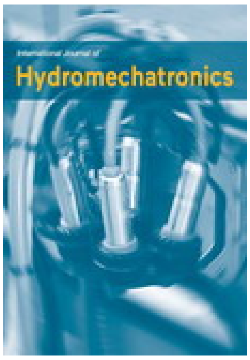

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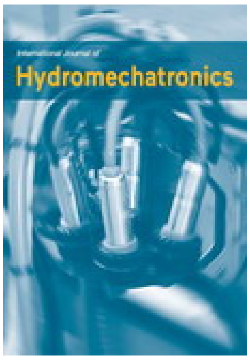

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A review of independent metering control system for mobile machinery

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Abstract: Independent metering control is an advanced electro-hydraulic control technology for mobile machinery. By decoupling the inlet and outlet orifices in the conventional hydraulic valve, additional control degrees of freedom and energy-efficient mode switching are introduced. With onboard electronics controller and feedback, the hydraulic control is dependent on the software programming rather than hardware structure, such that the advantages, including simplification of valve structure, standardisation of valve technology, functional integration, flexible system configuration, and advanced control features, can be obtained. However, the resulting diversity of different layouts, configuration complexity, and expected high control effort still hinder a successful spread into industrial applications. This paper reviews commercial products and applications using independent metering control. The challenges, together with their key countermeasures and future trends, including flow control, fast response pilot drive, active damping control, smooth mode switching, as well as fault diagnosis and tolerance, are focused on and demonstrated in detail.

Keywords: electro-hydraulic system; mobile machinery; independent metering control; multi-way valve.

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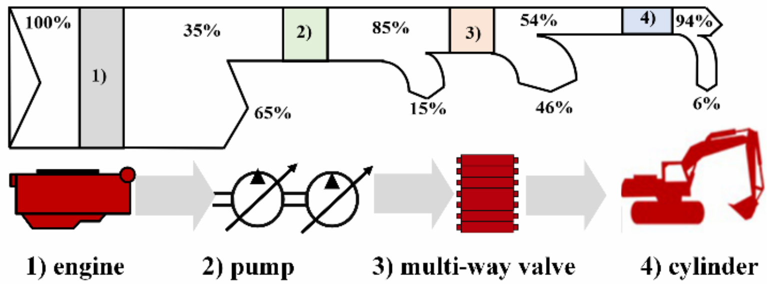
1 Introduction

Mobile machinery, including excavators, cranes, concrete pump trucks, and rotary drilling rigs, are usually driven by the hydraulic system. Two reasons can be identified for the successful utilisation of hydraulic drive technology. The first is addressed by the high power density of fluid power, and the second resides in the capability of robust and flexible motion control of both linear and rotatory movements with large forces. Typical mobile machinery is driven by multi-actuator, (e.g., cylinder or motor) hydraulic systems. To decrease costs, most machines have a limited number of pumps, which infers that each pump supplies flow to more than just one actuator at a time. The pump flow is distributed to the multiple actuators by controlling the multiway valve, which consists of a group of directional valves.

Energy efficiency is a critical concern for mobile machinery. A typically energy-inefficient machine is the excavator, whose energy efficiency is as low as 10% (Vukovic et al., 2017; Chen et al., 2022), which significantly increases CO_2 emissions (200 million tons per year). Nowadays, strict administrative regulations urgently demand industrial reductions in energy consumption and CO_2 emissions. At the One Earth Summit in December 2017, 29 countries committed to achieving zero carbon emissions by the mid-21st century, and signed the Carbon Neutral Alliance Statement. On June 12, 2020, 125 countries committed to achieving carbon neutrality by the 21st century (Net Zero Scorecard, 2020). A recent announcement presented by China determined the goal of carbon neutrality to advance green and low-carbon development. Dual objectives were proposed, including peak CO_2 emissions by 2030 and carbon neutrality by 2060 (Dong et al., 2022).

Energy losses of the pump and throttling losses in the hydraulic system account for significant energy inefficiency, as shown in Figure 1. A survey predicts that a 15% improvement in efficiency could save industry and consumers more than \$19 to \$25 billion per year in energy costs and reduce emissions by more than 90 million metric tons of CO_2 per year. Developments of energy-efficient hydraulic systems inspire the fluid power industry, increasing manufacturing capabilities and competitiveness in growing world markets (Stelson, 2011).

Figure 1 Energy loss of the hydraulic system in an excavator (see online version for colours)

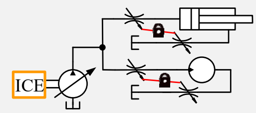
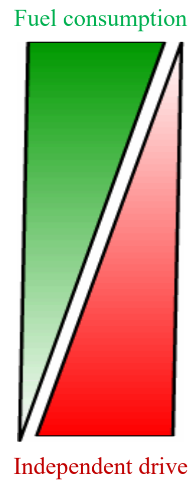


Source: Ding et al. (2024b)

As listed in Table 1, an intuitive method to enhance the energy efficiency of the hydraulic system is pump control. This system ensures that the supply pressure and flow of the pump can automatically match the load pressure and velocity without overflow. Direct pump control is notably energy-efficient due to the elimination of throttling losses. Two methods exist to conduct pump control: variable displacement and variable speed (Helbig, 2007). The former changes pump displacement to regulate the flow. Extensive research on this subject is conducted by Professor Ivantysynova (Jenkins and Ivantysynova, 2018). The latter changes the speed of the electric motor to drive the fixed displacement pump. Research on the characteristics and performance of variable-speed pump control was carried out (Fassbender et al., 2021; Schmidt et al., 2022; Qu et al., 2023). These systems are distinguished by their reduced energy usage, which leads to improved fuel efficiency and a decrease in CO_2 emissions. Nonetheless, due to challenges such as large inertia mass, leakages, weak stiffness, and high nonlinearities, it is difficult to achieve accurate motion tracking and fast dynamic response of the actuator compared with valve control systems. Moreover, each cylinder needs to be combined with a high-dynamic variable pump unit, which will significantly increase the cost and effort of the component.

When the scenarios are to use valve-controlled, the independent metering control system (IMCS) is an inevitable choice to increase energy efficiency, as listed in Table 1. It represents systems where the metre-in and the metre-out orifices are independently controlled. As shown in Table 1, the IMCS has changed from a single spool to twin spools, breaking the spool structural coupling compared with the traditional system, as shown in Figure 2. Meanwhile, additional electronic sensors and chip control energise more functions to the hydraulic system. Intensive investigations were carried out after Jansson and Palmberg (1990) proposed the concept of IMCS. Theoretically, a specific output force by the hydraulic actuator can now be obtained with an infinite number of chamber pressure combinations, which offers the possibility of decreases in energy consumption. The pressures can be regulated as low as possible in terms of high-precision chamber pressure tracking (Koivumäki et al., 2019). Moreover, the system with independent metering control can achieve energy recovery or regeneration modes by changing the flow path during operation, which can also significantly reduce energy consumption.

Table 1 Different independent electro-hydraulic control (see online version for colours)

<table>
<tr><th>System</th><th>Layout</th><th>Features</th></tr>
<tr><td>Conventional system</td><td>
</td><td rowspan="4">
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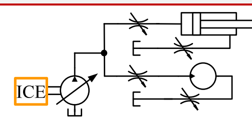
<tr><td>Independent metering control</td><td>
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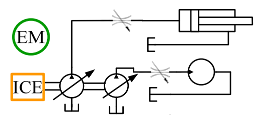
<tr><td>Independent variable-displacement control</td><td>
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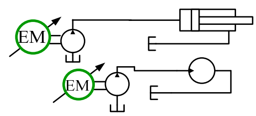
<tr><td>Independent variable-speed control</td><td>
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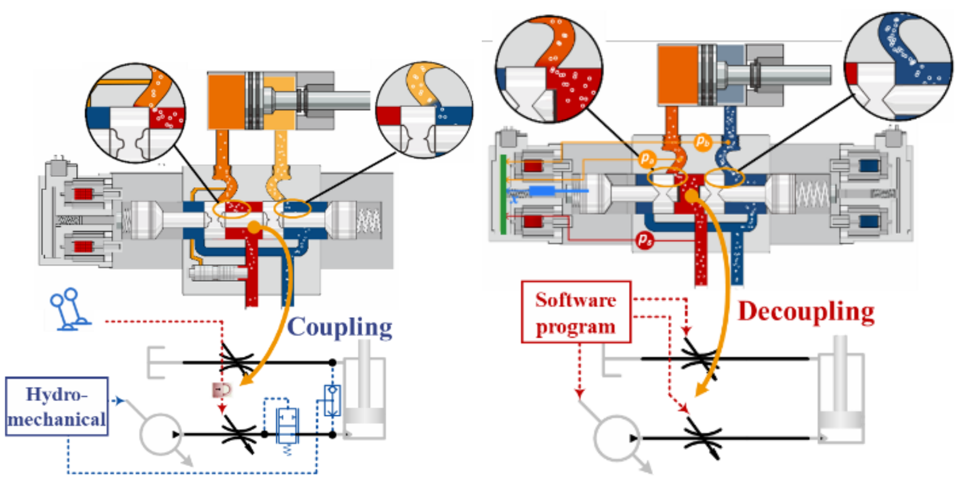
Figure 2 Comparison of valve configuration, (a) conventional valve, (b) independent metering control valve (see online version for colours)



(a) (b)

Apart from energy efficiency, desired features of the mobile hydraulic systems also include high-precision motion and force-tracking controls. The freedom degree of the system (DOF) can be expanded from 1 to 2~4 by introducing mechanically decoupled orifices in the cylinder chambers (Ding et al., 2018). Owing to the additional DOFs, the system is transformed from single input single output (SISO) to multiple input multiple output (MIMO), which enables simultaneous velocity and pressure control. Meanwhile, the control manner evolves from hydro-mechanical to intelligent software-based, as shown in Figure 2. At last, improvements in energy efficiency and control controllability strongly rely on software programming rather than hardware structure. More advanced and complex control methods are now required to adapt to various working conditions of different machines.

In summary, the IMCS is a commercial solution that can address rising energy costs and strict emission regulations and standards in mobile machinery compared to independent pump control. However, it relies on additional control DOFs and electronics, as well as sophisticated software programming, which also confronts the challenges against the strict requirements for operator comfort and safety, as well as constant demands for higher productivity in mobile machinery. This paper reviews commercial products and applications using independent metering control. The challenges that prohibit such technology from widespread commercial applications and their key countermeasures are focused on, together with the future trends.

2 Commercial products and applications

With in-depth investigations of IMCS techniques, some well-known manufacturers have introduced their commercial multi-way valves to the market to promote the development of the hydraulic industry. By transforming the main-stage valve types from the traditional 4/3 way valve into the two 3/3 way valves or several 2-way valves, the mechanical decoupling principle was established to develop different hardware layouts of multi-way valves (Ding and Cheng, 2024). Some mature products have also been involved in industrial applications, especially for mobile machinery.

