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Review Paper

Review: Research on the development trends of measurement while drilling (MWD) technology in oil and gas drilling

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ABSTRACT

As one of the pivotal technologies in oil and gas field exploration and development, downhole measurement technology provides a scientific basis for reservoir evaluation, drilling optimization, development efficiency improvement, and wellbore operation safety assurance. Compared to traditional cable-based measurements, measurement while drilling (MWD) technology can obtain downhole data in real time during the drilling process, accurately control wellbore trajectories, and provide more efficient solutions to address the challenges of exploring and developing unconventional oil and gas fields. This paper mainly focuses on MWD technology, reviewing the latest research progress in drilling data acquisition technology, drilling signal transmission technology, and downhole steering technologies and their instrument systems. It provides a detailed introduction to the workflows, working principles, key components, functional parameters, application scenarios, and performance comparisons of various typical systems, Furthermore, the challenges facing MWD technology and its future development directions are discussed.

1. Introduction

The progression of hydrocarbon exploration toward deeper onshore formations, offshore frontiers, and unconventional reservoirs—characterized by increasingly complex geology—has exposed inherent limitations in conventional downhole measurement techniques (e.g., wireline logging). These constraints manifest in data transmission rates, operational safety, efficiency, and flexibility. Measurement while drilling (MWD) technology addresses these challenges through real-time acquisition of critical drilling parameters: hole inclination, azimuth, tool face angle, bit vibrations (axial/lateral), torque, rotary speed, and annular clearance (tool-formation gap). This capability facilitates precise trajectory control, ensuring conformance to planned well paths while substantially improving drilling efficiency and reducing integrated development costs. Consequently, MWD represents a pivotal technological asset for efficient resource exploration and economic development (Qin and Xiao, 2003; Su et al., 2024; Wang and Ye, 2024), Furthermore, measurement while drilling (MWD) data holds significant importance for seismic while drilling (SWD) technology by providing accurate source positioning and attitude references, thereby enabling real-time seismic monitoring and formation prediction during drilling operations. Additionally, the integration of MWD with geosteering technology, particularly through logging while drilling (LWD), substantially enhances the precision of wellbore trajectory control and improves reservoir penetration rates. This synergy exemplifies the growing trend of multi-technology convergence in complex oil and gas exploration and development (Poletto and Miranda, 2022). Moreover, parameters derived from MWD offer vital data inputs for refined reservoir characterization, development planning, and optimization of stimulation operations including hydraulic fracturing (Hu et al., 2024; Zhai et al., 2024).

Current global MWD market dynamics are shaped by sustained oil demand growth across all major regions—North America, Europe, Asia-Pacific, Middle East & Africa, and South America—unconventional drilling activities utilizing MWD technology continue to expand. North America dominates the global MWD

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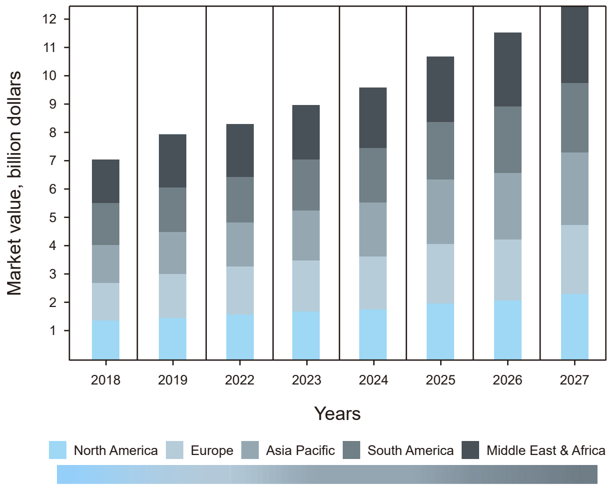


Fig. 1. Global MWD market is expected to account for USD (by regions) (according to a 2025 research study by Market Research Future).

market, leveraging its significant untapped resource exploration, advanced drilling technologies, and robust oil & gas sector. Europe follows closely, propelled by supportive regulatory frameworks and drilling efficiency initiatives. The Asia-Pacific MWD market is poised for substantial growth, fueled by increasing regional investments (Fig. 1). Regarding overall market size, the MWD market reached approximately $8.57 billion in 2022, increasing to $8.9 billion in 2023; the compound annual growth rate (CAGR) during 2024–2027 is projected at approximately 3.85%, with an estimated value of $12.5 billion by 2027.

SLB (erstwhile Schlumberger), Halliburton, and Baker Hughes are internationally recognized as the three major oil service companies, collectively holding nearly 80% of the international oil service market share, with annual R&D investments exceeding $2 billion each, and boasting robust MWD technology capabilities (Figs. 2 and 3). Their MWD instruments offer high resistance, high-precision data acquisition, fast data transmission, and precise steering control, and are widely used in global oil and gas field drilling and production. Each of these international oil service companies excels in specific areas within the MWD field: Halliburton's technical services tend to be more mainstream, focusing on enhancing drilling efficiency in highly deviated and horizontal wells; Baker Hughes emphasizes the simplification and miniaturization of MWD instruments as well as high-precision directional control technologies; SLB, with its long-standing technological accumulation, is characterized by its high-level, precise, cutting-edge, and specialized technologies, holding a prominent position in the industry (Su et al., 2024). Notably, SLB introduced the industry's first MWD device, the M1, in 1980 (Li, 2021; Liu et al., 2015; Pitcher et al., 2009). Although its functionality was limited to measuring inclination, azimuth, and tool face, and its application scope was relatively narrow, its debut laid a crucial theoretical foundation and practical reference for the subsequent development of a comprehensive and systematic MWD device system within the industry, providing a valuable framework and basis for other companies to develop mature MWD devices thereafter (Azizi et al., 2008; Yang et al., 2024).

During the early developmental phase (1980s), MWD technology was constrained by downhole sensor accuracy limitations, data transmission rates, and environmental adaptability. Its functional boundaries were consequently confined to real-time acquisition and transmission of well trajectory parameters (primarily via mud-pulse telemetry) (Li et al., 2022a), meeting only basic engineering data requirements. At that time, the academic consensus broadly regarded MWD as a tool for supplying foundational data to support geosteering operations, rather than as a system capable of direct involvement in downhole control processes. Following breakthroughs in microelectronics, sensor technology, and modern control systems, MWD progressively evolved toward multi-parameter integration and intelligent functionality. Meanwhile, the advent of Rotary Steerable Systems (RSS) has enabled the real-time data transmitted by MWD to be directly utilized for dynamic downhole control. By leveraging parameters such as inclination and toolface orientation measured by MWD, the RSS facilitates

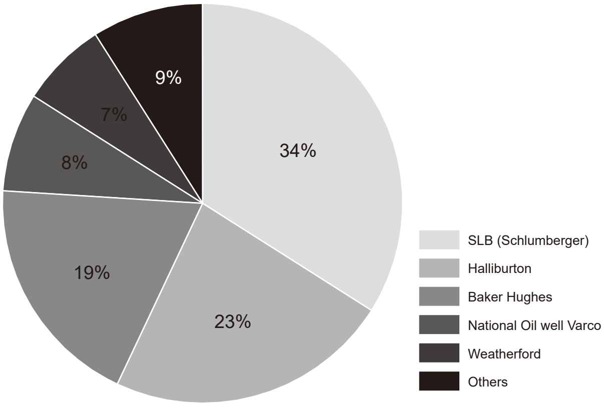


Fig. 2. Market share distribution of major oilfield service companies (based on the findings of a 2024 International Everbright Securities study).

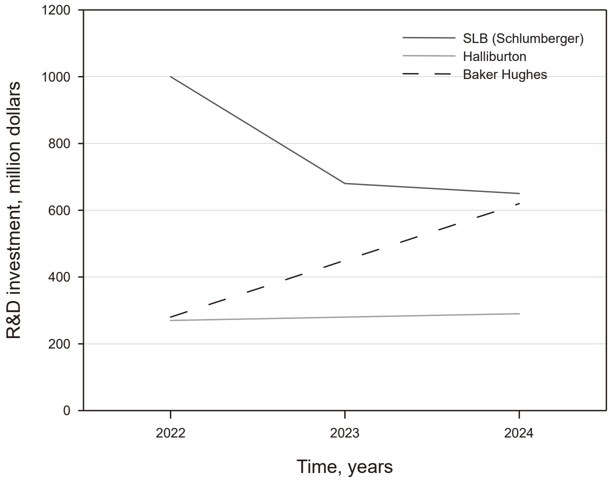


Fig. 3. Comparison of R&D investment among the three major oilfield service companies (based on the findings of a 2024 International Everbright Securities study).

automatic and continuous adjustment of the drill bit's direction through hydraulic or mechanical actuation mechanisms, thereby efficiently executing operational requirements.

This transition transformed MWD from a singular “data-gathering role” into a downhole closed-loop information nexus, expanding its functional boundaries to encompass downhole control and real-time decision support. Within this context, scholars (Su et al., 2023; Wang and Ye, 2024) proposed the “measurement control while drilling (MCWD)” concept, emphasizing coordinated integration of data acquisition, transmission, and execution. Industry implementations like SLB's Scope series and Baker Hughes' TRAK series (integrating intelligent drill pipes with rotary steerable systems) dynamically adjust bit orientation using real-time inclination data transmitted through MWD, establishing integrated “measurement-transmission-control” systems. Despite continuous functional boundary expansion, MWD's core orientation remains fundamentally centered on real-time reliability of downhole engineering parameters, necessitating prioritized assurance of data transmission stability. This technical philosophy of “system integration + functional extension” has gradually evolved into a pivotal reference for the intelligent development of MWD. Consequently, modern MWD systems comprise three functionally interlinked modules: the front end (data acquisition), the middle end (signal transmission), and the back end (steering control), each performing its respective functions through different devices (Su, 2018; Su et al., 2024). Data signal acquisition serves as the foundation of the entire system, primarily utilizing high-precision sensors to obtain critical parameters such as geosteering, weight on bit, and torque in real time, providing data support for drilling operations (Deng et al., 2025; Srivastava et al., 2024; Wang et al., 2014; Wang et al., 2024a). Signal transmission, as the core of information exchange, acts as a bridge for well-to-surface data communication, ensuring real-time data sharing and analysis through bidirectional communication between wired cables/wireless pulse generators and downhole receivers. Downhole steering, as the executive component, receives control commands from the terminal monitoring system (well site control) and precisely adjusts the wellbore trajectory relying on advanced steering mechanisms to ensure the drilling path aligns with design requirements (Afebu et al., 2025; Gao et al., 2024; Tang et al., 2012; Yue et al., 2006). These three components, with clear divisions of labor and interlocking functions, collectively achieve precise control and efficient execution of drilling operations (Figs. 4 and 5). Through real-time data acquisition, feedback, and precise control, MWD technology not only elevates the efficiency and safety of drilling operations in practice but also promotes the intellectualization and systematization of drilling engineering control methods at the theoretical level, laying a solid theoretical foundation and providing technical support for the automation and intellectualization (progressively shifting from human experience-based decision-making toward autonomous judgment and control systems that are built on system integration and information fusion, and that incorporate engineering rules with real-time data and algorithms) of future drilling operations, thereby gradually forming a mature “acquisition, transmission, and drilling” technology system.

This paper will conduct an analysis from three aspects: MWD data acquisition, signal transmission, and downhole steering. It will comprehensively compare the current technological status and equipment performance, explore the applications of MWD technology in high-precision data acquisition, high-speed information transmission, precise steering control, and safety, clarify the development trends of future drilling technology, and provide an outlook on its commercial development prospects.

