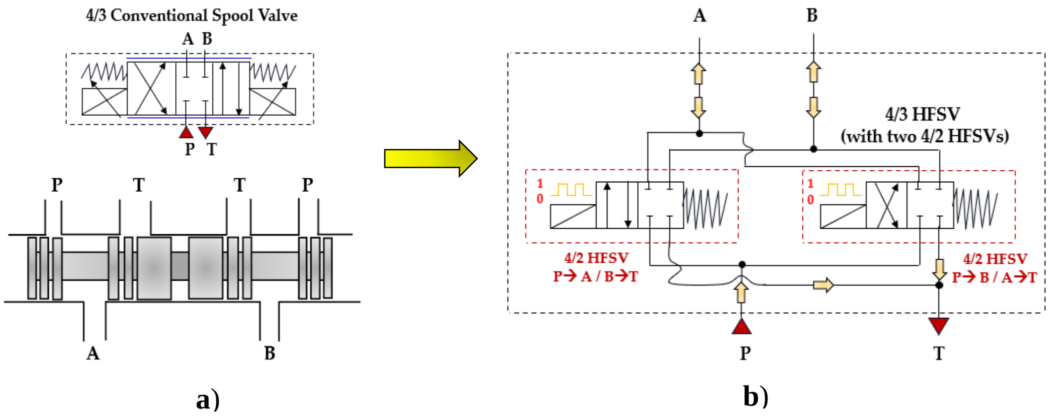


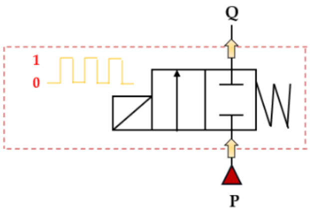
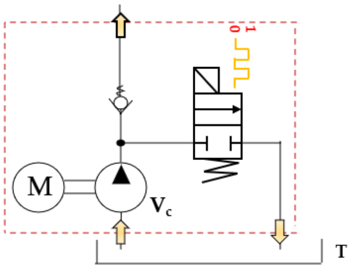
Figure 3. Comparison of Two Types of Four-Way Three-Position Valves: **a**) Conventional 4/3 Spool Valve; **b**) 4/3 HFSV with two 4/2 HFSVs.

Additionally, HFSVs play a crucial role in actively and intelligently controlling the displacement (V_c), the force (F) and the torque (T_q) generated by high frequency switching digital hydraulic pumps (HFSPs), cylinders (HFSCs), and motors (HFSMs) using PWM techniques [12]. By continuously switching at high frequency between the "On" and "Off" states, HFSVs effectively regulate the system's output. Therefore, the performance and characteristics of HFSVs significantly influence the overall dynamics and efficiency of the system [12].

To effectively perform their function, HFSVs require specific characteristics. They need to possess a high switching frequency and be capable of swiftly transitioning from fully open to fully closed positions in under 5 ms. Additionally, they should minimize pressure losses, accommodate high flow rates, and maintain a compact size [8]. However, it is worth noting that the current highest achievable switching frequencies for the fastest valves range from 50 to 150 Hz, and for very small valves, they can reach up to 1000 Hz for short-term operation [26]. These characteristics have led to use of HFSVs in the automotive industry, particularly for controlling the ABS (Anti Brake-locking System) brakes of cars and actuating wet clutches, specifically dual clutch systems, which contribute to enhancing vehicle safety [27], [28].

In Table 2, the hydraulic schematic of the four primary high frequency switching digital hydraulic systems is provided, illustrating their configuration and components.

Table 2. Hydraulic schematic of high frequency switching digital hydraulic systems, adapted from [12].