2.1 Eaton

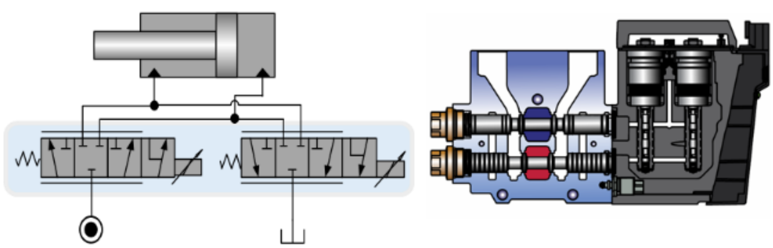
The ZT16 valve and its ultronics control architecture first appeared from Eaton, patented in 2004. It utilises twin-spool architecture and integrates pressure and spool position sensors with onboard electronics, as shown in Figure 3. Such twin-spool architecture is a layout starting from conventional cylinder drives with a 4/3 way valve spool type. It is a natural approach to introduce the decoupled inlet and outlet orifices, such that a control input is added and then an additional state variable can be controlled. Energy regeneration and float modes can also be conducted by the flexible configuration of the flow path (Liu et al., 2021b). Owning to the bidirectional flow of the spool, a hydro-mechanical pressure compensator is eliminated (Eaton, 2013).

In recent years, Eaton has developed an advanced independent metering control valve CMA based on ZT16, which immediately replaced ZT16 as the current key product. The CMA90/200 is an advanced CAN-enabled electro-hydraulic independent metering control valve with a sectional structure. Pressure and position sensors, onboard electronics, together with advanced software control algorithms are also involved. Conventional mobile multi-way valves must compromise on energy efficiency, precision, or response, but in contrast, the CMA delivers both. Higher performance with sub-micron hysteresis, closed-loop spool position control, and repeatable performance can be obtained by CMA. Representative applications of CMA include excavators, forklifts, and wheel loaders. Especially for concrete pump tracking, the serious vibrations of the boom could be decreased by 90% (Eaton, 2016).

Figure 3 Ultronics ZT16 and Eaton CMA90/200 (see online version for colours)

Source: Eaton (2016, 2018)

Figure 4 Danfoss PVX valve (see online version for colours)



Source: Danfoss (2016)

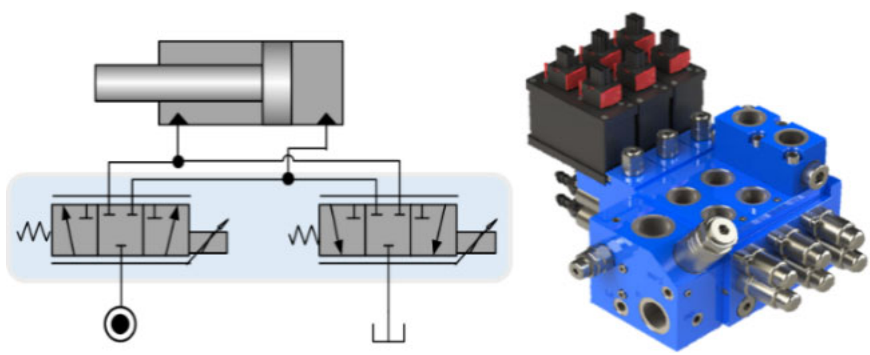
2.2 Danfoss

The twin-spool architecture also involves some variants. Danfoss develops an independent metering control valve PVX, as shown in Figure 4. Energy-saving flow paths, either recuperation or regeneration, can be switched by positioning the spool in a special setting, which requires the fabrication of a spool with a longer displacement. As the CMA valve, the sophisticated valve solution also offers the advantages of IMCS, including lower development costs, reduced compromise time, exceptional adaptivity, superior operator productivity, and improved energy efficiency. Meanwhile, such a valve layout is less flexible than Eaton CMA, and the complicated mode control can be simplified (Danfoss, 2016).

2.3 Wessel hydraulic

As shown in Figure 5, the PAS of Wessel hydraulic also uses two spools, but with a hardware layout different from CMA and PVX. Rather than connecting one of the cylinder ports to either pump or tank, one of the valves connects the pump/tank to one or the other cylinder port. Because the cylinder ports cannot be connected to the same supply or drain lines simultaneously, both regenerative and float modes cannot be achieved with such a layout. Besides, this product is designed as an open-centre valve suitable for only load-sensing hydraulic systems. Combined with onboard electronics, the valve also enables energetically optimised control concepts. The safety concept is also considerably improved since almost all functions have a redundant flow path (Wessel, 2013).

Figure 5 Wessel Hydraulik PAS valve (see online version for colours)

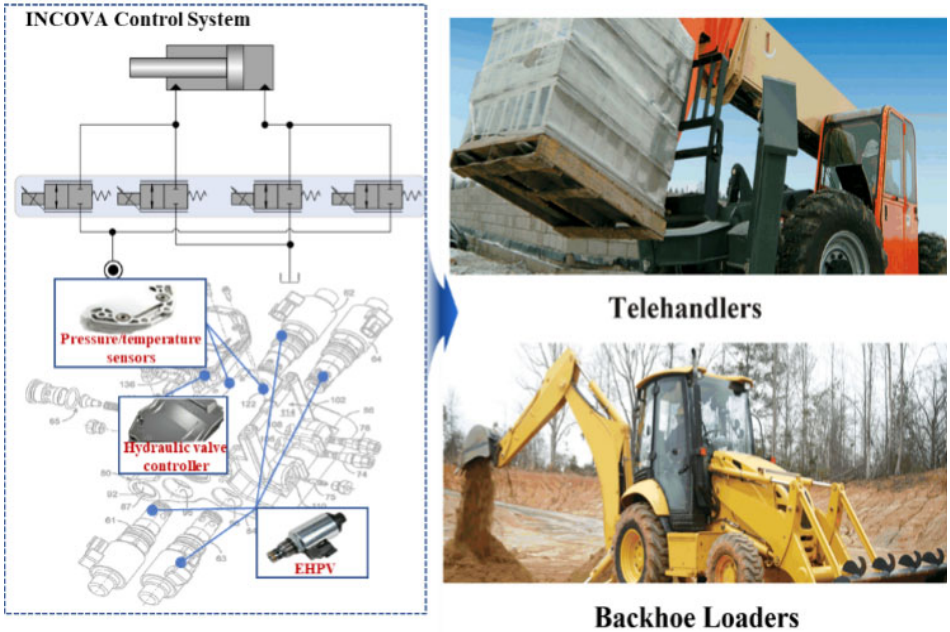


Source: Wessel (2013)

2.4 Husco

Compared with a two-spool layout, four 2-way valves offer higher flexibility. This layout typically employs poppet valves, which provide excellent sealing performance, greater resistance to contaminants, and lower manufacturing costs. With four 2-way poppet valves, an actuator port can connect to both the pump and the tank simultaneously (Ding and Cheng, 2024). Husco Inc. has developed an innovative hydraulic control technology based on this layout, known as INCOVA (Stephenson et al., 2007). This system integrates a hydro-mechanical pressure compensator to each electro-proportional poppet valve (EHPV), but it is known that the control accuracy of the poppet valve is lower compared with the spool valve (Nguyen et al., 2022). A group of integrated pressure and temperature sensors, together with onboard electronics and advanced control software, are also included. INCOVA has been successfully implemented in various mobile machinery, including excavators, telehandlers, backhoe loaders, and mining trucks (Husco, 2007), as illustrated in Figure 6.

Figure 6 Husco hydraulic control system INCOVA (see online version for colours)



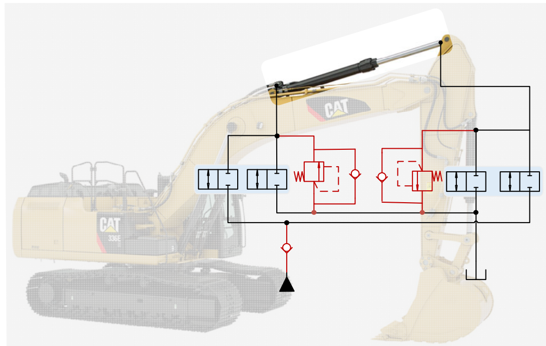
Source: Husco (2007)

2.5 Caterpillar, Volvo

Apart from OEMs in the field of fluid power components and systems, the internationally competitive manufacturers of construction machinery are also interested in developing the IMCS. Caterpillar developed a 336E hybrid excavator using the independent metering control valve in 2012, which is patented as ACS. Its layout is similar to INCOVA of Husco, which consists of four 2-way valves. To mitigate the risk of cavitation and overload, the system incorporates two check valves and relief valves at the drain lines. Additionally, a check valve is mounted in the pump supply line to prevent the reverse flow from the cylinder back to the pump. Furthermore, the advanced control system (ACS) has been effectively deployed in the Cat 336E-H hydraulic hybrid excavator and the 336D2 frontless excavator. It utilises a set of designed algorithms to control the execution of motion with minimal power loss, as evidenced by the pressure drop across the orifice (Caterpillar, 2008), as depicted in Figure 7.

An innovative EC530E/550E of Volve is equipped with IMCS, as shown in Figure 8, which improves fuel efficiency by 25% (Volvo, 2022). Furthermore, the operator experience is taken to new levels, including creep mode, motion priority, reduced bounce, and comfortable drive control.

Figure 7 The Caterpillar's 336EH/336D2 with IMCS (see online version for colours)



Source: Caterpillar (2008)

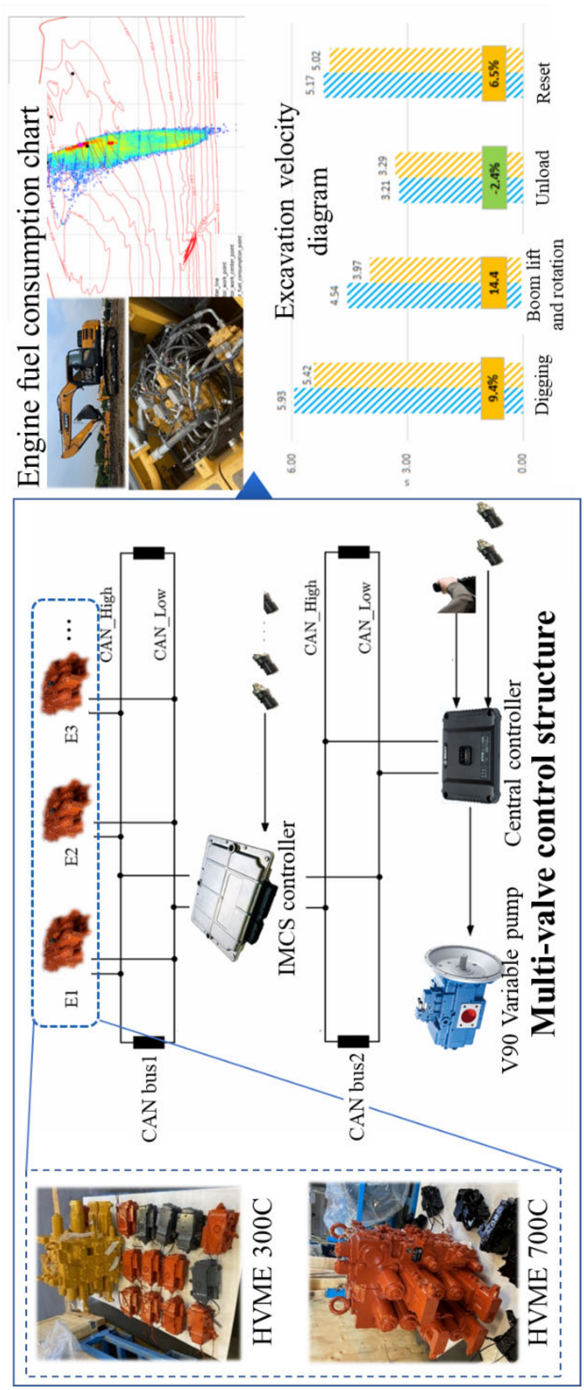
Figure 8 The Volvo's EC530E/550E with IMCS (see online version for colours)

Source: Volvo (2022)

2.6 Jiangsu Hengli

The aforementioned independent metering control valves, including Eaton, Danfoss, Husco, and Wessel hydraulic, are all sectional multi-way valves that contain a rated flow less than 200 L/min. However, higher-rated flows are required by mobile machinery with large sizes. Jiangsu Hengli developed a sectional multi-way valve HVSA 20 at first, which utilises a similar two-spool layout with CMA200. Then, towards large flow demand, the integrated multi-way valves HVME 300C/700C are developed to be applied to dual-pump circuits in the large-size excavator. The rated flow rates are increased to 300 and 600 L/min respectively. All three multi-way valves integrate pressure, temperature, and spool displacement sensors and onboard electronics.