2. Downhole data acquisition technology

The technology originally evolved from borehole inclination measurement techniques and was first proposed by Stanley D. Wilson in 1952, with a commercial version successfully launched in the 1950s (Isheyskiy and Sanchidrián, 2020). Over the next two decades, it achieved widespread adoption, with pendulum-type mechanical inclinometers dominating this period. In the 1980s, Conti, Helm, Fisher, and others (Yang et al., 2024; Zhang et al., 2006) introduced electronic accelerometers combined with electronic compasses to measure deviation angle and azimuth. This technology gained rapid market acceptance due to its relatively higher measurement accuracy. However, limitations in foundational industrial capabilities at the time resulted in bulky instruments with poor vibration resistance, insufficient accuracy, extremely limited downhole memory capacity, reliance on disposable batteries for power, and inadequate precision and stability of the system clock making them unsuitable for measuring deviation in small-diameter boreholes (Yin et al., 2022). Driven by market demand, MWD data acquisition technology advanced rapidly, leading to improvements in both measurement accuracy and instrument compactness. Downhole memory evolved from

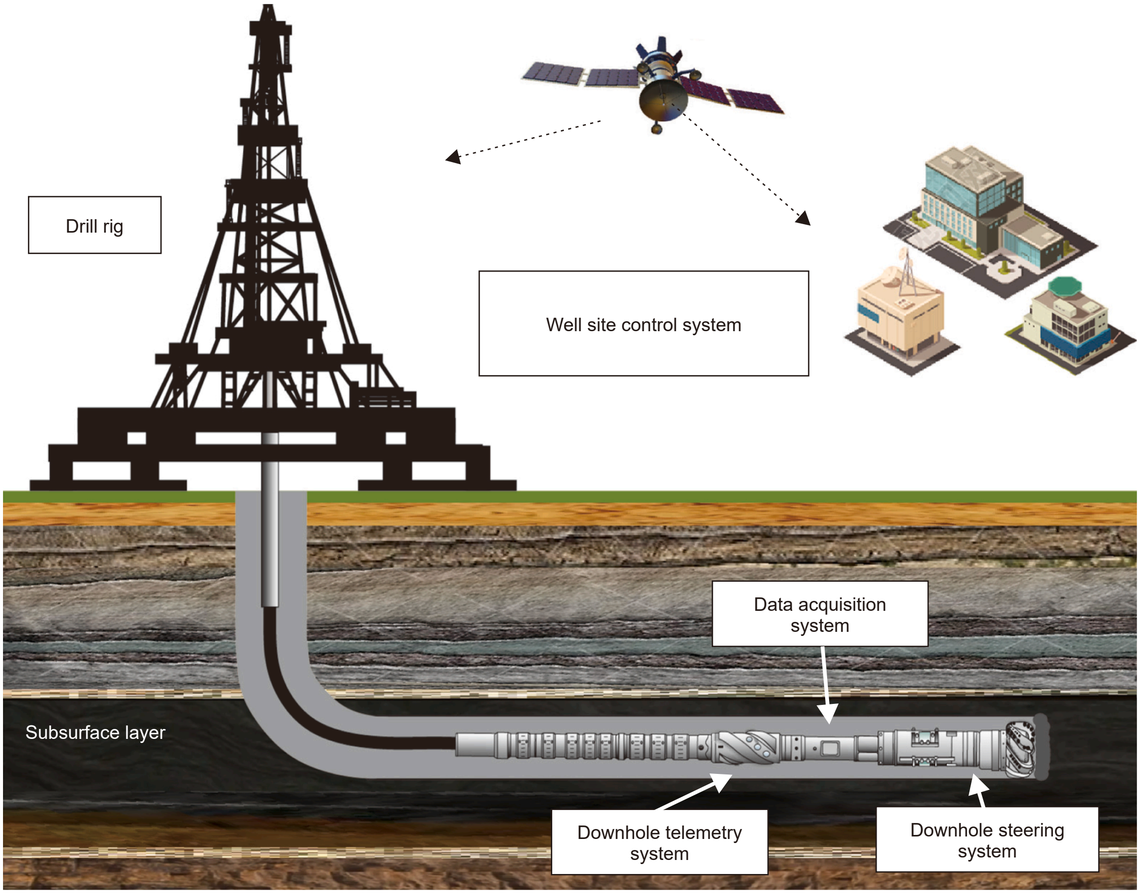


Fig. 4. MWD instrument working diagram.

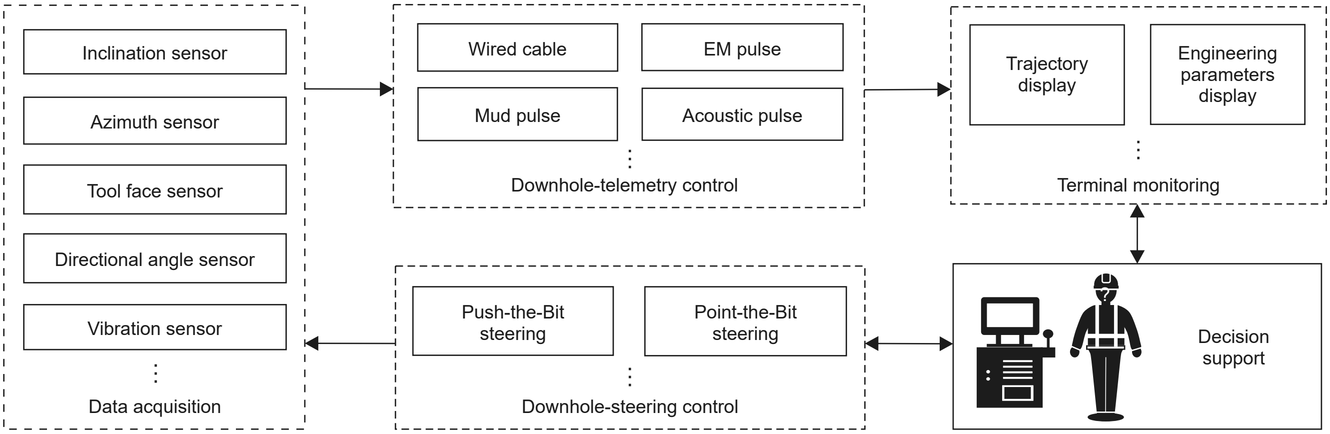


Fig. 5. MWD instrument working flow.

early kilobyte-level volatile storage to megabyte-level non-volatile flash memory with SPI bus architecture, enabling reliable downhole data storage; power systems progressed from disposable batteries to hybrid supply modes combining high-energy-density lithium batteries with downhole turbine generators, extending operational duration; meanwhile, the widespread adoption of highly stable temperature-compensated crystal oscillators (TCXO) (with frequency stability better than ±2 ppm across the full temperature range of −40 °C–175 °C) ensured highly synchronized timing for sensor sampling, data tagging, and transmission, laying the foundation for multi-parameter data fusion and precise analysis. The synergistic evolution of these core components collectively advanced comprehensive improvements in the measurement accuracy, miniaturization, and reliability of MWD systems. Downhole memory evolved from kilobyte volatile storage to SPI-based megabyte non-volatile flash for reliable storage. Power systems transitioned from disposable batteries to hybrid generation enabling extended operation. Meanwhile, adoption of high-stability temperature-compensated crystal oscillators TCXOs (±2 ppm from −40 to 175 °C) ensured precise synchronization of sampling and transmission, supporting multi-parameter data fusion and accurate analysis. These advancements collectively

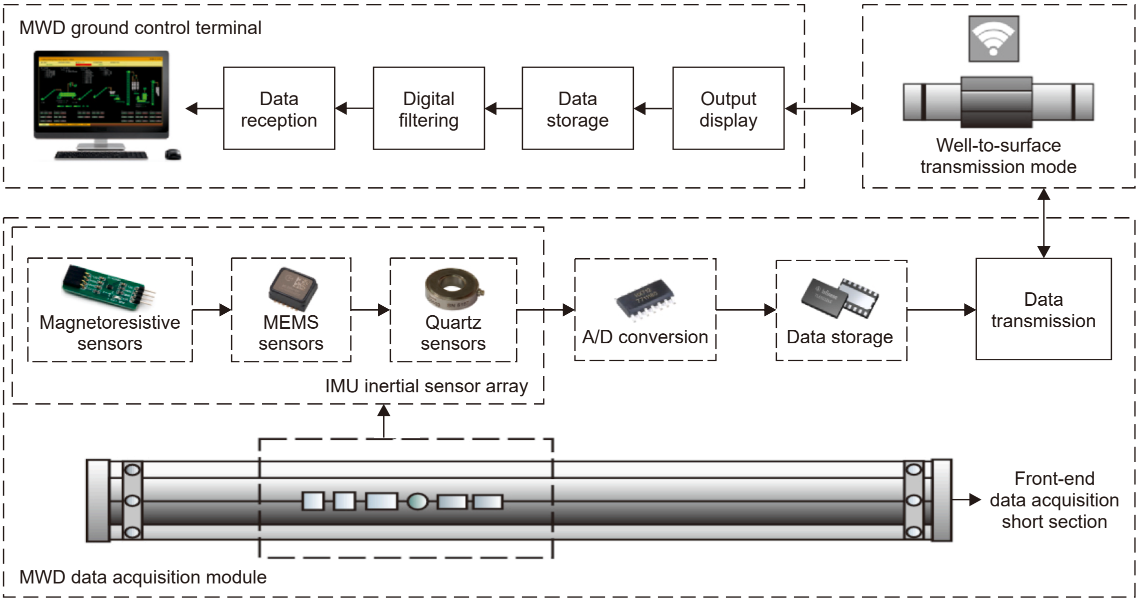


Fig. 6. Schematic diagram of downhole data acquisition process.

drove improvements in MWD system accuracy, miniaturization, and reliability.

Modern MWD data link systems are fundamentally composed of three subsystems: a downhole data acquisition module, a well-to-surface telemetry module, and a surface control terminal (as illustrated in Fig. 6). Among these, the downhole data acquisition module serves as the technical cornerstone of MWD systems. This module integrates three core components: an inertial sensor unit, an analog-to-digital (A/D) conversion unit, and a data storage unit (Wu et al., 2025; Yang et al., 2024). The system employs an inertial measurement unit (IMU) embedded in the downhole drilling assembly to continuously capture raw tool attitude signals. The inclination and toolface angles are calculated using measured components of the gravity vector, while the azimuth is resolved based on sensed components of the Earth's rotation rate. After spatial alignment of the IMU attitude data, it can be combined with measurements from other engineering parameter sensors (such as pressure and temperature) to enable more comprehensive drilling state monitoring. The analog signals acquired by the IMU are digitized by the A/D conversion unit (sampling rate 10–200 Hz) and, in conjunction with a high-precision crystal oscillator (ensuring temporal consistency of sampling and storage), are temporarily stored in the onboard memory. They are then transmitted to the surface control terminal via the telemetry module. This real-time data pipeline enables drilling personnel to monitor downhole conditions and make rapid decisions during drilling operations.

As pivotal components for signal acquisition, advancements in sensor technology hold transformative significance for breakthroughs in MWD. Traditional MWD systems have relied on conventional sensors—such as pressure, temperature, torque, vibration and azimuth sensors—for downhole data collection. However, recent progress in electronic measurement and semiconductor sensor technologies has revolutionized MWD capabilities. Modern data acquisition systems, centered around IMU sensor clusters, now enable highly integrated, real-time feedback architectures. These systems achieve multi-sensor fusion and enhance data processing capacity, providing robust support for the

Table 1
Categories and functional descriptions of data acquisition sensors.

Category		Function description	Measured parameters	Working principle
IMU inertial sensor group	Inclinometer	Measures bit inclination angle	Downhole inclination angle	Accelerometer + gyroscope detect angular changes
	Gyroscope	Measures angular velocity for attitude control	Angular velocity, attitude angle	Calculates rotation angle based on angular velocity
	Magnetometer	Measures downhole azimuth	Downhole azimuth angle	Detects geomagnetic field strength and direction to determine orientation
Engineering parameter sensor group	Pressure sensor	Monitors downhole pressure	Downhole pressure	Piezoelectric or resistive sensor converts pressure into electrical signals
	Temperature sensor	Measures downhole temperature	Downhole temperature	Thermocouple or thermistor converts temperature into electrical signals
	Azimuth sensor	Measures downhole azimuth	Downhole azimuth angle	Magnetometer or gyroscope provides azimuth information
	Vibration sensor	Captures mechanical vibration of drilling tools	Axial/lateral vibration	Utilizes piezoelectric effect to convert mechanical vibrations into electrical signals for frequency analysis

Table 2
Comparative analysis of downhole sensor technologies.