<table>
<tr><th>HFSVs</th><th>HFSPs</th></tr>
<tr><td>
</td><td>
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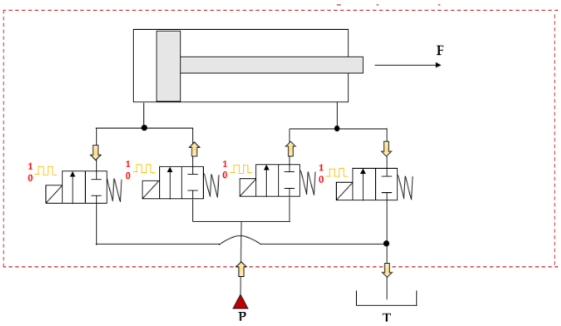
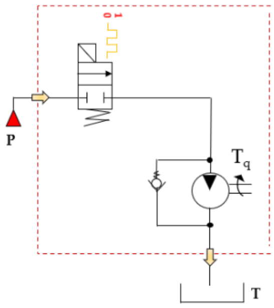
<tr><th>HFSCs</th><th>HFSMs</th></tr>
<tr><td>
</td><td>
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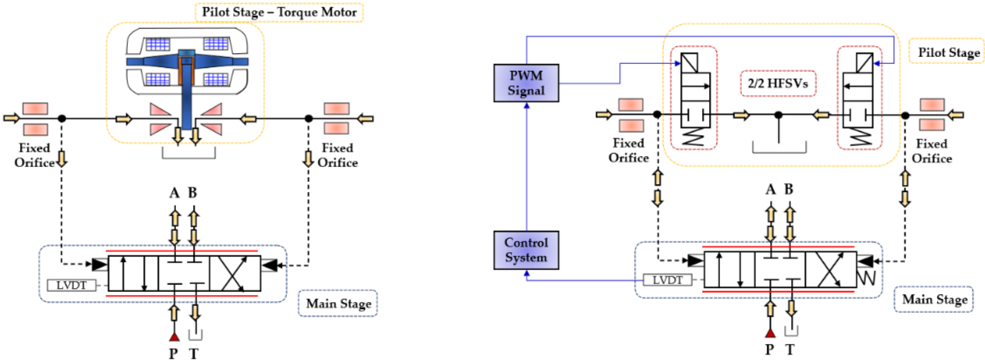
3. Digital Hydraulic Technology Applications

This section provides an overview of digital hydraulic technology applications and highlights their specific advantages, particularly in biomedical, industrial and aeronautical sectors, in comparison to conventional hydraulic technology.

3.1 Digital Proportional/Servo Valves

Over the past few decades, there has been significant research dedicated to the development of HFSVs [29]–[32]. These valves exhibited rapid response, although their flow rates are primarily suited for low flow applications. Consequently, researchers have explored the possibility of using HFSVs as pilot control components for other hydraulic components, thereby enabling intelligent digital control. A notable application of successful implementation is the pilot control of proportional and servovalves, which has gained prominence since the 1990s.

Gao et al. developed a digital servovalve using HFSVs to overcome challenges of conventional servovalves, such as oil contamination, high complexity and high-power consumption [33]. The prototype featured two 2/2 HFSVs as the pilot stage, replacing the traditional torque motor architecture, as depicted in Figure 4. A linear variable displacement transducer (LVDT) enabled closed-loop control for main spool position. Control parameters analysis revealed that increasing duty cycle improved spool displacement, while higher switching frequency reduced oscillations. Remarkably, the step test response indicated that the main spool achieved the set point within 3.5 ms. However, the HFSV switching frequency was limited to 100 Hz due to electromagnetic hysteresis, impacting main spool position tracking accuracy.



a) **b**)

Figure 4. Hydraulic Schematic: **a**) Conventional Servovalve; **b**) Digital Proportional/Servo Valve (this schematic is based on the work presented in [33] and has been redrawn for clarity and readability).

The previous research study [33] highlighted the limitations of using a PWM signal for main spool position control accuracy due to the low switching frequency. Moreover, the discrete flow generated by HFSVs introduced oscillations in the main spool displacement.

To address these issues and enhance the performance of fuel metering servovalves in aircraft fuel systems, Gao et al. introduced a novel digital fuel metering servovalve [34]. The design, depicted in Figure 5, utilized two DFCUs as pilot stages, each controlling five parallel-connected On/Off valves through a PCM coding scheme. Through numerical step tests, it was observed that the main spool exhibited an impressive response speed, achieving 90% of its final position within 4.1 ms. Main spool position tracking accuracy was assessed with three control strategies: velocity feedforward controller (VF), proportional integral controller (PI), and velocity feedforward proportional-integral controller (VFPI) with PCM coding. Implementing the VFPI controller significantly reduced position tracking error by 78%.

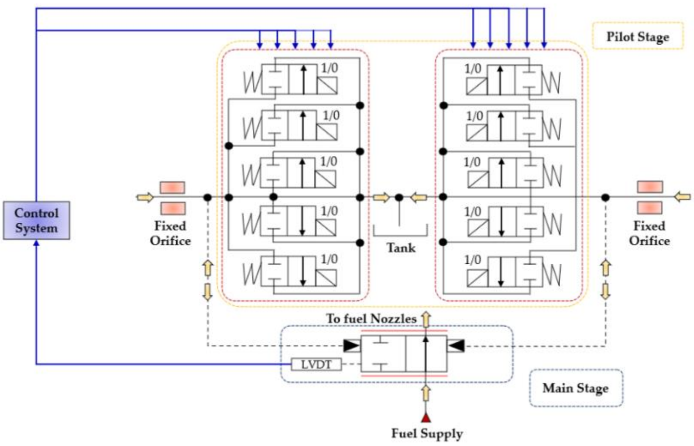


Figure 5. Redrawn of the hydraulic schematic of the digital fuel metering servovalve proposed in [34].