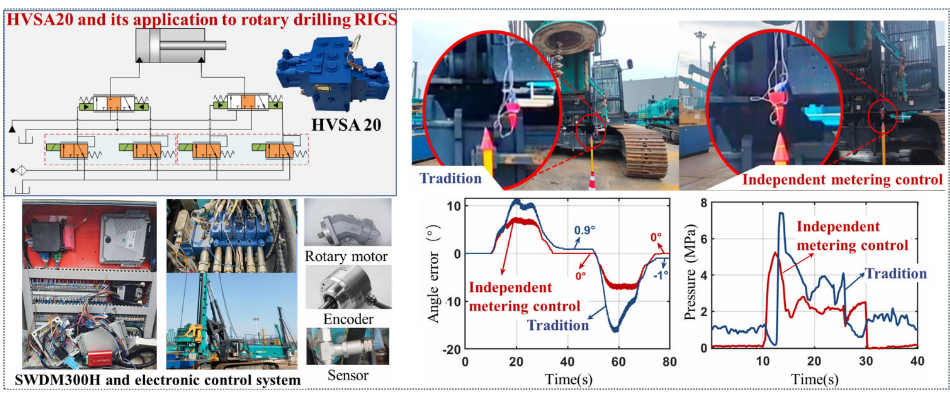
Figure 9 HVME300C and HVME700C developed by Jiangsu Hengli and their application in excavators (see online version for colours)



As depicted in Figures 9 and 10, HVME300C and HVME700C valves have been applied to the SANY SY205 and SY375 excavators respectively, in which the boom and arm are driven by the independent metering control sections. Tested under 150 cycles of digging action, both energy and operation efficiency can be improved, and the fuel consumption can be saved by 12.5%–14.4%. The HVSA20 valve has been applied to the Sunward SWDM300H rotary drilling rig. A swing positioning accuracy is improved from 0.9° to 0.1° under different postures. Besides, the pressure oscillations are reduced by 41%–67%, and 10% of energy consumption is saved at the same time.

Compared with the independent metering control valve abroad, the productions of Jiangsu Hengli involve the same advanced functions including twin spools, onboard electronics control, flexible mode switching, and fast programmable commissioning. Furthermore, a more complicated dual-pump double-loop structure and higher rated flow can be achieved, which makes the productions suitable for mobile machinery with large sizes.

Figure 10 HVME300C and HVME700C developed by Jiangsu Hengli and their application in rotary drilling rigs (see online version for colours)



3 Challenges and key technologies

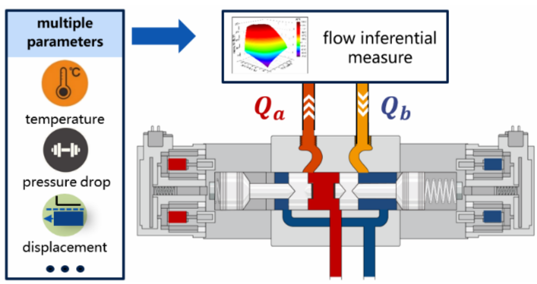
Although commercial products of the IMCS have been developed by companies in the hydraulic industry and construction machinery, the resulting diversity of different layouts, complex operating modes, and expected high control effort together with sophisticated software programming still hinder a successful spread into industrial applications. Then, the challenges and their key technologies are demonstrated in detail.

3.1 Flow control

In mobile machinery, the load characteristics are randomly time-varying during operations (Helian et al., 2023). For instance, the external load varies pertaining to various digging actions and conditions, while the internal load (such as gravity and inertia force) varies in terms of the crane's posture and the geometric configuration of its application, resulting in fluctuations in system pressures and flow. The actuator's velocity should be controlled independently with the load changes, and disturbances should be rejected among different loads. However, a significant challenge arises because the flows across the valve are influenced by multiple parameters, including spool displacement, pressure drops across the orifice, and temperature (Ding et al., 2018). In a conventional multi-way valve, the hydro-mechanical pressure compensator is integrated to maintain constant pressure drops across the orifice, such that the flow is only dependent on the spool displacement and temperature. However, due to the bidirectional flow in the IMCS, the pressure compensator is difficult to integrate, and thereby an electro-hydraulic flow control is necessary.

1 As shown in Figure 11, the flow inferential measurement is a crucial step in conducting the electro-hydraulic flow control. However, the valve flow is nonlinearly and uncertainly affected by multiple parameters, which makes its estimation inaccurate.

Figure 11 The valve flow pertaining to the multiple parameters (see online version for colours)

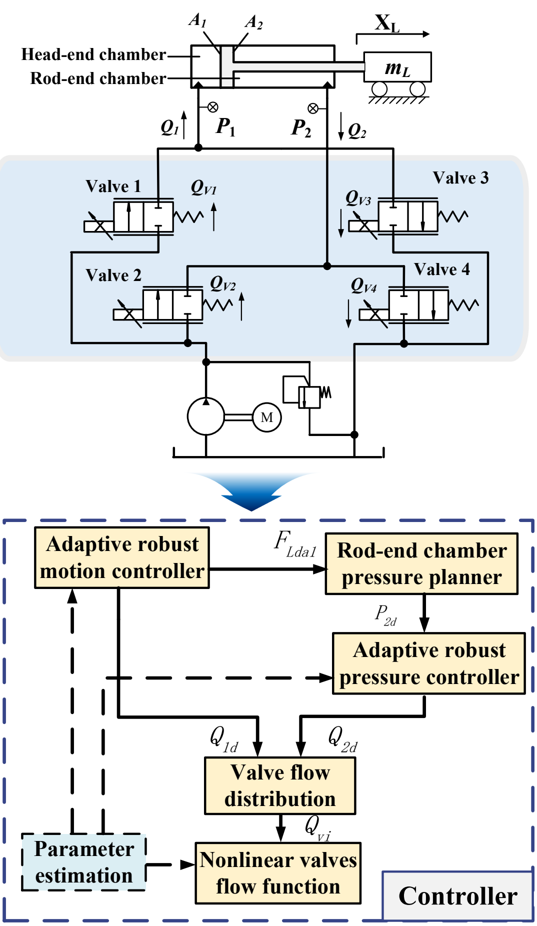


At present, there are two main ways to achieve flow inferential measurement. The first is adaptive control techniques. To address the issue of the nonlinear valve flow gain, Yao proposed an approach to decompose and approximate the unknown flow mapping with some localised orthogonal basis functions (Liu and Yao, 2006). The parameters of the flow mapping model and other unknown system parameters could be determined simultaneously from the pressure dynamics of the hydraulic system, in which certain intelligent integration of online parameter estimation algorithms and neural network (NN) nonlinear function modelling are employed. Adaptive polynomial fitting models are employed to compensate for high-precision control (Lyu et al., 2021; Lyu et al., 2024). As depicted in Figure 12, based on the polynomial flow model, an adaptive robust control approach was synthesised, in which the least-squares estimation law was utilised to online adapt the valve parameter and other system parameters (Li et al., 2022). However, the polynomial form of the valve model cannot deal with all valve characteristics, such as hysteresis and time delay.

Another way for flow inferential measurement is an auto-calibration approach. A computational flow feedback control method is proposed by incorporating an AdaBoost NN, as shown in Figure 13. A proportional-integral controller is coupled to accurately regulate flow changes influenced by spool displacement, pressure differential, and temperature. The global sensitivity analysis is employed on the flow calculation model, and then piecewise wavelet filters are applied to exclude noise interference (Zhang et al., 2019). However, the AdaBoost algorithm combined with

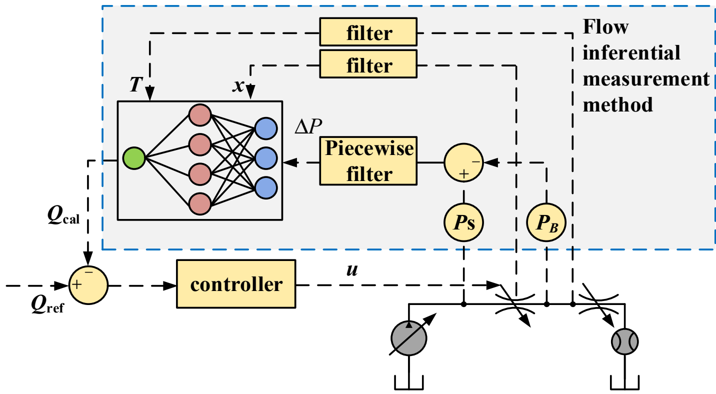
BPNN confronts a problem of the local optimal solution, which negatively influences the flow measurement. Specifically, when all parameters and methods remain consistent, the resulting outcomes can be vastly different. Consequently, a large number of calibration experiments are required, with unnecessary waste of time. Ding et al. (2023) proposed an improved flow measurement method using RBFNN. The parameters of the RBF are optimised automatically so that an increased accuracy of 13.08%–19.83% can be achieved compared with Adaboost BPNN (Ding et al., 2023). However, these algorithms focus on off-line flow calibration, which can not cope with changes in flow characteristics during the lifetime service. Opdenbosch et al. (2013) designed an online control algorithm to learn the inverse input-state map of an electro-hydraulic poppet valve with the aid of a nodal link perceptron network (NLPN). The intelligent controller that combines the auto-calibration state-trajectory-based control method can enforce the valve tracking of a desired reference.