Comparison item	Quartz crystal sensor (gyroscope)	Magnetoresistive sensor (magnetometer)	Capacitive sensor (accelerometer)	MEMS sensor (gyro/mag/accel)
Measurement principle	Piezoresistive effect	Geomagnetic field variation	Capacitance change	Micro electro mechanical systems (MEMS)
Size & weight	Large (cm-scale)	Miniaturized (mm-scale)	Miniaturized (mm-scale)	Miniaturized (mm-scale)
Temperature range	−40~\+180 °C	−40~+125 °C	−40~+125 °C	−40 ~+125 °C (up to +170 °C)
Accuracy	High (≤0.01°)	Medium (~0.1°)	Medium (~0.1°)	High (static 0.05°–0.1°, dynamic ≤0.3°)
Shock resistance	Poor (fails at ≤5 g sustained vib)	Moderate (10–20 g transient shock)	Moderate (20–50 g transient shock)	Excellent (50–100 g transient shock)
Temperature drift	Stable (Coeff. ≤ 0.001°/°C)	Negligible (Coeff. ≤ 0.05°/°C)	Minimal (Coeff. ≤ 0.1%/°C)	Requires compensation (initial drift ≤1.0°/°C; post-comp. ≤ 0.2°/°C)
Power consumption	High (20–50 mW)	Low (1–5 mW)	Low (0.5–3 mW)	Low (2–8 mW)
Output signal	Analog	Digital	Digital	Digital
Reliability	Low (50 k hours)	Low (60 k hours)	Moderate (80 k hours)	High (80 k–100 k hours)
Application scenarios	High-precision, low-vibration environments	Low-vibration, low-magnetic fields	Conventional drilling conditions	High-vibration drilling environments

integration and miniaturization of MWD systems (refer to Table 1 for technical specifications).

IMU technology is primarily used in high-precision positioning and attitude control systems such as aerospace, aviation, and missile guidance. Initially introduced from the military sector, IMU technology has gradually been applied to oil and gas drilling as the technology matures. In the oil and gas drilling industry, the introduction of IMU technology marks a revolutionary advancement in MWD systems. Traditional measurement technologies predominantly rely on external signals, such as vibrations, pressure signals, and conventional mechanical gyroscopes. In contrast, IMU sensor clusters operate independently of external signal inputs, enabling autonomous measurements in diverse downhole environments (including high-vibration environments, elevated temperatures and extreme pressures, strong electromagnetic interference, and multiphase flow impacts). Through data fusion techniques, these systems achieve higher measurement precision and real-time performance in complex borehole conditions. An IMU sensor cluster consists of three components: accelerometers, gyroscopes, and magnetometers. Accelerometers monitor drill bit acceleration to provide motion direction and velocity data. Gyroscopes velocity and orientation angles to calculate rotational displacement, ensuring precise directional control. Magnetometers determine azimuth angles by measuring the intensity and direction of the Earth's magnetic field. Together, these three components provide real-time attitude, angle, and azimuth data, ensuring precise control and path optimization for directional drilling. Common sensor types used in IMU clusters include quartz crystal sensors, magnetoresistive sensors, and capacitive sensors. In recent years, emerging micro electro mechanical system (MEMS) sensors have also been gradually integrated into MWD data acquisition systems (Table 2).

MEMS inertial devices enable the integration of multiple sensors (e.g., accelerometers, gyroscopes, magnetometers) onto a single chip, offering significant advantages in cost, power consumption, size, integration level, and shock resistance. This integrated design not only enhances functional capabilities but also lays the foundation for future innovative applications. However, under high-vibration conditions (transverse/longitudinal/torsional vibration acceleration reaching 20–200 g), compensation algorithms and structural optimization are necessitated to mitigate measurement inaccuracies. Concurrently, in extreme downhole environments (>175 °C), system accuracy is substantially compromised by temperature-induced drift. Enhanced performance requires material science advances and packaging process refinements targeting thermal stability, coupled with integrated structural-algorithmic compensation mechanisms specifically addressing vibrational and thermal error sources. SLB introduced its GyroSphere MEMS Downhole Gyro Service at the Offshore Northern Seas (ONS) Exhibition in 2018, marking the first commercial application of MEMS technology in downhole data acquisition (Liu et al., 2022). Other service companies have followed suit: Halliburton launched the DDSr drillstring dynamics sensor in 2019, combining MEMS and magnetoresistive sensors to monitor wellbore inclination, azimuth, and tool face angles in real time, thereby optimizing shale gas development and horizontal well drilling paths. Baker Hughes deployed its GyroTrak MEMS Sensor Sub in 2020, integrated with OnTrak & NaviTrak subs, to deliver precise vibration monitoring and tool face angle measurements under high-vibration conditions (Li et al., 2022b).

China's MEMS research initiated later, hindered by relatively underdeveloped electronics manufacturing. Although key technologies remained unaddressed during the Sixth and Seventh Five-Year Plan periods (1980s–1990s), foundational progress was achieved, exemplified by the successful deployment of fiber-optic inclinometers in the Huabei Oilfield in 2010. Research institutions such as Tsinghua University, Peking University, Southeast University, and the 10th Research Institute of China Electronics Technology Group have developed various MEMS sensor prototypes for data acquisition, achieving parity with international standards in scale factor and linearity. However, Chinese products still lag in precision and anti-interference performance compared to international counterparts, necessitating further innovation and improvement (Yang et al., 2024).

International renowned oilfield service companies such as SLB have developed various MWD downhole data acquisition devices in response to complex downhole environments and measurement requirements, and have put them into actual production. Table 3 summarizes the various types of while-drilling data acquisition devices developed by major oilfield service companies. Among them, SLB's exploration in new fields has provided valuable ideas and references for successors. For instance, its non-magnetic component module avoids magnetic interference without increasing the total length of the drill string, promoting the trend of miniaturization in the structure of acquisition devices. GyroSphere, as the first successful application of MEMS technology in the MWD field, saves up to 5 h of operation time compared to traditional sensor acquisition modules (as verified by 10 measurement experiments by ZERI company), marking a significant breakthrough in the integration and intelligence of MWD data

Table 3
Application of typical MWD data acquisition modules (Li et al., 2018; Lu et al., 2023; Wu et al., 2020; Zhang et al., 2025).

Company	Equipment	Sensor types	Measured parameters	Application scenarios
SLB	Synapse (2021)	IMU triaxial sensor group	Triaxial shock, triaxial vibration, inclination, azimuth, tool face angle	Real-time drilling optimization, efficiency improvement, tool failure reduction
		Basic engineering parameter sensor group (torsional vibration, temperature, memory mode, etc.)	Temperature, rotational speed, torsional acceleration, etc.	
	GyroSphere MEMS (2018)	MEMS sensor (Coriolis Vibratory Gyro - CVG) + basic engineering parameter sensor group	Azimuth, inclination, tool face angle, RPM, vibration, etc.	Offshore/land drilling, collision avoidance, sidetracking, deep wells, precise well placement
	Optiq (2021)	Fiber-optic sensors (DAS, DTS, DSTS, DTGS) + basic engineering parameter sensor group	Inclination, azimuth, vibration, pressure, temperature, strain, temperature gradient, etc.	Uses fiber optic cable as a continuous sensor, measuring Rayleigh backscatter to detect dynamic strain (e.g., micro-deformations caused by seismic waves)
Baker Hughes	GyroTrak (2020)	SPEAR solid-state sensor group (MEMS) + basic engineering parameter sensors	Inclination, azimuth, dip angle, true north tool face, turn rate, dynamic trajectory, etc.	HPHT wells, high-magnetic interference environments
Halliburton	GyroStar (2018)	Electronic gyro sensors (CVG-based), SPEAR solid-state sensor group + basic engineering parameter sensors	Full attitude, azimuth, dip angle, true north tool face, etc.	Cluster drilling, well collision avoidance, efficiency improvement
	QuickPulse-DDSr (2019)	DDSr drill string dynamics sensor, SPEAR solid-state sensor group + basic engineering parameter sensors	RPM, torque, acceleration, pressure, drill string dynamic behavior, and attitude measurement, etc.	Extended-reach drilling (ERD), complex well trajectories
Weatherford	Revolution Core (2018)	Acoustic azimuth sensor; IMU group; Gamma sensor + basic engineering parameter sensors	Inclination, azimuth, tool face angle, tilt, vibration, temperature, etc.	Conventional/unconventional wells, offshore production
NOV (National Oilwell Varco)	Black Star II (2014)	Directional sensor, gamma sensor, internal/annular pressure sensor, axial/lateral vibration sensor, temperature sensor, etc.	Borehole trajectory, drilling direction, downhole parameters (e.g., temperature, pressure, torque, etc.)	Applied in oil and gas field drilling, optimizing directional drilling
CNPC	Beijing Petroleum Machinery MWD Series (2020)	Resistive sensors, pressure sensors + basic engineering parameter sensors	WOB, torque, shock vibration, annular pressure, RPM, stick-slip, etc.	Applied in complex directional drilling operations
CNOOC	Drilog Series (2015)	DSM directional sensor group (triaxial accelerometer, triaxial fluxgate) + basic engineering parameters	Inclination, azimuth, tool face angle, caliper, annular pressure, vibration/shock, etc.	Directional drilling, complex well trajectory adjustment
SINOPEC	SINOMACS Series (2022)	Electronic gyro directional sensor group + basic engineering parameter sensors	Inclination, azimuth, temperature, tool face angle, dynamic trajectory, etc.	HPHT wells, extended-reach drilling, complex well trajectories

acquisition technology with microelectronics. Additionally, the Optiq optical fiber sensing equipment launched in 2021 measures acceleration and stress through distributed acoustic sensing (DAS) technology, providing real-time monitoring of physical parameters such as vibration and stress changes. This technology not only innovatively interprets existing functions but also lays the foundation for the gradual replacement of electrical components by optical fiber sensing materials. Baker Hughes' GyroTrak integrated sensor module “multi-tasks” simultaneously, measuring pressure, temperature, inclination, and azimuth, greatly simplifying the installation process and enhancing the comprehensiveness and reliability of the equipment. Halliburton's DDSr, through SPEAR solid-state technology, achieves adaptive control and real-time data adjustment while ensuring that the downhole dynamic sensor of the drillstring is not affected by vibration and magnetic interference, providing a path for the high-resistance development of downhole electronic components.

3. Downhole signal transmission technology

The data (e.g., inclination and azimuth) processed by the MWD system's downhole telemetry sub must be transmitted in real time to the surface terminal. This transmission process relies on efficient signal transmission technology, where data latency or loss may lead to incorrect subsurface condition assessments by surface drillers, ultimately causing drill bit trajectory deviations or even safety incidents. Unlike LWD, which involves extensive volumes of formation parameters (e.g., waveforms and energy spectra, often reaching MB levels), and primarily storage-focused transmission, MWD systems handle smaller data volumes (e.g., tens to hundreds of bits per frame) with a transmission principle centered on encoding and transmitting only critical information, emphasizing high speed, low latency, and efficient bitrate utilization within narrow bandwidth channels. This necessitates high-speed and real-time performance (Liu et al., 2015; Shi et al., 2024; Zhang et al., 2020). Consequently, data transmission rates have historically been regarded as a key metric for MWD system performance. This technology not only ensures the real-time operation of MWD systems but also plays a pivotal role in LWD and SWD technology. As the core hub for downhole-to-surface control, it serves as a critical enabler for advancing informatized and intelligent drilling (Lee and Lee, 2023; Qin and Xiao, 2003; Wang et al., 2014). In MWD systems, signal transmission is typically achieved via wired cables or modular telemetry subs, classified by transmission method into wired transmission (cable transmission, smart drill pipe, and fiber-optic transmission) and wireless transmission (mud pulse, electromagnetic pulse, and acoustic pulse) (Table 4). Different transmission methods exhibit varying data rates and are suited to distinct downhole environments and operational requirements, providing essential references for the comprehensive development of MWD transmission technologies (Han et al., 2024; Wang and Ye, 2024; Wu et al., 2025).

Among wired transmission technologies, while traditional wireline transmission technology (cable transmission) offers high data rates and strong anti-interference capabilities, it has gradually become a secondary option due to its susceptibility to damage, high costs, and limited applicability in various environments. Intelligent drill pipes enable real-time bidirectional communication through pre-embedded conductors using non-contact coupling, but they come with very high tooling expenses. Optical fiber transmission, employing specialized glass fibers (e.g., erbium-doped fibers) within drill pipes, offers high-speed data transfer with strong interference resistance and significant bandwidth potential. However, due to the fragile nature of optical fibers under dynamic drilling conditions, this method is currently limited mostly to static monitoring applications. Despite their advantages in transmission rate, wired technologies remain supplementary to wireless methods owing to cost and reliability constraints. Wireless transmission technology has gained widespread adoption due to its structural simplicity, relatively low technical costs, strong environmental adaptability, and reduced signal attenuation issues associated with cable limitations. As the most widely used wireless transmission technology in drilling operations, research on mud pulse telemetry dates back to the 1920s. A pivotal advancement occurred in 1969 when U.S.-based Teleco Inc. commercialized the first-generation mud pulse system while establishing standardized MWD signal protocols and performance metrics (Babaei Khorzoughi et al., 2018; Ding et al., 2024). This technology propagates pulse signals through drilling fluid circulation, eliminating requirements for insulated cables or specialized drill pipes, thereby substantially reducing operational expenditures. However, inherent bandwidth limitations restrict real-time data volume transmission to surface facilities (Faust et al., 2020; Martins de Souza et al., 2024; Xu, 2024; Yin et al., 2021). Early mud-pulse telemetry systems transmitted data at rates of 1–4 b/s, lower than those of cable logging systems. Modern advancements, achieved through improved signal-to-noise ratio (SNR) and optimized modulation/demodulation techniques, have

Table 4
Data transmission methods for MWD systems (Qin and Xiao, 2003; Wang and Ye, 2024).