The effective utilization of HFSVs as pilot control components showcases their ability to improve the performance and efficiency of conventional hydraulic control systems. One notable example that exemplifies this is the novel digital hydraulic propulsion system proposed in [35].

3.2 Digital Displacement Pump/Motors

Digital hydraulic valves can also be used to create a specific type of parallel digital hydraulic system known as a digital displacement pump [12]. This type of pump is specifically a radial piston pump that incorporates intelligent output control. Two On/Off valves, the high-pressure (HP) and low-pressure (LP) valves, manage the displacement of each piston chamber. The LP valve, an active solenoid valve, controls fluid intake from the tank. The HP valve connects the system output to the piston chamber and can be either a passive poppet valve or an active solenoid valve. The passive poppet valve opens for discharge when each piston chamber pressure matches system output pressure, while the active solenoid valve enables precise discharge time control. With an active HP valve, each piston can function as a pump or motor, forming a digital displacement pump/motor configuration. Figure 6 illustrates the hydraulic schematic of these parallel digital hydraulic systems.

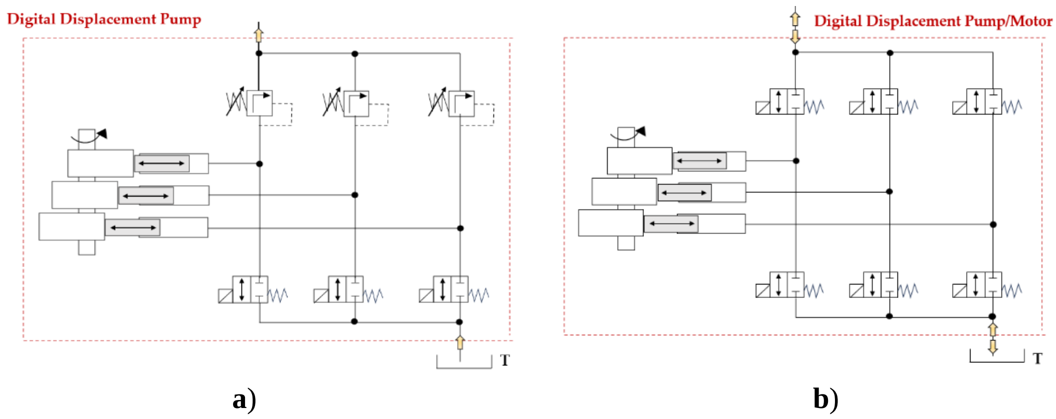


Figure 6. Digital Displacement Pump: a) pure pump system; b) pump-motor system, adapted from [12].

In 1994, the Artemis Intelligent Power company achieved a significant milestone with the invention of the first digital displacement pump [36], [37]. The pump design featured 12 pistons arranged in 3 groups of 4 [37]. When implemented in excavator transmissions, it delivered remarkable benefits, including a 20% reduction in fuel consumption and a 30% increase in productivity [37]. The pump also exhibited advantages such as minimal energy losses, rapid response time, and effective suppression of high-frequency noise [38], [39]. In another notable development, the company designed a specialized unit equipped with 68 pistons to harness energy from wind turbines [37].

3.3 Digital Hydraulic Buck Converters

Digital hydraulic technology finds another fascinating application in high frequency switching transformers, particularly in the realm of digital hydraulic buck converters. These converters enable precise adjustment of system pressure, regulation of flow rate, energy recovery, and enhanced overall system efficiency [40]. Achieving these functionalities involves leveraging the capabilities of HFSVs and the reactive behavior of specific hydraulic components, such as hydraulic tubes and accumulators. The latter create inductive and capacitive effects, respectively, effectively reducing pressure fluctuations caused by the switching process and optimizing system efficiency through the storage and utilization of kinetic energy [40].

The operating principle of a digital hydraulic buck converter is illustrated in Figure 7. To extend the piston, the supply line HFSV is activated, leading to fluid acceleration in the inertance tube. During the supply line HFSV 'off' time, the inertia of the fluid in the inertance tube creates a suction effect, drawing fluid from the tank line through check valve (b). This significantly boosts the average delivery flow, enhancing efficiency compared to conventional hydraulics. The accumulator A further helps in reducing the pressure ripples generated by the supply line HFSV switching process. On the other hand, the accumulator B and the pressure relief valve in the tank line have two important roles. The former stores the maximum oil volume required during the suction phase (i.e., during the piston extension), while the latter helps pressurize the tank system. Additionally, this type of digital hydraulic buck converter allows for energy recovery during the piston's retrieving stroke. To retract the piston, the tank line HFSV is activated, accelerating the fluid in the inertance tube and filling the accumulator B. However, as the tank line HFSV closes, the fluid's inertia in the inertance tube creates a spill effect from accumulator A. As a result, the pressure p_n increases above the supply pressure p_s, allowing the fluid to be redirected back to the supply line (HP) through check valve (a) [40].