Figure 12 Flow inferential measurement by adaptive control (see online version for colours)



Source: Li et al. (2022)

Figure 13 Flow inferential measurement by auto-calibration NN (see online version for colours)

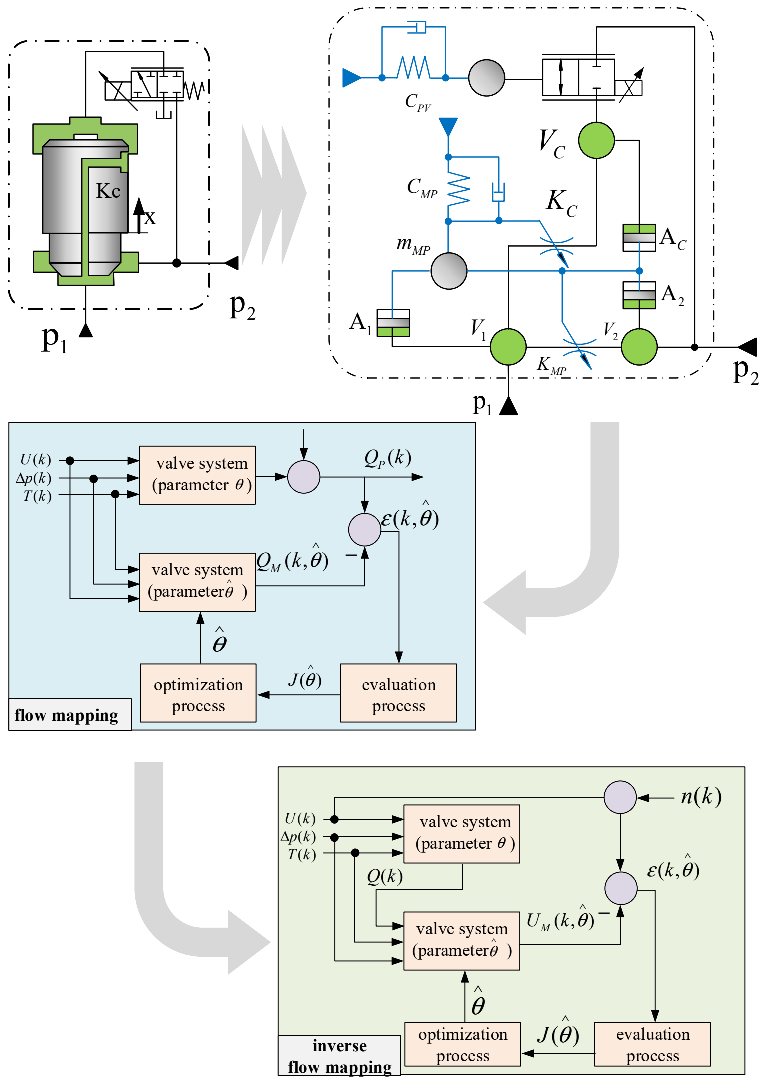


Source: Zhang et al. (2019)

The oil temperature continuously changes in the hydraulic system and then influences the valve flow mapping. To take into account the effect of temperature on the flow inferential measurement, Bachmann et al. (2023) proposed four-dimensional models to describe the flow as a function of temperature, pressure drop, and spool displacement. These flow models are parametrised based on a computationally efficient interpolation method considering the fluid flow state inside the valve. After that, the created flow descriptions can be used to refine the flow control strategy. Compared to the flow control without temperature compensation, this control strategy not only maintains good dynamic characteristics but also captures higher flow control accuracy. However, this investigation seldom considers the nonlinearities and uncertainty apart from valve flow characteristics. As displayed in Figure 14, Weber et al. proposed adaptive identification methods based on LSM, BPNN, RBFNN, GRNN, LSSVM, and RLSM to estimate the uncertain structure and parameters in flow mapping. It has been applied to obtain the evolving flow mapping and inverse flow mapping of a piloted proportional valve (Liu et al., 2021a).

2 Although the flow inferential measurement constructs the required state feedback, the electro-hydraulic flow control still confronts difficulties in large-flow steering and flow fine-tuning. A special-shaped valve port is difficult to fabricate and contradicts with standardisation of valve technology. Different from the above-mentioned general flow control algorithm in the valve, Quan et al. proposed a novel valve configuration that connects two flow-amplifying proportional cartridge valves in series at the inlet and outlet of the directional spool valve, and further developed a series spool valve port independently controlled multi-way valve. As exhibited in Figure 15, the strategies of disturbance compensation and nonlinear flow correction are designed, such that the flow can track the expected one with a decreased control error from 27% to within 7% under steady-state load (Wang et al., 2023).

Figure 14 Adaptive identification flow control methods based on LSM, BPNN, RBFNN, GRNN, LSSVM, and RLSM (see online version for colours)



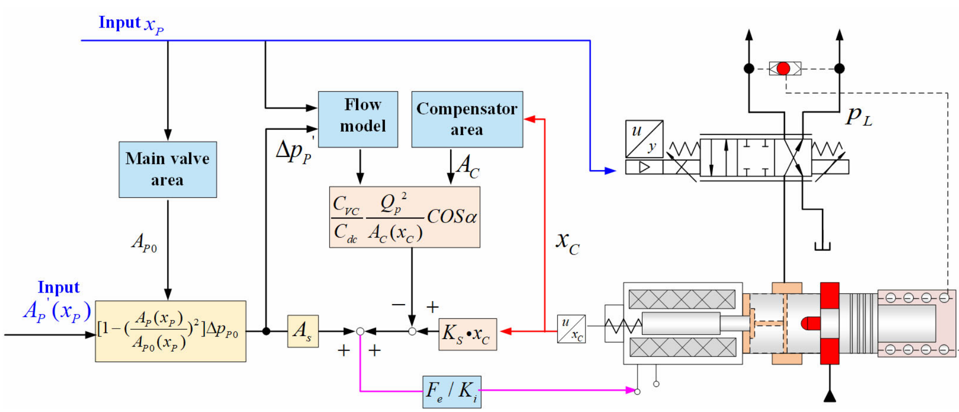
Source: Liu et al. (2021a)

3.2 Pilot-stage drive with fast response

In a conventional multi-way valve, the flow control is with a fast response because the natural frequencies of the hydro-mechanical pressure compensators are typically above 50 Hz (Vukovic and Murrenhoff, 2014). To reach similar response times using electro-hydraulic flow control; very expensive valves would be required. Since the multi-way valves in the mobile machinery are always actuated by the pilot-stage valves to control the oil pressure chamber at both ends of the main spool, the pilot stage in the

IMCS should be high-performance enough to capture a better dynamic performance of the valve, as depicted in Table 2.

Figure 15 Novel valve configuration to improve flow control (see online version for colours)



Source: Wang et al. (2023)

In the Eaton CMA (Eaton, 2016), a proportional directional spool serves as the pilot stage, with a voice coil used as the electro-mechanical actuator to enhance the natural frequency to 17 Hz. A 4/3 way spool couples the control of the two pilot pressures, offering precise displacement control and ensuring a reliable fail-safe state for the main stage. For an ultra-high-pressure hydraulic transmission system of a large-size hydraulic forging press, Yao et al. (2020) developed a prototype DN25, 70MPa two-way proportional cartridge valve. In this design, the pilot piston is actuated by a 4/3 direct-drive servo-proportional valve, which ensures precise control. The pilot rod is integrated into the main valve spool, facilitating efficient operation. The experimental results prove that the average idle displacement step response time of DN25 70TPCV is 23.5 ms, and the peak overshoot is 1.525% (Yao et al., 2020). This study was conducted at Xi'an Jiaotong University and involved a comprehensive simulation analysis of a cartridge proportional flow valve (Dong et al., 2016). However, there is a dead zone in the 4/3 way spool. Meanwhile, the spool motion mass and friction coefficient between the spool body are large, hindering the improvement of response.

To improve the dynamic performances, a decoupled pilot layout is proposed by Xu et al. (2014, 2017), in which a 4-way 3-position proportional spool is substituted by two independent 3/2 way valves. Such a pilot layout diminishes the dead zone and spool mass, such that the –3dB-frequency of the valve improves by 61.5%. To further improve the dynamics response, high-speed switching valves (HSVs) are recommended to be employed in the independent pilot stage due to their fast switching characteristics. Wang et al. (2017) used two 3/2 way high-speed switching ball valves as the pilot stage. They regulate the duty cycle of the PWM control signal to actuate the main spool to output continuous flow and pressure. Although the vibrations are introduced to the main spool actuated by HSVs, the displacement tracking of the hydraulic cylinder has only the maximum error of ±0.15 mm. Zhong et al. (2022) implemented an independent metering control valve, which consisted of four 3/2 way HSVs on the pilot stage and two 3/3 way valves on the main stage. Experiment results show that compared with traditional pilot spools, faster and more robust performance can be obtained. The step rise time is reduced from 21.4 ms to 16.8 ms, and the dynamic performance of the main valve is improved by 21.5%. The independent metering control valves developed by Jiangsu Hengli (HVSA20 and HVME300C/700C) integrate two HSVs as a pilot drive module.

Furthermore, the 3/2 way pilot valves can be decoupled to four 2-way poppet valves, in order to overcome the fundamental trade-off between the flow capacity and response in pilot valves. Han designed a water hydraulic proportional cartridge valve, in which four high-speed 2-way water hydraulic proportional valves are used as the pilot stage (Han et al., 2020). The simulation results show that the adjustment time is 25 ms when the valve opening is from 0 to maximal displacement. A similar configuration is also used in the Danfoss PVG multi-way valve (Danfoss, 2016). This layout employs 2/2 way valves, such that the advantages of the poppet valve can be inherited, including excellent sealing capabilities, higher resistance to contaminants and lower manufacturing costs. However, more components are needed to control than the two 3-way spool layout, and more complex control efforts are required.

Electric drives are successfully used in aircraft electric side sticks, robot joints, manufacturing, measuring instruments, etc. (Xiang et al., 2023, 2024) Therefore, some investigations have also conducted electric drives as the pilot stage. As shown in Figure 16, Niebergall and Ziegler (2024) presented a compact pilot control actuator consisting of a stepper motor with a ball-bearing screw, minimal self-locking, pressure sensors, and an electronic control unit. The pilot piston is arranged concentrically inside the power stage (control chamber, control sleeve, main piston). Through this pilot layout, the adjustment speed of the main spool can achieve 100 mm/s.

Table 2 The representative configuration of the pilot drive of the valve (see online version for colours)

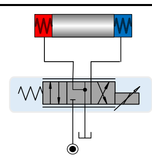
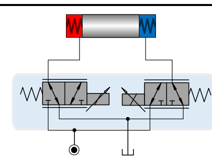
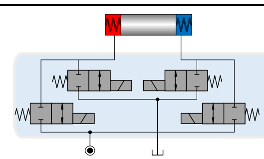
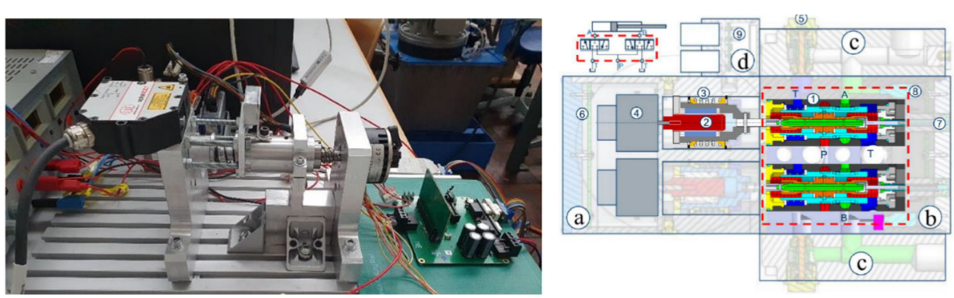
Type	*Single 4/3 way valve*	*Two 3/2 way valves*	*Four 2/2 way valves*
Pilot-stage			

Figure 16 Compact pilot control actuator using a stepper motor (see online version for colours)



Source: Niebergall and Ziegler (2024)

Other technologies have attempted to replace pilot valves, aiming for high response, large flow rate, and high force values while maintaining a reasonably sized electric actuator.

However, they encounter challenges. For instance, HSVs is difficult to achieve both high pressure and large flow simultaneously, due to valve stroke and magnetic force constraints (Zhang et al., 2020). Piezoelectric actuators, on the other hand, suffer from short stroke lengths (resulting in low flow rates) despite their high-speed and high-output force capabilities (Han et al., 2020). Therefore, both types of actuators are recommended as pilot stages under conditions of high flow demand. Especially, there is an ongoing tendency to use electro-hydrostatic actuators. However, achieving a comparable dynamic response at high flow rates and pressure levels poses a challenge for electro-hydrostatic actuators equipped with practical-sized motors. Moreover, in many circumstances, the use of electro-hydrostatic actuators is not cost-effective for mobile machinery that requires multiple actuators, such as excavators and concrete pump spreaders (Elsaed and Linjama, 2023).