Technology		Transmission method	Data rRate	Max depth	Advantages	Limitations
Wireless	Mud pulse telemetry	Pressure wave modulation	1–10 bit/s	>6000 m	No cables or special drill pipes required; low cost and wide applicability; excellent adaptability to saltwater formations (signal attenuation rate as low as 0.1 dB/m)	Limited bandwidth, slow transmission (1–10 bit/s); susceptible to mud property variations (transmission distance reduced by 30% in saltwater layers, remaining >4000 m)
	Electromagnetic (EM)	Electromagnetic wave propagation	1–15 bit/s	600–6000 m	Compatible with all mud types; simple implementation and moderate cost; low attenuation at low frequencies (1–10 kHz) (attenuation rate of 0.5–2 dB/m)	Signal attenuation depends on depth & formation resistivity (severe in saltwater layers, propagation <200 m; sensitive to EM interference in industrial settings, SNR < −50 dB)
	Acoustic	Acoustic wave transmission	10–30 bit/s	400–1000 m	Independent of mud environment; fastest wireless transmission rate (30 bit/s); suitable for air drilling and offshore operations	Susceptible to noise interference (e.g., pump vibrations, SNR = 10–30 dB); higher attenuation rate in saltwater layers (0.3 dB/m at 10 kHz); electronic components sensitive to electromagnetic interference (SNR drops to 10 dB under 100 mV interference)
Wired	Cable telemetry	Insulated wireline	1–2 Mb/s	>6000 m	High-speed bidirectional data transmission; suitable for deep wells	High cost (cable cost 200–500/meter, fragile) and prone to damage; complex installation (operation time increased by 15%–30%)
	Intelligent drill pipe	Magnetic coupling	1–2 Mb/s	6000 m	“Soft-connected” design enhances reliability; supports distributed measurements (monitors 5–15 parameters)	High cost (drill pipe cost increased by 30–50%); power supply limitations
	Fiber-optic	Optical signal transmission	Up to 1 bit/s	1000 m	Ultra-high speed potential; immune to electromagnetic interference	Immature technology (limited to shallow wells or specific scenarios); high deployment cost (>$1000/meter)

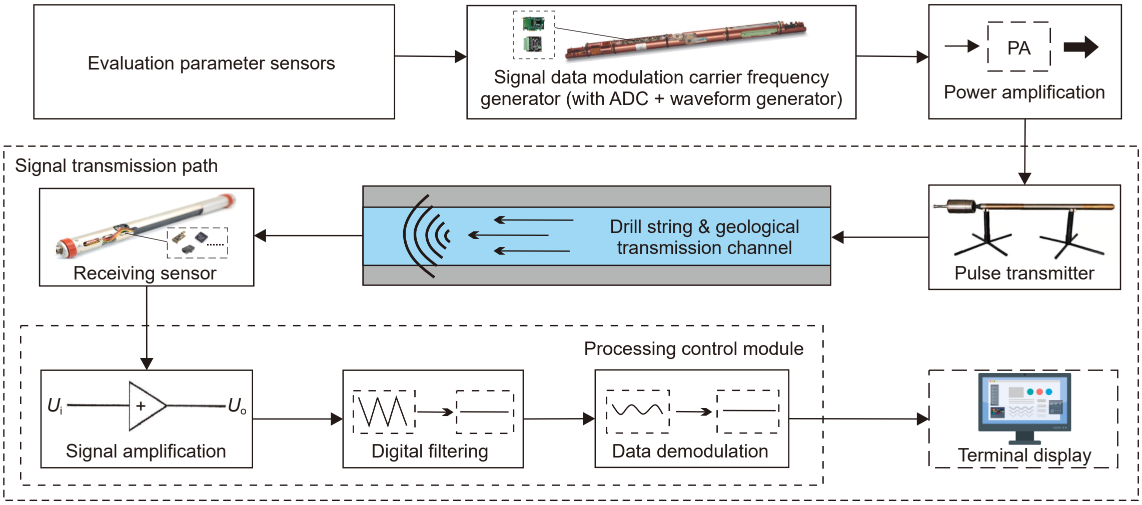


Fig. 7. MWD signal transmission flow (one-way scheme).

increased the data transmission rates of new-generation mud-pulse systems to 40 b/s. With technological progress, diversified wireless transmission technologies—such as electromagnetic wave pulses and acoustic wave pulses—have been developed, along with corresponding series of modular telemetry subs (van Eldert et al., 2020). These subsystems consist of a pulse transmitter, sensor module (receiver sensor), and processing control module (signal amplification, data demodulation, digital filtering). Fig. 7 illustrates the complete workflow from signal acquisition via the downhole module to terminal transmission.

Mud-pulse telemetry technology generates signals through a pulse generator (modulating mud flow area), which excites pressure pulse waves as the signal carrier. These pressure pulses propagate through the drilling fluid within the drill string (acting as the transmission channel) to deliver downhole measurement data to the surface, thereby enabling real-time downhole data upload. Electromagnetic pulse telemetry technology installs an insulating sub (in non-magnetic drill collars) near the drill bit, segmenting the drill string into two electrically insulated sections. An electromagnetic transmitting antenna modulates and encodes measurement data into low-frequency electrical signals, which are then injected as current through the drill string and formations to propagate to the surface (and vice versa: surface commands can be encoded as low-frequency signals, injected into the drill string-formation channel via a surface transmitter) (Shaik and Peddakrishna, 2025; Wu et al., 2025). Acoustic pulse transmission technology converts raw analog signals into digital format, encodes them, and drives downhole transducers to excite corresponding acoustic pulses. These pulses propagate along downhole media—whether liquid (drilling fluid) or solid (drill pipe/formation)—to transmit data in real-time to surface receivers for capture and decoding (Liu et al., 2025a). Fig. 8 illustrates the structural schematic of a typical pulse generator and MWD system.

SLB, Baker Hughes, and Halliburton, among other leading oilfield service providers, have established comprehensive transmission technology frameworks and implemented systematic optimizations across three categories of pulse telemetry subs. Mud-pulse technology encompasses three signal excitation types—positive pulse, negative pulse, and continuous wave pulse—providing broader technical flexibility. Electromagnetic pulse technology has advanced to achieve signal transmission depths of 3000 m, upgrading traditional turbo-generator and lithium-battery hybrid power systems, and developing dedicated power control systems to enable high-reliability downhole energy supply with 200-h operational reliability (Deng et al., 2025a; Jia et al., 2025; Zhang et al., 2025); Acoustic transmission technology employs digital signal processing and advanced waveform analysis techniques to enhance data transmission accuracy and stability. By integrating embedded technology (high-performance embedded processors), it achieves breakthroughs in technological integration and interference resistance, marking a significant leap in system performance (Xu, 2024). Product iterations from these companies demonstrate a clear trend from low-speed single-channel to high-speed multi-channel systems, and from single-medium to hybrid transmission architectures. Taking SLB as an example, its evolution from early low-speed mud pulse systems (SlimPulse, 10–16 b/s) to

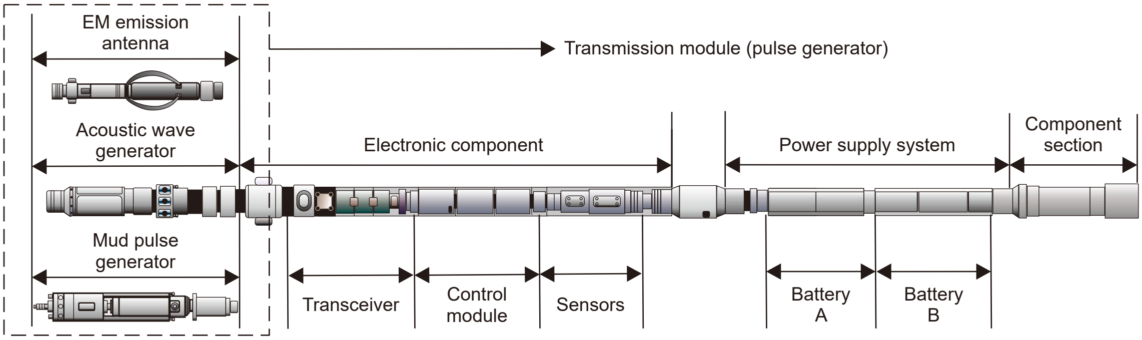


Fig. 8. MWD instrument wireless signal transmission modular diagram.

highly efficient compressed transmission (Scope series, 36–50 b/s), and finally to the introduction of mud/EM dual-channel systems (xBolt), reflects a continuous pursuit of higher rates and operational flexibility. To enhance the overall performance of transmission equipment, optimizations have focused on environmental adaptability. Key advancements include mud-pulse telemetry devices tailored for small-diameter wellbores (Slimpulse), continuous-wave pulse systems achieving 36 bit/s high-speed data transmission (PowerPulseMWD), high-temperature and high-pressure pulse instruments (TeleScopeICE, HeatWave), and ultra-high-speed signal transmission devices with enhanced thermal/pressure resistance (QuickPulse, QusarPulse) (Fediuk et al., 2020). From the perspective of channel redundancy (hardware optimization), MWD systems have evolved from single-channel to multi-channel transmission (Islam and Hossain, 2021; Liu et al., 2022). Multi-channel parallel transmission increases available signal bandwidth, with dual-channel technologies (xBolt, NaviTrak UT) improving transmission rates while mitigating downtime risks caused by drilling accidents. Regarding data optimization (software optimization), systems employ data encoding and compression algorithms to establish a compressed data transmission platform (Orion II), reducing data loss in deep wells, enhancing signal validity, and improving decoding success rates under low signal-to-noise ratio (SNR) conditions. Table 5 compares the performance of representative MWD signal transmission systems (Su, 2018; Su et al., 2023).

These innovations have substantially elevated MWD system performance through enhanced data transmission rates, improved signal fidelity, and expanded environmental tolerance, thereby optimizing drilling precision and real-time monitoring efficacy in complex wellbore conditions. However, these technologies cannot fully resolve the fundamental limitations of signal transmission in deep wells. As a novel optimization approach, intelligent drill pipes utilize built-in magnetic coupling rings at both ends to achieve a “soft connection” for cables, mitigating signal attenuation and interference during propagation through drilling fluid or formation media. While effectively addressing low transmission rate issues, remaining challenges in downhole power supply require further breakthroughs (Wang et al., 2025; Wang et al., 2024b; Wu et al., 2025).

China National Petroleum Corporation (CNPC), SINOPEC, and CNOOC have largely achieved practical implementation of drilling fluid pulse technology, while electromagnetic wave transmission technology is gradually being applied in initial stages (Li et al., 2022c). These companies are now actively advancing research in acoustic transmission and high-speed drilling fluid pulse technologies—including negative pulses and continuous wave pulses—to address technical challenges in complex downhole environments (high-vibration shallow wells, deep drilling, horizontal wells, and high-noise conditions). Developed at China University of Petroleum (East China), this acoustic telemetry system employs transducers to generate acoustic carrier signals. These propagate through drilling fluid inside drill strings, with data demodulation performed by surface-based equipment. Western Drilling's CS-MWD system employs stress wave technology for downhole data transmission (Zhang et al., 2020). Daqing Drilling's electromagnetic wave MWD system achieves real-time transmission via insulated dipole antennas (Wang, 2018), while Chuanqing Drilling's CQ-EMWD system implements modular “Series-Connected ” transmission using repeater cables (Liu et al., 2015). These innovations have filled critical gaps in China's MWD transmission capabilities and laid the technical foundation for subsequent advancements in electromagnetic pulse, acoustic pulse, negative pulse waves, continuous pulse wave, intelligent drill pipes, and data compression technologies.