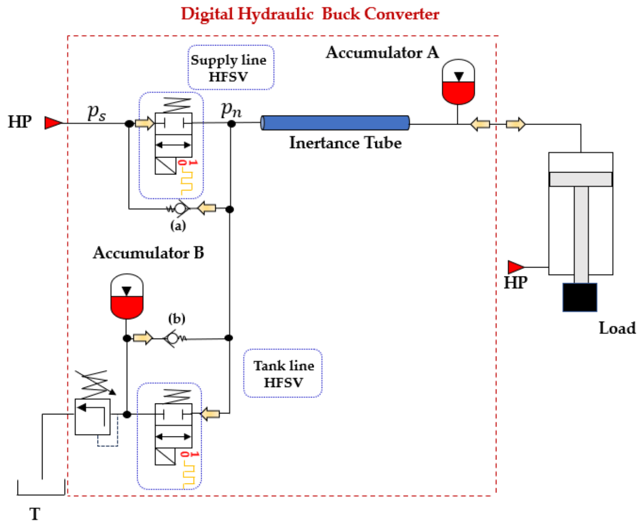


Figure 7. Digital Hydraulic Buck Converter, adapted from [40].

Scheidl et al. investigated the application of digital hydraulic buck converters in advanced casting systems to facilitate mold oscillation [26]. These converters were employed as substitutes for conventional spool valves. This implementation resulted in significantly reduced energy consumption and lower installation costs.

3.4 Digital Hydraulically Driven Knee Exoskeleton

One more intriguing application of digital hydraulic technology is its utilization in the development of hydraulically driven exoskeleton devices. These devices hold immense potential in assisting individuals with impaired mobility by providing additional support and enhancing their physical capabilities. By incorporating digital hydraulic systems into exoskeleton designs, researchers and engineers aim to achieve improved functionality, efficiency, and versatility.

Recently, Rituraj et al. made significant advancements in the field of hydraulically driven knee exoskeletons by developing and testing a prototype with a parallel digital hydraulic drive system [41]. The design of this innovative exoskeleton is illustrated in Figure 8, showcasing its two primary components: the thigh and shank sections, which can be easily attached to the corresponding human limb parts. These components are interconnected via a revolute joint positioned at the knee. To enable the exoskeleton's movement, two mechanisms are used, each comprising a hydraulic cylinder and a connecting rod. The joint between the cylinder rod and connecting rod in each mechanism incorporates a guide pin that follows a precisely curved path defined by grooves on the guide plates, ensuring precise and controlled motion. The parallel digital hydraulic system employed in driving the exoskeleton device encompasses a pressure source (P), a tank (T), digital hydraulic valves (highlighted in yellow in the illustration), and the two hydraulic cylinders. The digital hydraulic valves establish a parallel configuration for the hydraulic cylinders by connecting each cylinder chamber to the pressure source (P) and tank (T).

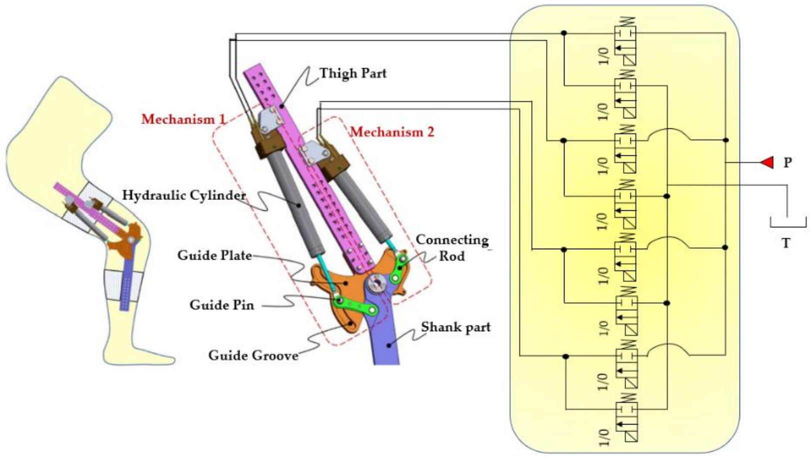


Figure 8. Redrawn of the design of the digital hydraulically driven knee exoskeleton developed in [41].