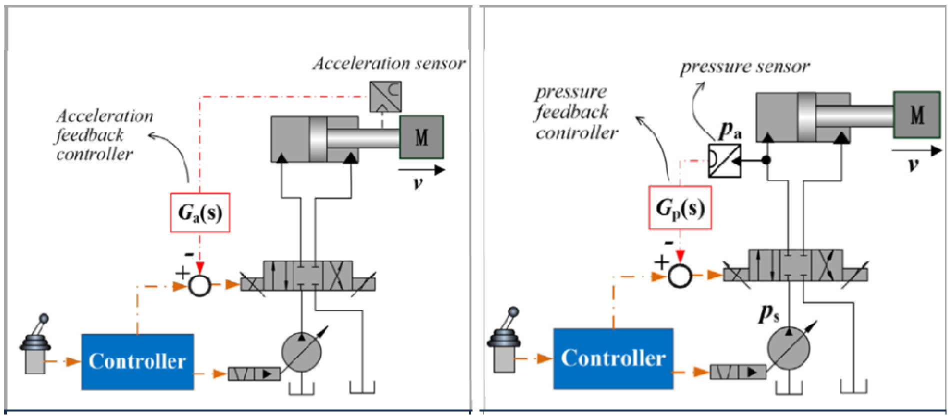
3.3 Active damping control

Mobile machinery with heavy-duty manipulators, such as excavators, cranes, and concrete pump trucks, can easily oscillate due to the low stiffness of the boom structure. Using the IMCS, the decreased system damping and natural frequencies caused by the increased valve opening and energy-efficient regeneration/float modes will further exacerbate the oscillations, which decreases the lifetime and control performance of the machines and even degrades the operation comfort and safety levels of the operator.

1 To damp oscillation, the active damping compensation methods have been investigated. The basic concept involves adjusting valve opening or pump displacement based on oscillation feedback from system states, such as chamber pressure, cylinder velocity, and structural acceleration. As shown in Figure 17, the main types of feedback include acceleration feedback and dynamic pressure feedback (DPF). Compared to acceleration feedback, DPF is more widely applied due to its lower cost, flexible installation, and higher reliability. Zaev et al. (2013) investigated the impact of DPF on a servo-hydraulic system equipped with a load-sensing pressure compensated (LSPC) system. They also analysed the effects of DPF on an IMCS. They proposed a novel energy-efficient dynamic pressure feedback (EE-DPF) system. The system features by three independent metering control valves, in which a third valve is introduced as the cross-port valve. This new system demonstrated an improved damping effect and significantly reduced energy consumption from the pump (Zaev et al., 2013). Cheng et al. (2021) compared acceleration control and DPF for active damping and vibration reduction. The analysis revealed that the DPF compensator alters the system's zero location and open-loop gain, resulting in significant overshoot and slow convergence. Its compensation effect can be enhanced through multi-objective optimisation algorithms (Cheng et al., 2021). Kjelland and Hansen (2015) developed a DPF control based on the natural frequency and damping information of a simplified crane model. An open-loop input shaping and closed-loop DPF are integrated into the actuation of the electrohydraulic proportional directional control valve. The effectiveness of the method in reducing vibrations was experimentally validated through trajectory tracking experiments at the crane (Kjelland and Hansen, 2015).

Although the aforementioned DPF methods have shown significant effectiveness in reducing oscillations of mobile machinery, the load characteristics can vary drastically due to changes in the positions of manipulator joints and external loads. Consequently, the pressure and flow demands also change significantly. Constant control parameters are not suitable for addressing these variations. Therefore, there is a need for online adjustment of key parameters, as shown in Figure 18, including cut-off frequency, feedback gain, etc. Pedersen and Andersen (2018) explained various types of DPF that can be applied, how they affect a given system, and how to adjust the parameters of the DPF to achieve optimal results. This is applicable to both traditional symmetric cylinder servo systems and systems with differential cylinders using both pressure-compensated and non-pressure-compensated proportional valves. Based on the presented models, the analysis provides guidance on how to properly adjust the parameters (Pedersen and Andersen, 2018). To capture optimal damping under different loads, Zaev et al. (2013) conducted an analysis and design of proportional-integral (PI) pressure control, demonstrating that pressure control can enhance the damping of load oscillations. The investigation examined the influence of the P and I parameters on the dynamic characteristics through the poles of the system's transfer function. An operating point was identified where the system's damping reached its maximum, and an optimising method was provided. The initially complex problem involving two fourth-order equations was simplified to the solution of a third-order equation (Rath et al., 2021). To ensure a comprehensive optimal damping compensation under different load conditions, Ding et al. (2017) designed a hybrid control method combining DPF and pole-zero placement. Meanwhile, the dominant pole placement was guaranteed such that the optimal damping could be accurately captured under varied operating conditions. Trade-offs between the high stability and fast response were made by optimising the damping (Ding et al., 2017). However, this method only ensures optimal damping at local operating points, making it challenging to cover the entire range of load conditions. Vacca et al. utilised the boom position and either the hydraulic pressure in the boom lift cylinder, or the boom acceleration as oscillation feedback to calculate control outputs. The feedback was processed through a proportional-derivative controller, which employed a gain scheduler based on an extremum-seeking algorithm to capture the optimal proportional and derivative gains in terms of the time-varying operating conditions (Alexander et al., 2017). To enhance the practicality and usability of active damping control in mobile machinery, Cheng et al. (2023) proposed a damping compensation performance evaluation index for IMCS by considering global load conditions. Based on this index, they introduced a method for tuning damping compensation parameters using electro-hydraulic coupled modelling and automatic optimisation of control gains. Experimental studies were conducted on a 20-ton excavator with an IMCS platform, validating the effectiveness of this method (Cheng et al., 2023). To address parametric uncertainties, some researchers have incorporated adaptive laws into the control structure. Huang et al. (2019) investigated the damping characteristics of IMCS and proposed a novel active damping strategy to suppress oscillations. A robust backstepping controller incorporating a tracking differentiator and a nonlinear disturbance observer is designed (Lin et al., 2019).

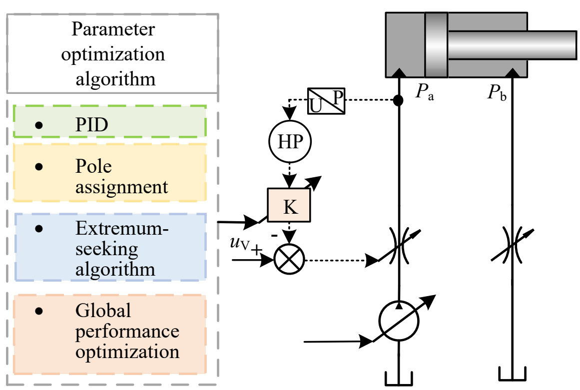
Figure 17 Feedback of the active damping compensation, (a) damping vibrations by acceleration feedback, (b) damping vibrations by DPF (see online version for colours)



(a) (b)

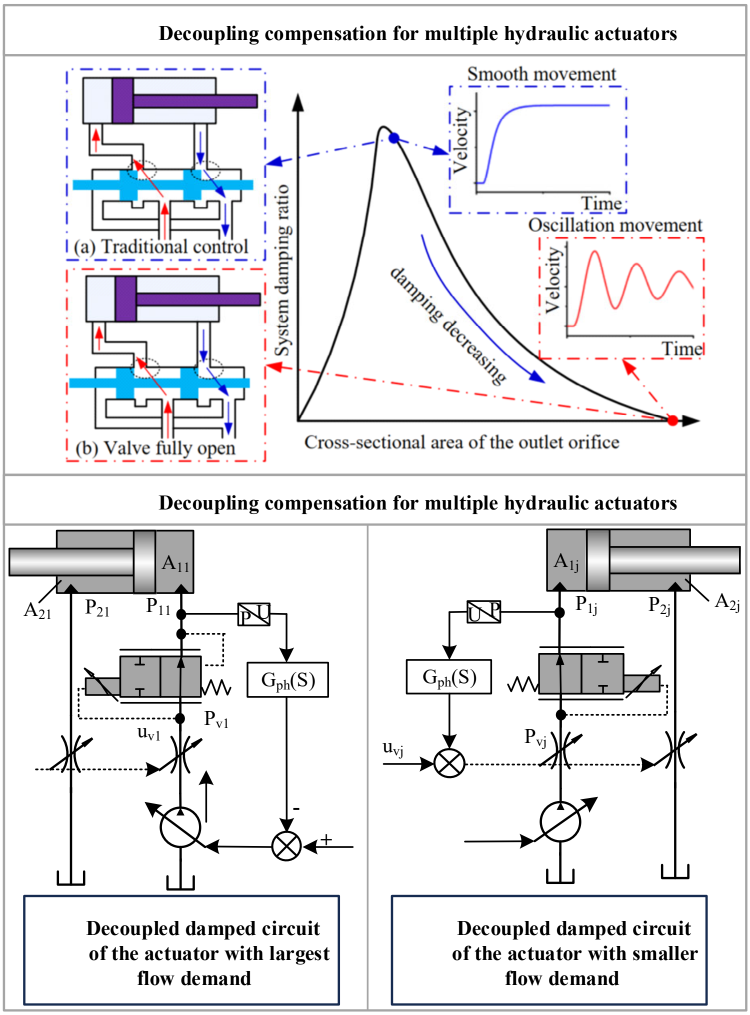
Source: Ding et al. (2017)

Figure 18 DPF control with parameter optimisation (see online version for colours)



The aforementioned methods primarily focus on improving the dynamic behaviour of systems with a single actuator. However, mobile machinery is a multi-actuator system with complex coupling effects among different actuators, and the issue of poor damping in multi-actuator systems remains challenging. When the dynamic behaviour of one actuator is enhanced through valve or pump control, the damping performance of other actuators may be adversely affected. Henikl et al. (2016) proposed an infinite-dimensional decentralised damping control method, utilising a constant pressure system with load-independent control to improve the dynamic behaviour of a 4-DOF mobile concrete pump. Cheng et al. (2018) proposed a decoupled damping compensator based on pump/valve hybrid control, as shown in Figure 19. By decoupling control of different load branches, the coupled hydraulic circuit with multiple cylinders is transformed into multiple separate single-cylinder circuits with damping compensation. This allows the dynamic characteristics of different actuators to be improved synchronously without cross-coupling. The compound motion validation was conducted on a 2-ton hydraulic excavator, which resulted in a reduction of velocity and pressure oscillations under various operating conditions, effectively enhancing the dynamic performance of the multi-actuator system (Cheng et al., 2018).