4. Downhole steering technology

The RSS emerged in the 1990s as an advanced downhole automated directional drilling technology designed to address the limitations of traditional guidance systems, which lacked real-time directional control capabilities. Traditionally, RSS relied on attitude parameters provided by MWD as the foundation for geometric steering. With the introduction of LWD, RSS systems have further evolved into geosteering systems. By enabling real-time identification of lithological changes, reservoir top and bottom boundaries, and fluid properties, LWD allows RSS to promptly adjust the wellbore trajectory, ensuring the drill bit continuously remains within the optimal reservoir section. As a critical enabler in the transition from “uncontrollable trajectory” to “precision control”, RSS is characterized by high reliability, high drilling efficiency, and broad applicability, offering a viable solution for downhole control in the “intelligent era” of MWD systems (Matheus et al., 2012; Su et al., 2024). A typical RSS system comprises two core modules: the bearing unit (BU) and the control unit (CU) (Huo et al., 2019). These units communicate wirelessly via communication link (C-link) technology to transmit real-time tool status data, enabling precise adjustments to wellbore inclination and azimuth (Fig. 9). This architecture ensures continuous trajectory optimization while maintaining mechanical simplicity and operational flexibility in complex downhole environments.

Modern downhole steering systems utilize diverse actuation mechanisms, including hydraulic, mechanical, and electric motor-driven systems, to achieve precise trajectory control in complex geological environments. These systems ensure the generation of smooth and accurate wellbore trajectories while maintaining operational reliability across varying drilling conditions. Based on their guiding principles, steering methods are categorized into three primary types: Push-the-Bit, Point-the-Bit, and hybrid systems (He et al., 2025; Jing et al., 2025; Matheus et al., 2012).

Push-the-Bit systems employ steering pads to generate frictional forces against the wellbore wall, enabling gradual trajectory adjustments ideal for low-build-rate applications. In contrast, Point-the-Bit mechanisms actively control bit inclination and azimuth through optimized cutting structures, achieving higher build rates critical for navigating complex formations. To balance these complementary strengths, Hybrid rotary steering systems achieve enhanced performance by synergistically integrating the mechanical simplicity of Push-the-Bit mechanisms with the directional precision of Point-the-Bit actuators. This design strategy optimizes trade-offs between durability and agility, enabling simultaneous adaptation to complex geological challenges while maintaining operational reliability in varying downhole environments. Based on the operational mechanisms of measurement-control platforms and drill string dynamics, steering methods are further classified into dynamic and static systems. Dynamic systems rely on real-time feedback from MWD/LWD platforms to adjust tool face orientation, whereas static systems maintain fixed operational parameters during drilling. Table 6 summarizes the structural configurations and operational principles of various steering methods (Li et al., 2023; Su et al., 2024).

Static Push-the-Bit steering systems utilize predefined control algorithms and feedback signals from downhole measurement tools to adjust tool face orientation. Their structurally simplified

Table 5

Comparative analysis of MWD systems by major service companie (Fediuk et al., 2020; Liu et al., 2015; Qin and Xiao, 2003; Wang et al., 2014; Wang et al., 2024a; Wang and Ye, 2024; Wu et al., 2025; Yin et al., 2022; Zhang et al., 2020).

Company	Equipment	Function	Transmission method	Data rate	Advantages	Limitations
SLB	SlimPulse MWD (2000)	Measures inclination, WOB	Mud pulse	10–16 b/s	Retrievable in slim holes	Low bandwidth, slow transmission
	PowerPulse MWD (2000)	Real-time monitoring of inclination, azimuth, tool face	Mud pulse	10–16 b/s	Low power consumption with continuous rotary valve	Complex decoding algorithm
	Scope series (2000–2010)	Multi-functional integrated system	Mud pulse	0.5–36 b/s (compressed to 100–140 b/s)	High-temperature (200 °C) capability, works in slim holes	High cost, poor adaptability in complex environments
	xBolt (2016)	Dual-channel transmission	Mud/EM	16 b/s & 4 b/s	High flexibility	Unstable in complex environments
Halliburton	QuickPulse (2008)	Tool face and trajectory monitoring	Mud pulse	16 b/s	Strong noise reduction, stable	Low rate, limited effectiveness in deep wells
	QuasarPulse (2015)	Measures pressure, temperature, WOB, torque	EM pulse	16 b/s	Works in HPHT (200 °C/172 MPa) environments	Low rate, limited application scope
	EMT-MWD (2015)	Real-time downhole monitoring	EM pulse	10 b/s	Cost-effective, simple operation	Limited data processing capability
BakerHughes	NaviTrakMP (2006)	Trajectory monitoring	Mud pulse	10–12 b/s	Suitable for conventional operations	Sensitive to mud properties
	NaviTrakEM (2006)	Downhole parameter monitoring	EM pulse	10–12 b/s	High-speed, multi-environment adaptability	Signal attenuation issues
	NaviTrakUT (2008)	Real-time stable monitoring	EM & Mud	10–12 b/s	Dual-channel, highly adaptable	Low transmission rate
	OnTrak MWD Series (2000)	Real-time data acquisition, path optimization	Mud pulse	5 b/s	High transmission rate, stable	Poor adaptability
	aXcelerate XACT AT (2010)	Monitors downhole pressure, temperature	Acoustic	10–12 b/s	Adjustable repeater spacing, optimized signal strength	Susceptible to interference in complex environments
	aXcelerate EM (2018)	High-speed data transmission	EM pulse	10–14 b/s	High-speed, multi-environment adaptability	Signal attenuation may affect data quality
NOV	Intelliserv (2015)	Distributed measurement & high-speed transmission	Wired drill pipe	57 kb/s–2 Mb/s	High-speed bidirectional communication	High cost, complex installation/ maintenance
	RDS (2016)	Downhole temperature monitoring	Mud pulse	6 b/s	High-temperature/ pressure reliability	Large data volume causes transmission delays
	BlackStar II (2018)	Measures inclination, pressure	Mud/EM	4 & 11 b/s	Highly adaptable, wide application	Moderate transmission rate, limited bandwidth
Weatherford	Heatwave (2018)	Directional/pressure measurements	Mud pulse	6–16 b/s	Stable in high-temperature environments	Highly dependent on network conditions
CNPC	CQ-EMWD (2020)	Well trajectory and bit status monitoring	EM pulse	11 b/s	Independent measurement sub, strong decoding	Limited measurement range ($\leq$50 m)
	CG-MWD (2020)	High-precision long-distance positioning	Mud pulse	6 b/s	Reduces signal interference/valve clogging	Challenging in complex geology
SINOPEC	SINOMACS NBGSII (2021)	Real-time downhole monitoring	Mud pulse	6 b/s	Strong real-time capability, good environmental adaptability	Short transmission distance, limited bandwidth
CNOOC	Drilog-HSVP (2023)	High-speed alternative to conventional mud pulse	Mud pulse	12 b/s	High-speed transmission, high decoding rate, works in harsh conditions	Demanding mud parameter requirements (bubbles, viscosity)

design, relying on drill string physical properties, offers enhanced stability and is ideal for stable drilling environments. However, their performance diminishes under high-build-rate requirements, potentially compromising wellbore quality. In contrast, dynamic Push-the-Bit systems achieve real-time trajectory control by synchronizing rotation with the drill string and actively adjusting motion parameters (e.g., weight-on-bit, torque) (Pitcher et al., 2009; Zafarian et al., 2021). This design enables precise adjustment of drill bit angles and positions, delivering higher build rates and precise trajectory control for complex geological formations. Nevertheless, these systems feature complex mechanical architectures, are sensitive to drilling fluid conditions, and incur higher maintenance costs. Static Point-the-Bit steering employs a combination of a non-rotating outer sleeve and a rotating inner shaft. The outer sleeve contains an array of hydraulic pistons that use reactive force to bend the shaft and change

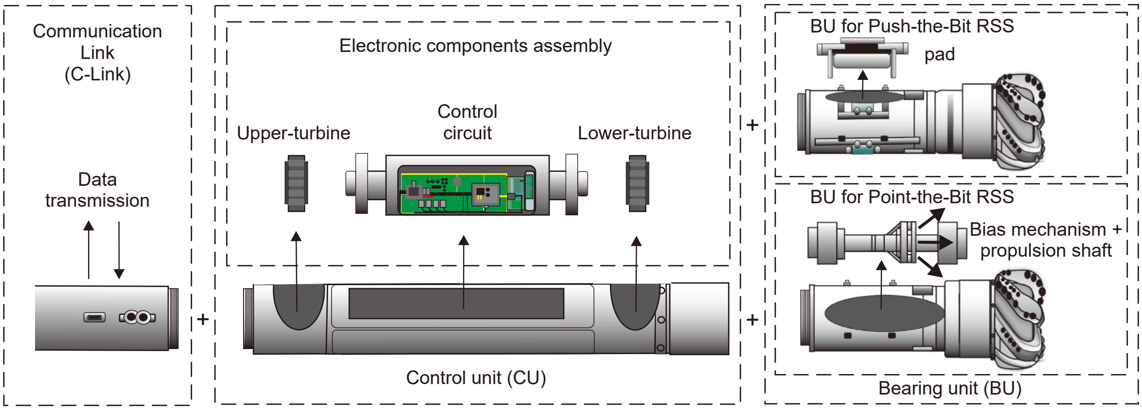


Fig. 9. RSS system structure diagram.

Table 6
Rotary Steerable System (RSS) steering mechanisms (Huo et al., 2019; Li et al., 2023; Su et al., 2024).

Steering type		Key components	Working principle	Example equipment
Push-the-Bit	Static Push-the-Bit (Fig. 10(a))	Non-rotating sleeve, rotating shaft, steering ribs	Uses steering ribs to push against the borehole wall; hydraulic pressure deflects the bit for trajectory control	Baker Hughes: AutoTrak G3
	Dynamic Push-the-Bit (Fig. 10(b))	Stabilizer, bias unit, extendable ribs	Ribs extend dynamically during rotation; drilling fluid pressure generates lateral force to steer the bit	SLB: PowerDrive Orbit G2
Point-the-Bit	Static Point-the-Bit (Fig. 11(a))	Non-rotating outer sleeve, bias mechanism, rotating shaft	Bias mechanism tilts the shaft via pistons; stabilizer supports bit deflection	Halliburton: Geo-Pilot
	Dynamic Point-the-Bit (Fig. 11(b))	Mechanical housing, universal joint, rotating shaft	Universal joint allows 360° bit tilting for precise directional control	SLB: PowerDrive Xceed
Hybrid steering		Combines push/point-the-bit components	Integrates both mechanisms for adaptive steering in complex formations	SLB: PowerDrive Archer

the bit direction. While capable of providing high build rates, this method is prone to vibration and fatigue. Dynamic Point-the-Bit steering enables fully rotational drilling, with the entire tool rotating along with the drill string. The bit sub is driven by a gimbal mechanism to deflect freely in any direction. This approach eliminates static friction and yields higher-quality boreholes, but requires complex structure and extremely precise control. (Figs. 10 and 11) (Han et al., 2024; Huo et al., 2019; Li et al., 2023; Matheus et al., 2012; Wang, 2018).

SLB, a global leader in oilfield services, has developed a mature lineup of rotary steerable systems (RSS) with standardized product architectures and widespread field applications. Its flagship PowerDrive series exemplifies this advancement, integrating three distinct guidance mechanisms within fully rotational designs and dynamic MWD platforms. These systems are tailored to specific downhole challenges: the PowerDrive X6 and PowerDrive Orbit G2 emphasize high build rate capabilities (≥6°/30 m) with enhanced corrosion resistance through advanced materials, making them ideal for extended-reach horizontal wells. The PowerDrive Xceed employs a dynamic Point-the-Bit rotary steerable system, which provides azimuth control accuracy within ±0.1°, which is critical for complex reservoirs requiring millimeter-level accuracy. By combining Push-the-Bit and Point-the-Bit mechanisms, the PowerDrive Archer offers operational flexibility across varying wellbore conditions, while the PowerDrive ICE addresses high-temperature environments with sustained performance up to 200 °C. For high-friction drilling scenarios, The PowerDrive Vortex integrates an internally embedded motor to deliver additional torque, addressing high-friction environments and enabling rapid trajectory adjustments for high-build-rate applications (Liu et al., 2022; Wang et al., 2023).