Compared to traditional hydraulic technology used in previous exoskeletons [42]–[44], the digital hydraulically driven exoskeleton device offers improved compactness, efficiency, and robustness. It provides a significant advantage as it is designed specifically for paraplegic patients, capable of delivering 100% of the required torque at the knee joint. In contrast, previous exoskeletons primarily focused on partial disability or power augmentation, enabling them to supply only 30% to 50% of the knee torque.

3.5 Digital Hydraulic Gap Control for Rolling and Paper Mills

Currently, hydraulic gap control is accomplished through the use of precise conventional servovalves. However, these valves encounter issues such as oil contamination, significant energy losses, and wear of the metering edge [6]. To overcome these challenges, digital hydraulics presents a promising solution. Digital hydraulic systems can effectively address both oil contamination and energy losses, while also providing enhanced robustness, which is a crucial requirement for steel mill applications.

Scheidl et al. conducted a comparison between a conventional hydraulic gap control actuator, driven by a conventional servovalve, and a HFSVs block in rolling and paper mills [26]. The hydraulic schematic is depicted in Figure 9. The results showed that the digital hydraulic system with HFSVs offered comparable performance to the conventional hydraulic system. Additionally, the digital hydraulic system exhibited advantages such as increased robustness, extended lifespan, and significant energy savings.

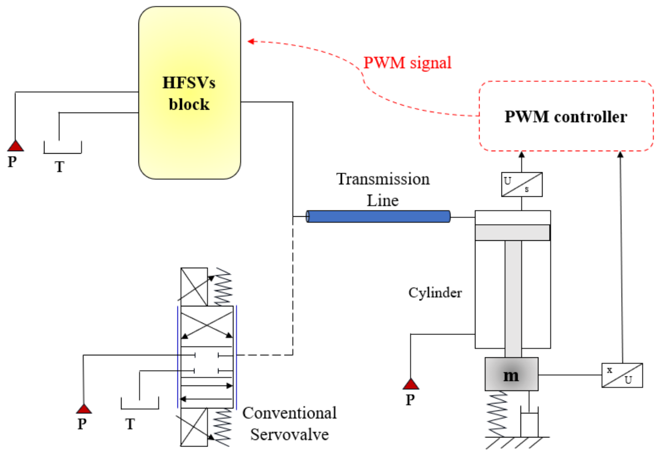


Figure 9. Hydraulic gap control actuator with two different control mechanisms: an analogue control system represented by a conventional servovalve, and a digital control system represented by a HFSVs block (the schematic has been redrawn from the original source [26] to enhance clarity and readability).

4. Digital Hydraulic Technology Challenges and Future Directions

Digital hydraulic technology faces several challenges that need to be addressed for its successful implementation. Here are some of the key challenges [11]:

- HFSVs Design and Durability: Developing digital hydraulic valves, especially HFSVs, that can withstand fast switching speeds, maintain durability, and resist wear and fatigue is a significant challenge. It is crucial to design HFSVs that can handle high frequency switching while delivering large flow rates at low pressure drops without compromising durability;
- Noise and Vibration: Digital hydraulic systems, especially those utilizing HFSVs, can generate significant noise and vibration due to rapid valve switching. Managing and minimizing these undesirable effects is crucial, particularly in applications where noise and vibration can impact system performance;
- Large Number of Valves: Parallel digital hydraulic systems, which employ multiple valves, can lead to a significant increase in the number of components. This can result in challenges related to system size, cost, and complexity;
- Control Strategy: Developing and implementing a control strategy for digital hydraulic systems can be complex, as it requires unconventional approaches compared to conventional hydraulic systems. Designing effective control algorithms and strategies that can maximize the benefits of digital hydraulic technology poses a challenge;
- System Integration: Integrating digital hydraulic systems into existing machinery can pose challenges. Compatibility and space constraints need to be carefully considered during the integration process.

Conclusions

Digital hydraulic technology has emerged as a promising alternative to conventional hydraulic technology, offering numerous advantages such as enhanced reliability and reduced energy consumption. This paper has provided an overview of the recent advancements in digital hydraulic technology and highlighted its various applications and benefits. It has examined how digital hydraulic systems can be implemented in sectors such as aerospace, biomedical, and industrial engineering. The advantages of digital hydraulic systems, especially in terms of improved performance and functionality, have been emphasized in comparison to conventional hydraulics. Nevertheless, it is crucial to acknowledge the existing challenges and limitations that accompany this novel technology. Moving forward, further research and development in digital hydraulic technology are necessary to overcome these challenges and expand its utilization across various industries.

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