Figure 19 Damping compensator based on pump/valve hybrid control (see online version for colours)

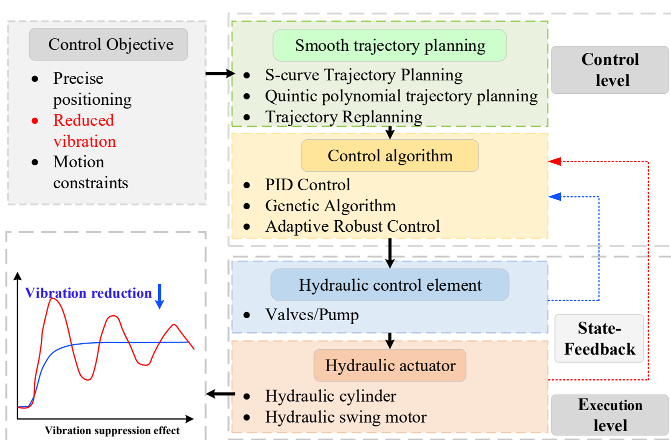


Source: Cheng et al. (2018)

2 Active damping compensation is a feedback control strategy that responds to oscillations after they occur. For certain predictable system oscillations, some researchers have adopted feedforward control methods through trajectory planning to design smoother trajectories and thereby reduce system oscillations, as shown in Figure 20. For example, Quan et al. introduced S-curve trajectory planning to design smooth acceleration in the hydraulic swing system of excavators. This allows the hydraulic system to experience more stable speed changes during startup,

acceleration, constant speed, deceleration, and stopping, which effectively avoids abrupt changes and pressure shocks (Huang et al., 2019). The oscillations may be caused by factors other than sudden acceleration changes, such as coupled low damping in the hydraulic system and low stiffness in the boom link. Ding et al. (2024a) concluded all the oscillation factors into an accumulated elastic potential energy, and an optimal trajectory planning method based on genetic algorithms was proposed to minimise this energy function in mobile concrete pumping equipment. This pre-processing procedure does not require complex oscillation feedback and control algorithms, making it more conducive to mobile applications (Ding et al., 2024a). To address parameter uncertainties and nonlinear disturbances in hydraulic systems, Zhou et al. (2023) propose a novel duel-loop control strategy that considers the physical limits as state constraints. An ARC is utilised in the inner loop to achieve high tracking accuracy and handle the nonlinearities, uncertainties, and disturbances. A third-order trajectory algorithm is synthesised to modify the original trajectory, which ensures that the state constraints are not violated. This method provides an effective solution for improving the control accuracy and stability of IMCS (Zhou et al., 2023).

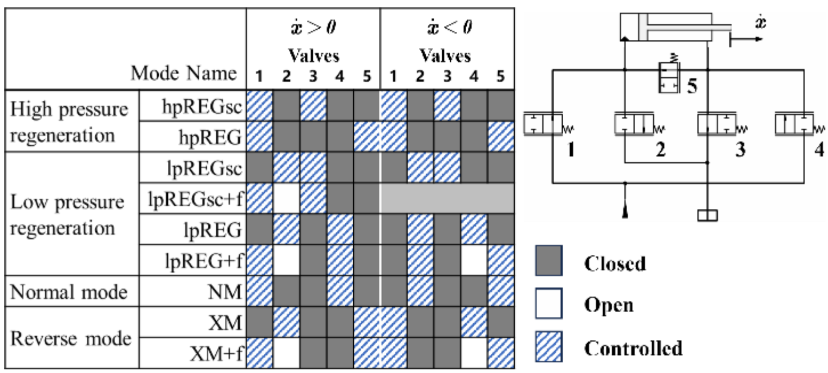
Figure 20 Feedforward control through trajectory planning (see online version for colours)



3.4 Smooth mode switching

The IMCS allows for different operating modes, as shown in Figure 21, which improves energy efficiency by reducing the pump supply flow and pressure. However, a system with multi-mode switching is typically a hybrid system composed of multiple subsystems (Liu et al., 2020). This type of hybrid system can experience significant discontinuities between the initial and target modes. The switch instant may contain the transfer of flow path and activated valves, as well as metre-in/metre-out controllers. The discontinuities cause a sudden, step-like change of the desired flow or the pressure drops over the activated valve, as shown in Figure 22. However, the valves and pump cannot react on a step signal rapidly due to the limited dynamics, which causes unintended shocks during the switching phase. Additionally, some valve layouts, such as Eaton's CMA, would interrupt the flow path in a switching instant, which intensifies velocity oscillations and pressure shocks (Eaton, 2016). In this case, a stable and smooth mode switch is crucial. To make IMCS suitable and attractive for mobile machinery, all involved components must be coordinated and controlled such that this complex switch will not be noticed by the operator of the mobile machinery. There are three approaches to overcome the major challenges of IMCS, as shown in Table 3.

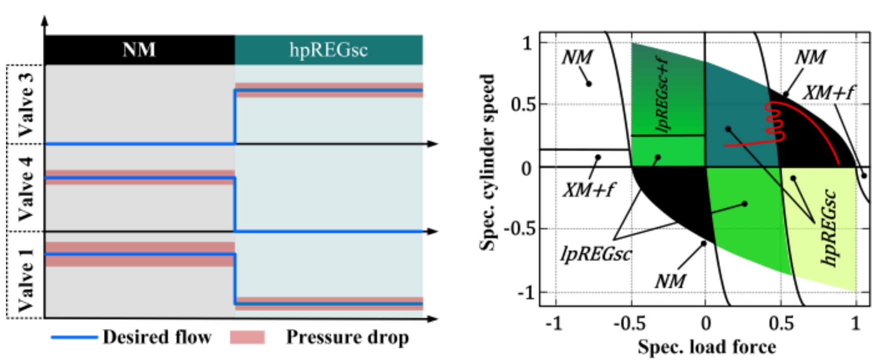
Figure 21 A general valve architecture and physically feasible control modes (see online version for colours)



Notes: The hpREG is for the high-pressure regeneration mode, lpREG is for the low-pressure regeneration (float) mode, NM is the normal mode, the XM is the reverse mode, the suffix (sc) is for the short circuit, and the suffix (f) is for additional pressure obtained from the supply pressure line.

Source: Kolks and Weber (2016)

Figure 22 There is a step-like change of the desired flow or the pressure drops over the participating valve, before and after the discrete switching transition (see online version for colours)



Note: As a result, the frequent mode switch occurs, indicated by the solid red line.

Source: Lubbert et al. (2024)

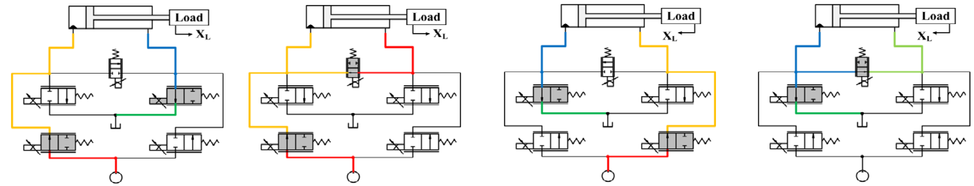
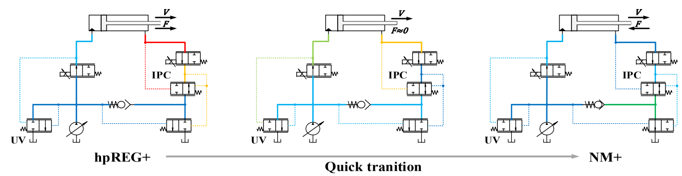
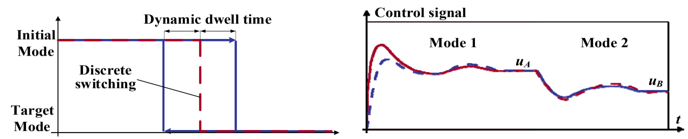
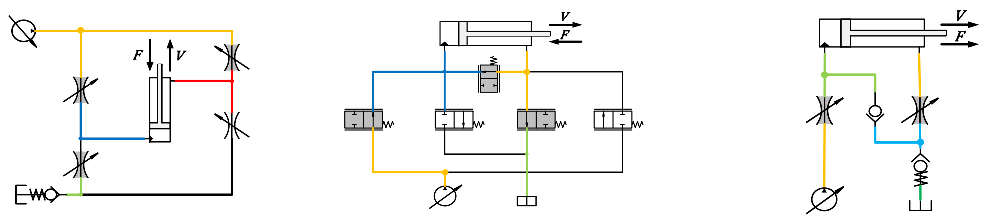
1 Prevented switching by predefining modes for each consumer and moving direction. This approach can be accomplished by predefining suitable flow modes for typical movements and loads (Lee et al., 2016). It prevents mode switching during the movement. For specific applications with predictable loads, such as cranes and concrete placing spreaders, this is sufficient. However, for common applications of

varied loads for mobile machinery, such as excavators and forest machinery, the approach will lead to inefficient operating situations without switching into the optimal mode.

2 Discrete switching with a smooth remedy. The discrete switch is an instantaneous transition to step from one mode to another. The drawback of the discrete switch is the jerk induced into the movement inevitably. One remedy is to make efforts on the hardware layout. Lubbert et al. introduced a hydro-mechanical pressure compensator to suppress the impact of sudden changes in the pressure drops over the affected metering orifices (Lubbert et al., 2016). As mentioned in Section 3.2, the hydro-mechanical pressure compensator reacts much faster than a mobile proportional valve with its relatively sluggish magnet. To prevent undersupply due to the relatively slow dynamics of the pump after the fast switching, the controller increases the pump flow shortly in advance. The unloading valve UV opens and drains the excessive pump flow to the tank, limiting the pump pressure to inlet pressure beyond a present LS margin. Another remedy is to incorporate a smooth control strategy, such as a 'dwell-time switch' method, which changes modes after a specified window time to avoid a frequent switch (Karabacak, 2013). Ding et al. (2016) designed a bumpless mode switch approach, which contains the dynamic dwell-time switch and a bidirectional latent tracking loop. The dynamic dwell time is used to reduce transient instability by slowing the switching into sufficient time. The time value is obtained based on the Multi-Lyapunov function. The bidirectional latent tracking aims to solve the unsmooth switching by eliminating the discontinuity of the control signal.

3 Continuous switching. This approach is only available for the specific hardware layout, such as four (five) 2/2 valves. Shenouda (2006) used the aforementioned INCOVA hydraulic control system with a Wheatstone-Bridge layout and applied it to a loader backhoe boom. They show that the optimal switching point for their application is the intersection of the capability curves, which is the cross-over point of the 'normal mode' and 'regenerative mode' in a force-speed diagram. Based on this quasi-static method, an approach to continuously variable modes for smooth transition is proposed by activating three valves simultaneously. It aims to transfer the mode switch with a continuous system dynamic, but this solution suffers from extra power losses because the additional third valve during the continuous mode switching introduces throttling losses. Linjama et al. used a stepwise change in valve state to enable smooth mode switch (Huova and Linjama, 2012). Feasible switching modes when using five 2/2-directional valves are systematically investigated. Mode-switching algorithms are proposed and implemented by means of digital-hydraulic system design. Based on the modiciency method, Kolks et al. proposed a smooth mode-switching algorithm for multi-mode transfers (Kolks and Weber, 2016). The drawbacks of three activated valves are the increased components and the summation of flow control errors during the shifting phase. Before and after the switch, different valves control the velocity, which may lead to permanent velocity deviations due to the different flow accuracy errors of the valves. To prevent the aforementioned issues, Lubbert et al. redesigned the secondary relief and anti-cavitation valves to implement a low-pressure regeneration mode, featured with good operating behaviour and low complexity (Lubbert et al., 2024).