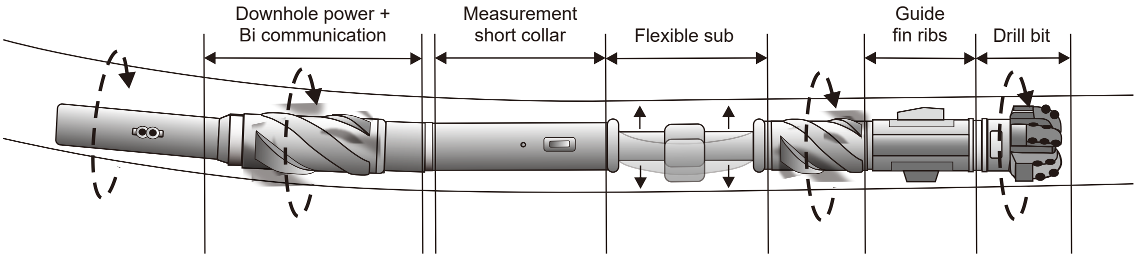
In 2021, SLB introduced the NeoSteer system, a dynamic Push-the-Bit innovation positioned close to the drill bit to maximize build rate efficiency. Its closed-loop automated control ensures real-time inclination and azimuth corrections, while near-bit measurements optimize trajectory adjustments during steerable and lateral sections. This design achieves high rates of penetration (ROP) and extended lateral reach (≥3,000 m) in extended-reach drilling (ERD), demonstrating SLB's leadership in RSS technology evolution (Wang et al., 2018).

Apart from SLB, companies like Baker Hughes and Halliburton have their own independent technological systems and product lines. In addition to their conventional product lines (main equipment), they have developed specialized products to meet different specific needs, such as high build-up capabilities and high-temperature resistance. For example, Baker Hughes' AutoTrak series (G3, X-treme, Curve, etc.) is centered around static push-the-bit technology and is primarily used in formations with good stability, emphasizing smooth wellbore trajectory control and closed-loop automation. Additionally, Baker Hughes launched the Lucida RSS system in 2020, which enhances drilling efficiency and precision by integrating hardware, software, and automation, ensuring reliability in extreme temperatures (up to 204.4 °C) (small boreholes), automatically adjusting wellbore trajectory, and optimizing drilling accuracy. Halliburton's Geo Pilot series (XL, GTX) focuses on high precision in static steering and adaptability to complex formations. Among them, the iCruise intelligent Push-the-Bit rotary steering drilling system, launched in 2018, relies on its autonomous CruiseControl core and the decision-making LOGIX platform—which uses machine learning algorithms to predict bit behavior—to automatically adjust the drilling path based on real-time drilling data with 80% autonomy, achieving efficient and precise intelligent trajectory control, performing exceptionally in high-speed rotation and high-temperature environments. The advanced RSS technology mentioned above meets the stability requirements of RSS tools in complex underground formations and harsh operating conditions at the local level; at the overall level, it ensures the accurate execution of MWD system directional commands. Its features are as follows: 1) High mechanical drilling speed—combined with downhole motors to improve efficiency; 2) Coexistence of basic and high-performance models; 3) Multi parameter—integrating real-time and geological and geophysical parameters; 4) Automation and intelligence—remote informatization technology driving autonomous directional drilling. Table 7 summarizes the advanced technologies currently applied by other oil service companies in their RSS systems.

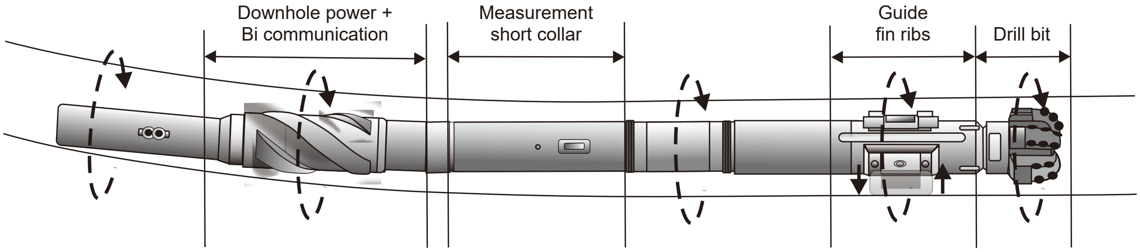
Over two decades of independent innovation, major Chinese oilfield service companies including CNPC, Sinopec, and CNOOC have achieved breakthroughs in static Push-the-Bit RSS technology, transitioning from research to large-scale commercial applications. China National Petroleum Corporation (CNPC)'s CGSTEER system has progressively advanced toward high-temperature (175 °C) and modular designs with intelligent capabilities, achieving an annual production capacity of 100 units. Over 300 well operations have been completed, with 80 applications in 2023 (Li and Xue, 2020; Liu et al., 2022; Wang et al., 2018, 2022; Zhang et al., 2024), while a high-temperature (175 °C) variant is under active development. CNPC Engineering Technology's GW dynamic Point-the-Bit steering system has undergone testing in 35 wells and was first deployed in the Liaohe Oilfield (Liu et al., 2022).

Table 7
Performance comparison of RSS tools from major oilfield service companies (Babaei Khorzoughi et al., 2018; Jia et al., 2024; Li et al., 2023; Liu et al., 2022; Su et al., 2023; Wang et al., 2018; Yang and Peng, 2018).

Company	Tool/product	Steering type	Temp. limit, °C	Build rate	Advantages	Limitations
SLB	PowerDrive Orbit G2 (2013)	Dynamic Push-the-Bit	150	16°/30 m	High-build-rate formations	Significant vibration, lower control precision
	PowerDrive X6 (2016)	Dynamic Push-the-Bit	150	12°/30 m	Complex formations	–
	PowerDrive Xceed (2017)	Dynamic Point-the-Bit	150	15°/30 m	High-stability, precision control	Poor mud adaptability
	PowerDrive Archer (2018)	Hybrid (Push + Point)	150	15°–18°/30 m	High-build-rate & complex formations	Complex structure, high cost
	PowerDrive ICE (2018)	Hybrid (Push + Point)	200	18°/30 m	High-temperature & high-build-rate wells	Demands extreme stability
	PowerDrive Vortex (2019)	Hybrid + power steering	150	18°/30 m	High-build-rate & horizontal wells	Requires high system pressure resistance
Baker Hughes	NaviTrak (2006)	Static Push-the-Bit	150	5–8°/30 m	High precision, slim-hole compatible, low cost	Limited performance, narrow applicability
	NaviGator (2010)	Static Push-the-Bit	150	10–12°/30 m	Accurate reservoir boundary detection	High cost, limited to specific reservoirs
	AutoTrak X-treme (2008)	Static Push-the-Bit	165	12°/30 m	High efficiency, real-time feedback	High cost, low control precision, bulky design
	AutoTrak G3 (2005)	Static Push-the-Bit	175	6.5°/30 m	Closed-loop control, high precision	Complex system, requires technical support
	AutoTrak eXpress (2013)	Static Push-the-Bit	170	10–14°/30 m	High-speed drilling, real-time steering	Complex maintenance, high cost
	AutoTrak Curve (2017)	Static Push-the-Bit	180	15°/30 m	High-build-rate capability	Expensive, limited hole size compatibility
	Lucida (2020)	Dynamic Push-the-Bit	200	18°/30 m	Automated high-precision control	High cost, limited applicability
Halliburton	Geo Pilot Series (2011)	Static Point-the-Bit	175	15°/30 m	HPHT and high-friction resistant, stable	Prone to fatigue, limited service life
	NaviGuide (2015)	Static Point-the-Bit	165	10°/30 m	High precision, bidirectional data transmission	High cost, complex maintenance, skilled ops needed
	iCruise (2018)	Static Push-the-Bit	150	12°/30 m	High-speed rotation, high-temperature resistant	–
Weatherford	Revolution Series (2004)	Static Point-the-Bit	175	10°/30 m	Flexible for various hole sizes	Sensitive to mud flow rate
	Magnus (2012)	Static Push-the-Bit	160	12°/30 m	Modular design, easy maintenance	Limited extreme-environment performance
NOV	NOV Russell (2018)	Static Push-the-Bit	175	12°/30 m	High precision and reliability	High cost, limited hole size compatibility
CNPC	CG-STEER (2020)	Static Push-the-Bit	150	12.5°/30 m	Precise trajectory control, real-time monitoring	Limited by flow rate and circulation system
	GW (2020)	Static Point-the-Bit	150	7.14°/30 m	Bidirectional communication	Limited geological adaptability
SINOPEC	SINOMACS ATS I (2019)	Static Push-the-Bit	165	4.2°/30 m	High-precision trajectory control, bidirectional	Immature technology, requires optimization
	IB Plus (2023)	Static Push-the-Bit	165	–	Trajectory control	Pending functional optimization
CNOOC	Welleader 1.0 (2019)	Static Push-the-Bit	150	6.5°/30 m	Near-bit measurement, optimized positioning	High cost, still in promotion phase
	Welleader 2.0 (2023)	Dynamic Point-the-Bit	150	12.31°/30 m	High-build-rate capability	Complex tech, high cost, difficult maintenance

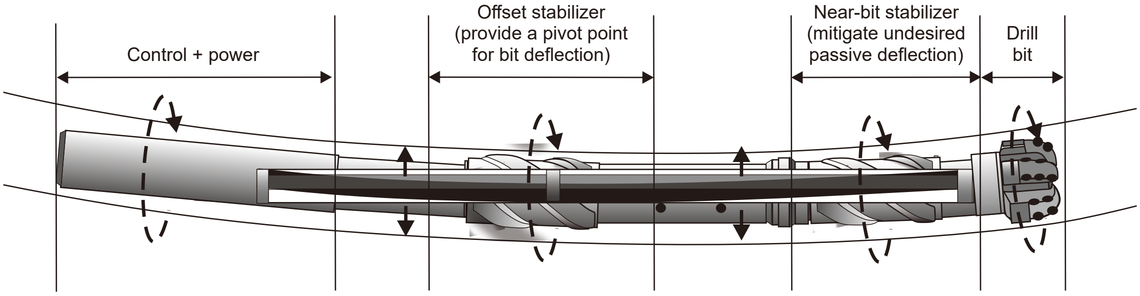


(a) Static Push-the-Bit Rotary Steerable System

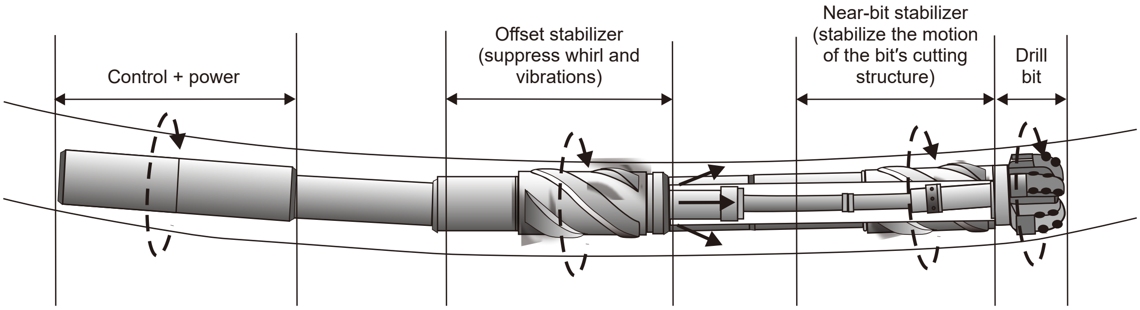


(b) Dynamic Push-the-Bit Rotary Steerable System

Fig. 10. Schematic diagram of Push-the-Bit Rotary Steerable System action.



(a) Static Point-the-Bit Rotary Steerable System



(b) Dynamic Point-the-Bit Rotary Steerable System

Fig. 11. Schematic diagram of Point-the-Bit Rotary Steerable System action.

Sinopec's SINOMACS ATSI system accomplished a continuous 141-h operation in the Shengli Oilfield, drilling 857 m with a maximum build rate of 6.6°/30 m. Meanwhile, CNOOC pioneered dynamic Point-the-Bit RSS technology, launching its first-generation static Push-the-Bit Welleader system followed by the second-generation dynamic Point-the-Bit Welleader, which completed its inaugural field test in late 2023 at the Xinjiang Luntai Scientific Test Well These milestones collectively represent significant progress in China's indigenous RSS technology, marking accelerated innovation and industrialization capabilities (Guo et al., 2022; Long et al., 2020).

5. Future perspectives

Modern MWD technology is undergoing a profound transformation driven by intelligent upgrades. Persistent challenges posed by downhole extreme conditions (including high-temperature, high-pressure, and highly corrosive physico-chemical environments; high-vibration and high-impact mechanical conditions) necessitate continuous advancements through hardware innovation and software optimization to enhance system-wide performance. This includes systematic intelligent breakthroughs in measurement accuracy, transmission efficiency, and steering control capabilities, alongside sustained upgrades in environmental adaptability—specifically high-temperature resistance, high-pressure tolerance, and vibration mitigation. Collectively, these efforts aim to propel MWD toward greater precision, reliability, and intelligence, marking a pivotal development trajectory for next-generation downhole measurement systems (Fig. 12).