Table 3 The main approaches to deal with the mode switch problem (see online version for colours)

Smooth mode switching		*Features*
Prevent switching		(a) Adopted to bucket in, boom up, arm in (b) Adopted to arm in (low load) (c) Adopted to bucket out, arm out, boom down (d) Adopted to boom down (low load) Operation modes for IMV excavator in Lee et al. (2016)
Discrete switching	One remedy with IPC	Discrete shifting with IPC at a simplified example valve layout in Lubbert et al. (2020)
	Another remedy with a smooth control strategy	The dynamic dwell-time switch and a bidirectional latent tracking loop in Ding et al. (2016)
Continuous switching		(a) Four 2/2 valves with three active valves in Shenouda (2006) (b) Five 2/2 valves with three active valves in Huova (2008) (c) A continuous switching with two active valves in Lubbert et al. (2024)

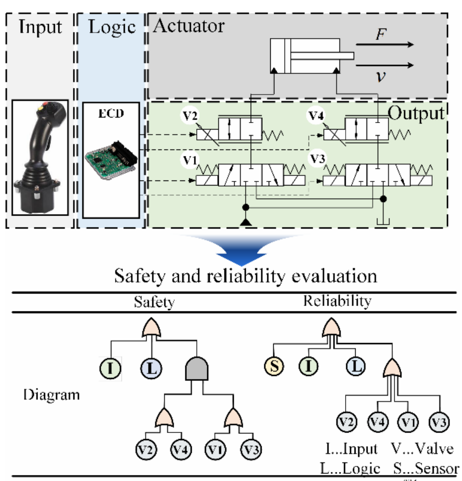
In the state of the art, commercial products of IMCS are almost not capable of mode switching in an ongoing movement. Eaton CMA valve can regenerate but not switch into regeneration while moving (Eaton, 2016); Danfoss PVX valve incorporates regeneration flow paths at large spool displacement, mostly from rod to piston side (Danfoss, 2016); their switching would interrupt the flow path. A completely smooth switching method can be implemented by Husco in their INCOVA system (Husco, 2007), in which normal mode, as well as regeneration/float and continuous switching among these modes, are permitted. The system is intended for decentralised mounting and connection with a P and T bus hose line, which is incompatible with traditional machine architectures and its cost may not be well-promoted in the market (Lubbert et al., 2020).

3.5 Fault diagnosis and tolerance

3.5.1 Safety performance evaluation

The introduced electronic feedback and control, as well as complex control strategies, make the IMCS less safe and reliable than conventional systems (Abuowda et al., 2020). In addition to the hardware layout investigations carried out at the IFD led by Weber, the safety and reliability are also systematically analysed. Their investigations utilise fault tree analysis and Boolean algebra to describe the IMCS. Then, the failure probability could be calculated considering the system layout and two operating modes. The correlation from the fault-tree model to the predefined safety structure in ISO 13849 is established, such that the calculations of the system safety level PL and its PFHd are derived. Furthermore, the PL level is evaluated considering different fault diagnosis coverage (DC) (Beck and Weber, 2016), as shown in Figure 23.

Figure 23 Safety and reliability evaluation for IMCS (see online version for colours)



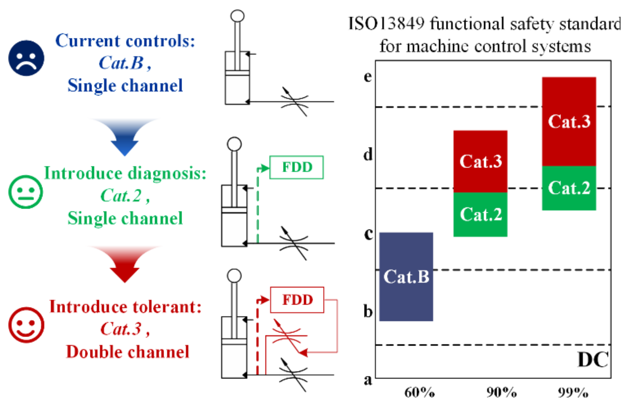
Category/ Function	Category3 DC=60%	$F_{Sys} = 1-(e^{\frac{TM}{MTTF_d}})^4$ $PFH_d = \frac{4}{MTTF_d}$
$PFH[a^{-1}]$	0.0014	0.0267
$PFH[h^{-1}]$	1.57×10^{-7}	3.04×10^{-6}

Source: Beck and Weber (2016)

Based on the investigation of Weber, a safety model covering the four load quadrants is built using fault-tree analysis (Ding et al., 2022). The normal controller, fault detection and diagnosis (FDD), and fault-tolerant control (FTC) are all considered. The results also verify that the PL of the IMCS only reaches the b-c level, which can not meet the requirements of the d level for the mobile machinery. By introducing fault detection, PL increases to the c-d level, which is improved by increased DC. d level of or even the highest e level of PL can be obtained by the FTC, which optimises the functional safety categories by extending a parallel channel to duel channels, as shown in Figure 24.

From the safety assessment of the IMCS, it is noticeable that to enhance safety, the next work should continue to introduce fault detection to improve DC and develop FTC to extend channels in function safety.

Figure 24 PL evaluation considering different control methods (see online version for colours)



3.5.2 *Fault detection and diagnosis*

There is a lot of research on the FDD of hydraulic systems and components, especially for hydraulic cylinders and pumps. At present, there are two main FDD methods: data-driven and model-based. In the state of the arts, common FDD used in IMCS are classified in Figure 25.

At first, Weber et al. developed a software-in-the-loop system architecture setup on the IMCS, and accordingly, an FDD algorithm was derived utilising limit checking of the applied pressure sensors. Additionally, the same pressure sensors are utilised for functional and fault detection without incurring additional costs, which renders this solution particularly appealing (Beck and Weber, 2017).

Nevertheless, the detection performance is upgradeable and a deep diagnosis is not achievable with limited checking. Therefore, the parity equations are employed, and the measures to compensate for the negative effects are introduced. The results show that the detecting and diagnosing performance of safety-critical faults is improved by 56% compared to limit checking based on the sensor signal (Beck et al., 2019). Considering the relevant limitations of the mobile hydraulic system, different operating points, and various fault scenarios, parity equations are established. In addition, the applicability of the set of parity equations is evaluated and the threshold of the faulty component is determined through the simulation data. The fault tree analysis method is introduced to show how to locate the fault from the residual of the parity equation (Fischer and Weber, 2022).

Figure 25 FDD methods in the state of the arts (see online version for colours)

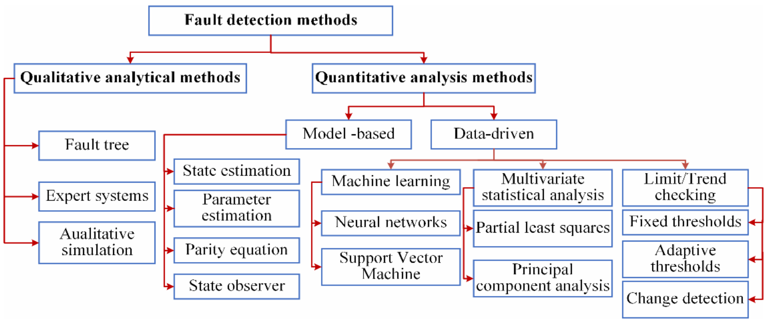
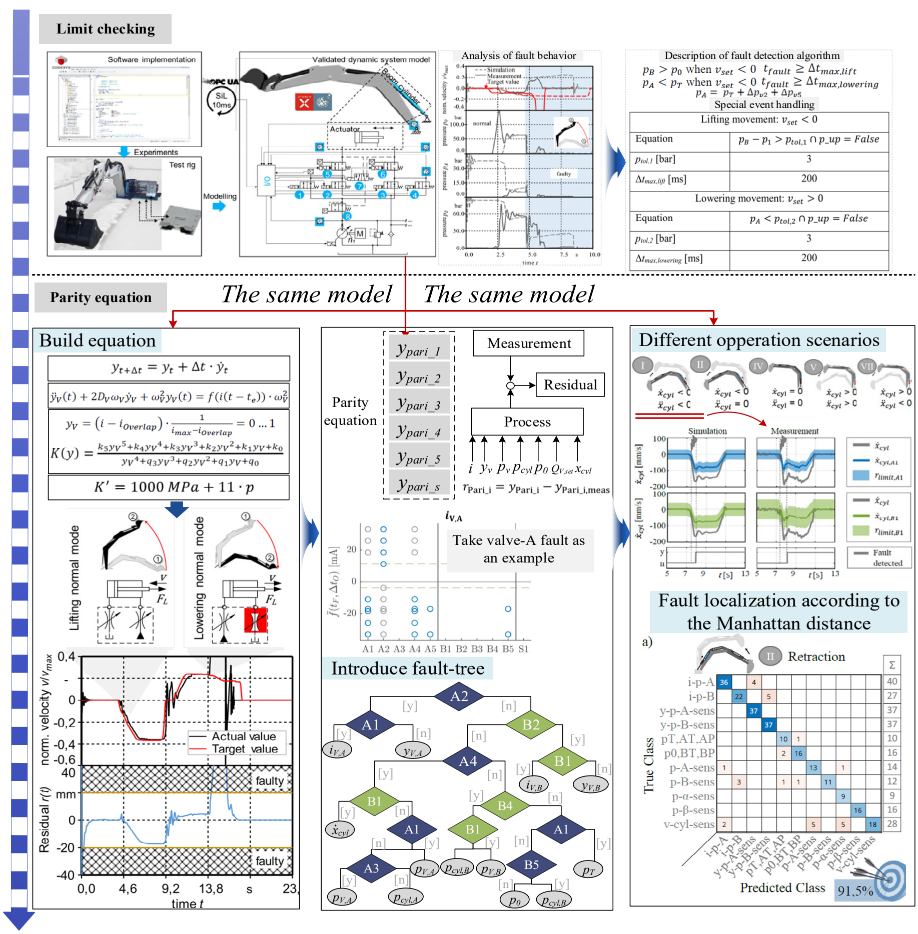


Figure 26 Investigation development on FDD by Weber's team (see online version for colours)

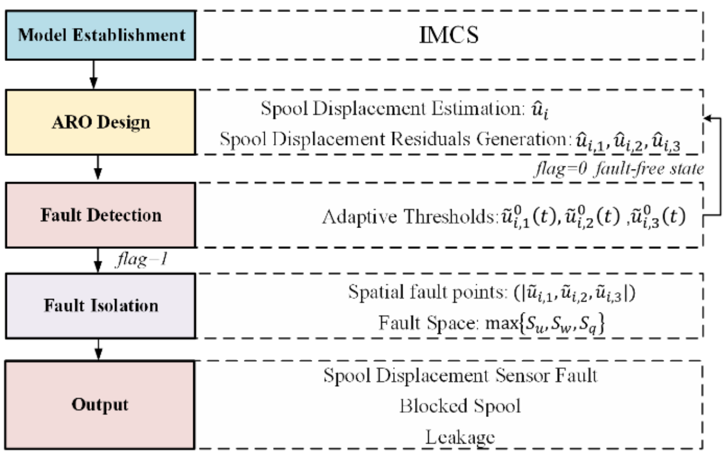


Source: Beck et al. (2019), Fischer and Weber (2022) and Fischer et al. (2024)

Four different fault location methods are discussed, including the basis of complete feature matching, decision fault trees, Manhattan distance, and learning vector quantisation. Therefore, the parity equation provides in-depth research about fault detection and the location of IMCS. At last, the experimental results demonstrated that the FDD accuracy reached 92% (Fischer et al., 2024). Figure 26 reviews the investigation development on FDD by *Weber's* team.

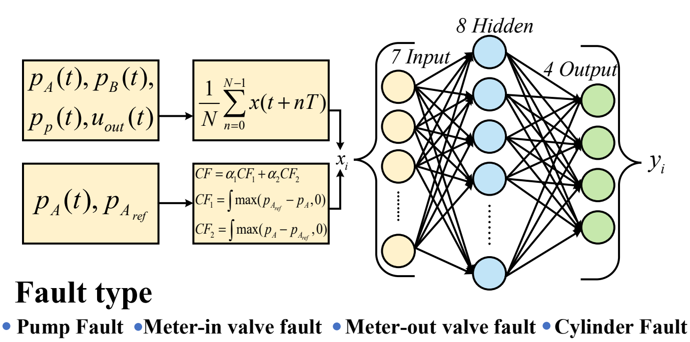
Zhang et al. (2024) propose a new idea for model-based fault diagnosis using an adaptive robust observer (ARO). The designed ARO can estimate the spool displacement well despite the high model uncertainty, high nonlinearity, and time-varying operating conditions of the IMCS. The pressure sensor and displacement sensor provided by the system are used for parameter estimation and residual generation. At the same time, by collecting the residual to calculate the spatial fault point, the fault can be accurately isolated with a small amount of data, such that the efficiency of fault diagnosis is improved (Zhang et al., 2024), as shown in Figure 27.

Figure 27 FDD based on ARO (see online version for colours)



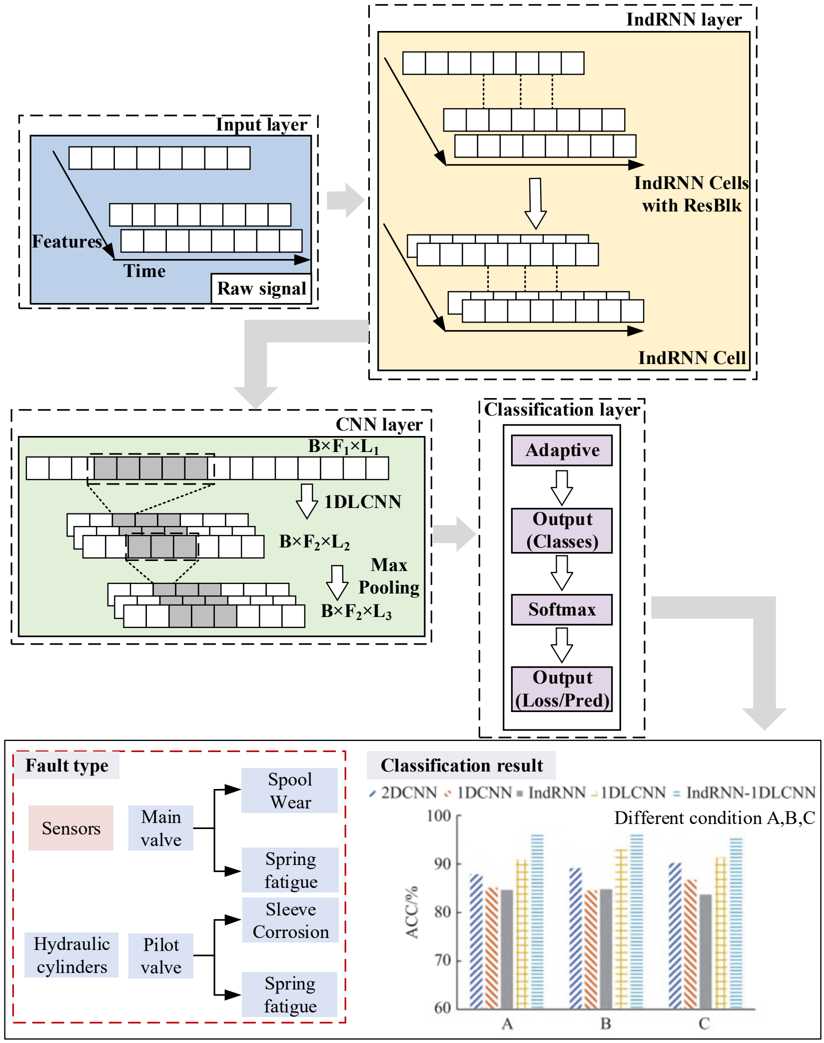
Source: Zhang et al. (2024)

Figure 28 FDD using NN by Andrea Vacca team (see online version for colours)



Source: Bianchi and Vacca (2018)

Figure 29 FDD based on IndRNN-1DLCNN (see online version for colours)



Source: Sun et al. (2023)

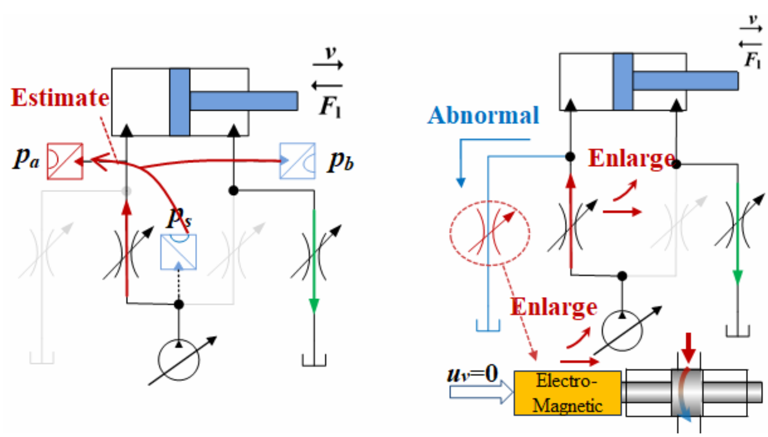
In the above investigations, a model-based method is on one hand used to analyse and compare the model output with the process system. On the other hand, data-driven approaches have also been studied. Vacca et al. from Maha Fluid Power Research Center presented a NN FDD algorithm based on the pressure signal of the hydraulic cylinder and the pump outlet, together with the additional information from the controller, as shown in Figure 28. Only three pressure sensors are used for the diagnostic function to avoid the use of expensive sensors such as flow and position sensors, and the method can be extended to many other cases by appropriately modifying the topology of the NN. The results show that the proposed method can detect faults effectively when the number of sensors is limited (Bianchi and Vacca, 2018).

Also, in terms of data-driven methods, a deep NN model based on INDRNN-1DLCNN is designed (Sun et al., 2023). The residual structure is introduced to design multi-layer IndRNN and 1DLCNN to capture the global information. With the fusion of multi-source signals, the specific fault components could be identified. The results show that under different load conditions, the proposed method can accurately locate the eight types of faults including four pilot valves, two main spools, one group of displacement sensors, and a hydraulic cylinder. The overall diagnosis accuracy of the system is up to 96%, and the fault identification accuracy of a single component is greater than 93%, as shown in Figure 29.

3.5.3 Fault-tolerant control

According to the fault information by detection and diagnosis, FTC is a critical process to guarantee the safety of IMCS. Benefiting from the additional control DOF and multi-information electronics feedback, the analytical redundancy in IMCS can be captured to carry out the FTC. Rannow from Eaton Corp. proposes a principle of cross-port pressure control towards the sensor faults, in which the fault side of the valve is utilised to control the pressure on the fault-free side. By reconfiguring the controller and the coordinated operation with four sensors, the flow control could be guaranteed even if two of the sensors fail, such that the operation could be continued when the sensor fault occurs (Rannow, 2016).

Figure 30 Fault tolerance principle for sensor or valve fault (see online version for colours)



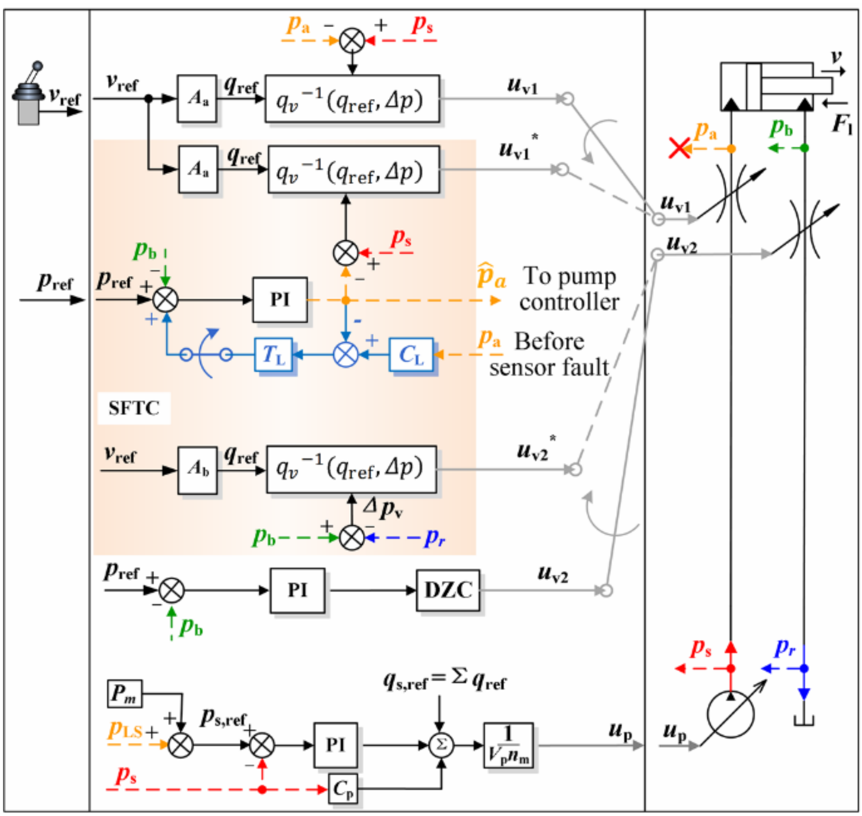
After that, Ding et al. (2021) introduced an active sensor-fault-tolerant control (SFTC) for IMCS. By analysing redundancy in Figure 30, the metre-in and metre-out control loops are switched and exchanged according to fault types of sensors (shown in Figure 31), such that the faulty sensor feedback can be estimated online. Moreover, an active FTC against the valve faults (VFTC) was proposed. This control system comprises a set of reconfigurable controllers and a decision-making process, enabling precise reconfiguration of control signals, loops, and modes to accommodate unmodelled fault dynamics. Meanwhile, a bumpless transfer controller based on a latent tracking loop is also designed to smooth the switching from the normal controller to FTC (including SFTC and VFTC). Through the experiment on a 2-ton excavator, the effectiveness of

FTC in practical application is verified, and its potential in industrial application is proved (Ding et al., 2021).

The aforementioned FTC is based on the online reconfigurations of control, which can address both valve and sensor faults. Specifically, the valve faults are divided into performance degradation, functional destruction, and flow obstacle in terms of fault type, location, and degree. Accordingly, three reconfigurable strategies, including control signal, valve controller, and operating mode, are established to adapt to different types of faults and system configurations.

The state of the arts on FDD or FTC has made excellent contributions to the problem of the high safety risk of IMCS. However, certain assumptions are given. For example, the fault can be accurately identified only if it is the fault of a single component. The precondition of FTC is to assume that the fault location and degree are captured timely. However, these assumptions are challenging to realise in mobile applications. In the future, concurrent multiple faults are expected to be diagnosed at first. Secondly, the degree of fault should also be further evaluated. Finally, an integrated FDD and FTC of IMCS are necessary for future work.

Figure 31 SFTC with Pa fault as an example (see online version for colours)



Source: Ding et al. (2021)

4 Conclusions

In this paper, independent metering control technology for mobile machinery applications is presented. Compared with the conventional system, its hardware layout provides multiple control DOFs and multiple information perceptions, which introduce the possibility for high energy efficiency, sufficient compatibility, and better controllability. However, these advantages required higher requirements for the components and control efforts.

Commercial products developed by OEMs in the fields of hydraulic components and construction machinery, as well as their mobile applications, are reviewed. Although there are many independent metering control multi-way valves or hydraulic control systems in the markets, the technology is still unsuccessfully widespread in industrial applications. Therefore, the challenges, together with their key countermeasures and the future trends are reviewed. Especially, flow control, fast response pilot drive, active damping control, smooth mode switching, as well as fault diagnosis and tolerance, are summarised and demonstrated.

Declarations

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