(1) Equipment adaptation to harsh downhole environments

The development of MWD systems faces significant challenges under extreme downhole conditions, including high temperature, high pressure, and intense vibration. These conditions lead to signal attenuation and tool failure. This reality makes environmental adaptability optimization essential for enhancing the stability and reliability of MWD systems in downhole operations. It serves as a necessary precondition for extending depth limits, ensuring scientific data acquisition, and enabling accurate resource assessment in deep formation development. Overcoming these technical barriers represents a critical direction in MWD research and a core bottleneck in system development, directly determining the operational depth limits and reliability thresholds of deep-well operations. It also serves as a pivotal breakthrough for the exploration and development of “two deep and one unconventional” resources (ultra-deep oil/gas, deep-sea resources, and unconventional hydrocarbons) and geothermal energy. Current advancements in novel semiconductor materials, gradient buffering architectures (hydraulic damping + elastomer cushioning + inertial balancing), and hybrid cooling technologies have substantially improved the physical tolerance of MWD systems to high temperatures and pressures. For instance, traditional sensors have achieved stable performance under 150 °C/70 MPa conditions. However, in more extreme environments exceeding 200 °C/140 MPa, only a handful of globally leading enterprises possess the core component manufacturing capabilities and proprietary process technologies. Collaborative innovation across material systems, structural design, and intelligent control has emerged as a consensus approach to mitigate the impact of harsh downhole conditions. For example Deng et al. (2025) proposed a hybrid thermal management system integrating liquid cooling and phase-change materials (PCMs) for downhole electronics, extending operational duration from 230 to 450 min while reducing the maximum temperature difference between electronics and PCMs from 30 to 2 °C. Soprani et al. (2018) developed a downhole heat transfer sensor design combining thermal intervention databases with active cooling systems, enabling stable operation in corrosive and aggressive environments. Zhang et al. (2021) optimized high-temperature logging tools through 61 iterative refinements by integrating finite element analysis (FEA) and the Nelder-Mead algorithm, reducing peak heat source temperatures from 163.1 to 123 °C. Furthermore, Cai et al. (2023) developed a 3D nonlinear drill string-rock interaction model, augmented by hardware-based hybrid dampers and multistage buffering configurations. This multidimensional optimization framework substantially enhanced operational reliability through vibration energy dissipation. These advancements transcend incremental improvements in individual metrics, achieving systemic performance breakthroughs through integrated design. Future innovations, particularly the adoption of third-generation semiconductor materials (e.g., silicon carbide, gallium nitride, and high-temperature optical fibers), are expected to push technical boundaries to 250 °C/175 MPa, providing robust support for ultra-deep oil/gas and unconventional resource development. Such progress underscores the transformative potential of MWD systems in redefining operational paradigms for deep-earth exploration.

(2) Intelligent development of high-precision sensor integration technology

The cognitive evolution of sensor systems has emerged as a pivotal solution to address signal interference and dynamic errors caused by dynamically coupled multi-field conditions downhole during operations. The latest modular measurement units incorporate multi-modal sensing technologies—including MEMS sensors, quartz accelerometers, and fiber-optic sensors—to achieve a attitude measurement accuracy of 0.1°/h while maintaining compact structural designs. Advanced laboratory-stage quantum inertial sensing technologies, such as thermal atom beam interferometry gyroscopes developed by Stanford University and the Precision Measurement Institute of the Chinese Academy of Sciences, have further pushed angular measurement precision to the 0.001°/h level (at the laboratory stage). However, breakthroughs in measurement accuracy represent only the foundational data layer for smart sensors. The true value lies in constructing a closed-loop “sensing-decision” system. For example, (Li et al., 2018) proposed and demonstrated a quasi-distributed high-temperature fiber-optic sensor array deployed at critical positions in drill collars. By integrating the Hong-Ou-Mandel (HOM) interferometry method (Zhang et al., 2025) to eliminate phase wrapping issues, this system achieves an expanded dynamic measurement range. The adoption of IEEE 1588 Precision Time Protocol (PTP) combined with adaptive weighting algorithms (Alghamdi and Schukat, 2022) enables microsecond-level time synchronization, establishing a highly interference-resistant measurement network. Simultaneously, industrially embedded edge computing units (Dai et al., 2019) reduce raw data processing latency to the 50 ms level.

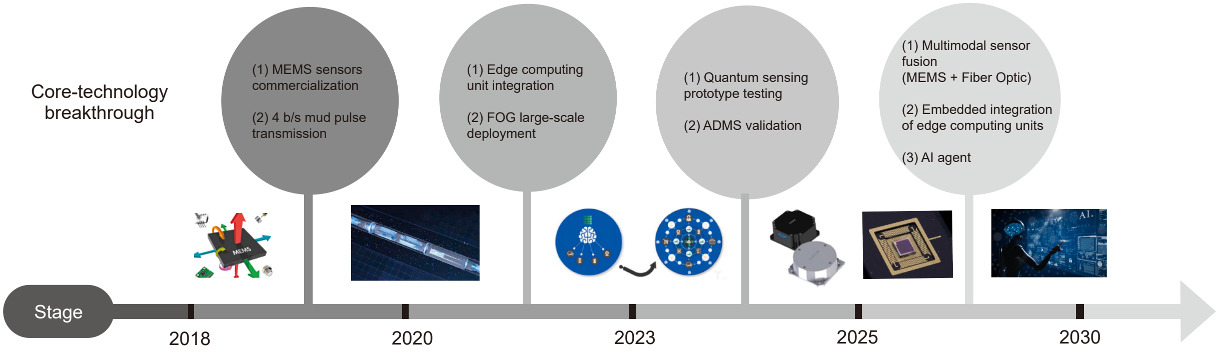


Fig. 12. Intelligent technology roadmap for MWD.

When paired with cloud-coordinated intelligent diagnostics platforms, real-time anomaly detection and compensation are realized, while modular interface designs ensure system compatibility and scalability.

This “integrated sensing-edge computing-cloud coordination” architecture not only accelerates autonomy and intelligence in MWD systems and creates favorable conditions for large-scale deployment, but also strengthens reliability in MWD measurement data and establishes a more accurate spatial coordinate framework for LWD and SWD. It supports the evolution from geometric to geological steering, enabling complementary use of MWD (dynamic parameters) and geophysical data. This integration breaks down information barriers between static geological characterization and the dynamic drilling process, creating new opportunities for real-time formation identification and drilling parameter optimization. These capabilities are further strengthened through the combined use of high-resolution resistivity and electromagnetic imaging modules in LWD systems. Unlike conventional logging that only provides averaged macroscopic responses of formation parameters, high-resolution resistivity imaging—with vertical resolution reaching 2 inches—together with borehole micro-imaging can accurately identify thin interbeds and complex sedimentary structures. Simultaneously, enhanced petrophysical measurements improve the evaluation accuracy of porosity and fluid properties through optimized detector design and acquisition methods. Such a combined measurement system elevates logging data interpretation from one-dimensional curves to two-dimensional imagery and three-dimensional geological models, achieving a fundamental transition from indirect inference to direct characterization, and from post-drilling analysis to real-time evaluation. Meanwhile, technical challenges such as miniaturization and deep-sea deployment are gradually being addressed through integrated applications of micro/nano-processing technologies, qubit carriers + high-precision control modules, new material packaging technologies, and anti-corrosion/anti-interference solutions. Multiple national-level laboratories (USTC, University of Birmingham) are conducting breakthrough experiments in photoelectric collaborative mm-scale sensing, high-durability materials (salt spray testing), anti-corrosion packaging (EU Quantum Flagship deep-sea environment testing), wide-temperature-range electronics, and electromagnetic shielding, accelerating the transition of high-precision quantum sensors from lab to harsh downhole operations (slim-hole/deep-sea). However, these sensor core components—NdFeB permanent magnets for magnetic signal acquisition and terbium-dysprosium compounds for magnetic core temperature stabilization—remain highly dependent on rare-earth materials, leading to high costs and fragile supply chains. Global rare-earth resources are concentrated (reserves/production dominated by a few countries), with high-purity separation and eco-friendly smelting technologies not widely mastered. Long-term over-exploitation faces resource depletion pressures (reserve-to-production ratio ~130:1), restricting expansion into ultra-deep wells and polar exploration. Solutions include expanding resource development, researching non-rare-earth alternatives, strengthening supply chain collaboration and localized production, and improving recycling systems to reduce dependence, ensure stability, and support reliable intelligent drilling operations. According to SPE forecasts, next-generation intelligent sensor systems (IMS) are projected to achieve 70% industrial-scale application in deep-well projects by 2030. This technological leap will enhance operational efficiency in deep exploration while safeguarding national energy security, underscoring the transformative role of intelligent transformation in advancing MWD system performance.

(3) Convergent innovation and performance breakthroughs in signal transmission technology

The evolution of MWD signal transmission relies fundamentally on maximizing existing technologies while innovating transmission methodologies. As hydrocarbon exploration advances into deeper and more complex subsurface environments, conventional transmission methods face escalating challenges. Established technologies—including mud pulse, electromagnetic wave, acoustic, and optical fiber transmission—will continue serving vital roles in future MWD systems, with ongoing technical innovations enhancing their performance. Traditional positive pulse systems improve transmission stability through structural optimizations such as precision machining of rotary valves and flow channel adjustments, exemplified by SLB's PowerPulse maintaining 3–16 bit/s rates in deep wells. Negative pulse and continuous wave technologies have reached industrial application stages: Halliburton's JetPulse enhances signal-to-noise ratio by 30% through pulse frequency optimization and adaptive filtering algorithms, while APS RotaryPulser achieves precise modulation exceeding 5 bit/s via variable-section valve plates and high-frequency motor drives. Chinese research has made breakthroughs in negative/continuous wave technology, currently focusing on core continuous wave generator components through precision machining and high-frequency motor optimization, with laboratory CFD simulations validating pressure signal generation (Cai et al., 2024; Jiang et al., 2024). Electromagnetic transmission systems like ZTS-MWD address deep-well signal attenuation via external antennas, though penetration depth and stability require further breakthroughs. Acoustic transmission solutions such as Baker Hughes' XACT AT improve efficiency in complex environments through adaptive modulation but necessitate enhanced spectral management and noise-reduction algorithms. Optical fiber transmission overcomes high-temperature/high-pressure limitations using advanced materials like silicon carbide fibers, providing stable support for smart drilling. These three modalities achieve synergistic breakthroughs through “structural innovation + algorithmic optimization + material upgrades,” establishing a downhole multi-modal transmission matrix. Against this backdrop, limitations of single-mode transmission systems are becoming increasingly apparent, demanding cross-domain technological convergence and architectural innovation to overcome traditional bottlenecks (Zhai et al., 2025b). Consequently, MWD signal transmission is entering a transformative phase characterized by intelligentization and multi-modal collaboration, evolving from standalone technologies toward an integrated “multi-channel unified” architecture that forms a multidimensional downhole information highway. However, the goal of building high-speed communication channels extends beyond one-way data acquisition and uplink—it also establishes the feedback foundation for intelligent closed-loop control of the drilling process. Going beyond traditional trajectory steering applications, the high-speed, low-latency data links ensured by a multi-modal transmission matrix enable the surface system to perceive downhole dynamic drilling conditions—such as drill string vibrations, torque variations, and pressure anomalies—in real time, and to convert this information into precise control instructions. SLB's xBolt G2 dual-channel MWD system (combining 4 bit/s mud pulse with 16 bit/s electromagnetic transmission) pioneers this transition. Future systems may upgrade to a “triple-relay architecture” integrating mud pulse, electromagnetic, and acoustic transmission: acoustic transmission (~20 b/s, vibration immunity & attenuation-induced interference rejection; enables real-time monitoring of bit vibration and formation changes) for near-bit sections; electromagnetic transmission (~16 bit/s, medium-low resistivity formation-adapted; synchronously transmits inclination and toolface data) for mid-well sections; and mud pulse (~20 bit/s, deep-well compatible; reliable transmission of annular pressure and temperature data) for upper sections. This methodology delivers carrier optimization frameworks (acoustic + electromagnetic + optical fiber) targeting signal attenuation mitigation in deep-sea drilling environments. While this hybrid architecture maximizes modality-specific advantages, it requires solving multi-access protocol challenges to eliminate cross-medium interference.

Simultaneously, intelligent drill pipes bridge wired and wireless technologies through evolution from mechanical contact-based “hard connections” to magnetically coupled ring “soft connections,” breaking mud pulse rate limitations for the first time though still requiring repeaters due to power constraints (simultaneously enables continuous monitoring of drill string vibration and torque). Future development should concentrate on two directions: magneto-electric fusion through optimized magnetic circuit design (distributed magnetic pole arrangements to reduce reluctance, as in Reelwell's DualLink), development of high-temperature superconducting magnets (advances and challenges in 2G HTS tapes) (Yan et al., 2019), and 3D-printed micro-magnetic structures (Zhang et al., 2025); and intelligent control via dynamic transmission protocol optimization using hybrid algorithms to adapt to complex downhole conditions such as signal attenuation in gas-bearing formations, simultaneously enables continuous monitoring of drill string vibration and torque (Yan et al., 2017). These advancements will propel MWD technology toward three transformative goals: >100 kb/s transmission in 10,000-m wells, multimodal integration, and full-borehole real-time closed-loop control (Zhai et al., 2025a).

(4) Deep application of intelligent control algorithms

Intelligent control algorithms are enabling measurement while drilling (MWD) systems to transition from “passive execution (tools)” to “active decision-making (intelligent agents),” marking a paradigm shift in system intelligence. Unlike traditional hardware-centric performance improvements, algorithmic innovation establishes dynamic environment-adaptive frameworks, granting unprecedented autonomous decision-making capabilities. Machine learning (ML) has long been utilized in MWD to extract weak downhole signals—such as mud pulses—from intense noise interference caused by drilling vibrations and fluid flow. Techniques including neural networks and wavelet transforms have proven more effective than conventional filtering in enhancing signal separation and decoding accuracy under low signal-to-noise ratio (SNR) conditions, thereby reducing data retransmission requests. Furthermore, ML enables predictive maintenance by analyzing historical operational data to anticipate failures in key components such as pulsers and batteries, preventing potential downhole failures (Liu et al., 2025b). As demands grow and the technical boundaries of MWD continue to expand, the application of ML is further evolving to support more complex and reliable drilling operations. In data acquisition, NABORS’ SmartDrill employs synergistic adaptive and robust control strategies to dynamically regulate real-time parameters, effectively suppressing environmental interference and reducing measurement errors by 42%. Weatherford's Victus (Liu, 2024) intelligent managed pressure drilling system integrates AI algorithms (dynamic optimization + redundant throttling + predictive maintenance), leveraging global well data from thousands of oilfields to analyze downhole parameters and execute second-level pressure regulation, enabling precise overflow prevention (demonstrated in Egyptian field trials). For signal transmission, SLB's Muzic Aeon HPHT reservoir wireless telemetry system (Smith et al., 2022) couples ceramic hardware with cognitive algorithms, constructing a closed-loop “neural hub” that spans signal acquisition, noise suppression, network optimization, and decision support. Meanwhile, Huawei and Daqing Oilfield have pioneered the integration of 5G + edge computing with MWD signal transmission, introducing “deep learning-based dynamic routing optimization” to enhance communication reliability. In trajectory control, Halliburton's iCruise Smart steering system (Zuan and Huang, 2018) employs machine learning (ML) algorithms to analyze downhole data in real time, achieving sidetracking errors <1 foot through automated deviation correction and high-curvature drilling (12°/100 ft) via geology-model-guided trajectory optimization. China National Petroleum Corporation's (CNPC) CNPC-IDS Advanced Directional System integrates multi-dimensional intelligent algorithms (magnetic correction to eliminate current interference and ensure data precision; vector closed-loop force control with ±0.1 kN accuracy; weak signal “filtering + matching + notch” decoding achieving a success rate exceeding 95%), effectively enhancing system performance. Advanced research institutions such as Baker Hughes and China University of Petroleum (East China) have developed multimodal knowledge-based control systems combining fuzzy logic, neural networks, and adaptive algorithms for precise tool attitude regulation. Notably, reinforcement learning algorithms—capable of autonomously optimizing control parameters by continuously learning downhole environmental features—have been modularized for flexible deployment across diverse scenarios. This shift from “environmental adaptation” to “cognitive decision-making” represents a transformative leap in system intelligence. With the maturation of 5G + edge computing, the maturation of integrated 5G and edge computing technologies has progressively facilitated their downhole deployment. Edge computing achieves localized real-time decision-making through hardware acceleration and model compression. Concurrently, universal technical standards for 5G terminals continue to evolve within the industrial ecosystem, with 23 offshore drilling platforms globally implementing private 5G networks. Chinese oilfields demonstrate accelerated terminal adoption, rising from 5% penetration in 2022 to 37% in 2024 (Sun et al., 2024). Significant challenges nevertheless impede large-scale implementation: RedCap 5G module costs exceed exceeds $27.80 USD (equivalent to 200 CNY) per unit, while explosion-proof and high-temperature adaptations increase R&D expenditures. Protocol incompatibility between industrial control systems and 5G transmission mechanisms obstructs wireless retrofits of critical equipment (PLC/DCS), and standardization frameworks for downhole-specific operational scenarios remain underdeveloped. Future advancement requires integrated progress across three domains—technical cost reduction, protocol compatibility enhancement, and standardization refinement—to enable 5G's transition from monitoring applications to core motion-control scenarios. This “intelligent core + modular hardware” innovation model is poised to redefine the global drilling equipment industry, establishing new technical standards and business paradigms. This environment-model-centric, algorithm-synergy-driven framework will catalyze next-generation intelligent drilling systems. Its standardized architecture enables rapid adaptation to geological conditions and engineering requirements, providing critical support for unconventional resource development (e.g., shale oil, tight oil) and breakthroughs in ultra-deep (>8000 m) and high-temperature/high-pressure (250 °C/175 MPa) reservoirs (Ding et al., 2025; Liu et al., 2025a; Sun et al., 2024).

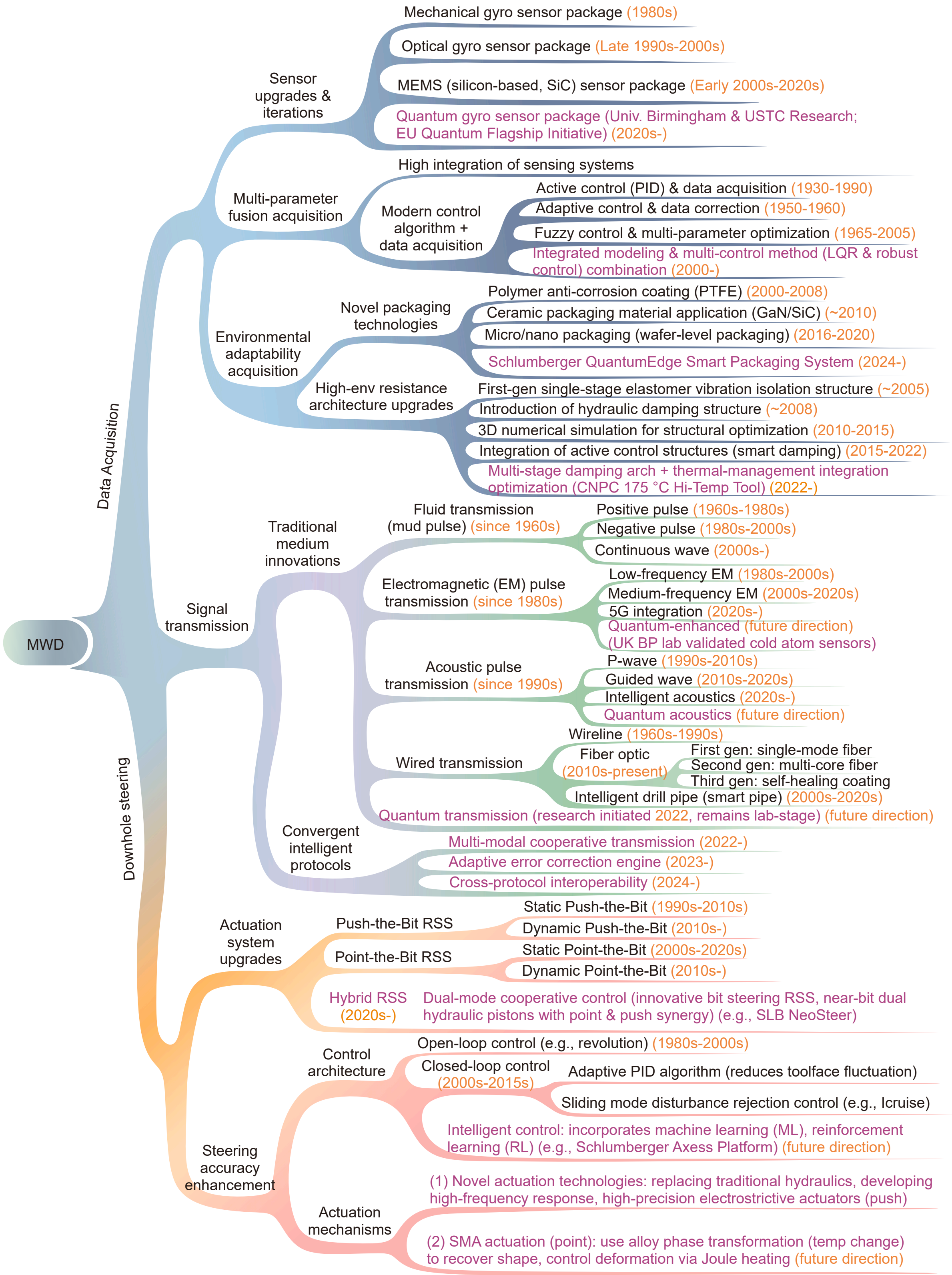


Fig. 13. Hierarchical trend analysis of MWD "acquisition-transmission-drilling" workflow.

Fig. 13 delineates the four-decade evolution of modern MWD technology: The data acquisition domain has undergone a progression from mechanical and optical gyroscopes to quantum-grade precision sensors, achieving breakthrough high-temperature resilience at 175 °C through advanced ceramic encapsulation and multi-stage damping structures. Advancements in signal transmission have transitioned from conventional wired systems to wireless/fiber-optic architectures with intelligent protocols, establishing robust anti-interference channels via multimodal signal coordination and high-speed compression platforms for efficient and stable downhole data transmission. Steering mechanisms have transitioned from static push-/point-the-bit configurations to dynamic hybrid platforms, incorporating algorithm-driven closed-loop control for precision trajectory adjustment. The synergistic convergence of these domains continues to propel the system toward more reliable accuracy, proactive adaptability, and autonomous operational capability. The synergistic convergence of MWD, LWD, and SWD systems has fundamentally reshaped the landscape of real-time drilling measurement and control platforms, delivering exceptional levels of operational proficiency and formation assessment functionality.

6. Conclusions

MWD technology is undergoing a profound transformation from hardware performance breakthroughs to system-wide intelligent upgrades. As downhole extreme conditions—high temperature, high pressure, and intense vibration—persist, the industry drives systematic improvements in measurement accuracy, transmission efficiency, and steering control through synergistic advancements in materials innovation, multi-sensor fusion, and intelligent algorithms. Novel composite materials and multi-stage damping structures markedly enhance environmental adaptability, while quantum sensing and edge computing redefine high-precision measurement capabilities. Adaptive control and reinforcement learning algorithms empower autonomous decision-making, transitioning systems from passive execution to active optimization. Nevertheless, non-technical bottlenecks constrain technology adoption: high R&D costs (technical complexities, expensive core materials, rare-earth dependencies), fragmented standards, and cross-disciplinary talent shortages. Notably, as AI-driven autonomous drilling technologies advance, their regulatory and liability implications urgently require resolution. Algorithmic “black-box” characteristics may obscure decision transparency, necessitating comprehensive “data-model-decision” traceability mechanisms. Moreover, if algorithmic biases or data inaccuracies during autonomous operations trigger downhole incidents (e.g., kick misidentification, trajectory deviation), liability attribution among developers, deployers, and users lacks legal clarity. Establishing AI governance frameworks with defined accountability boundaries is therefore imperative to enable MWD's intelligent evolution.

Looking ahead, MWD, LWD and SWD systems will accelerate their evolution towards “full-link autonomy”. This development process, in addition to achieving continuous breakthroughs in core technologies such as material science, sensor technology, and intelligent algorithms, also requires the establishment of an open industrial ecosystem that includes industry chain collaboration, standard system development, and business model innovation. By addressing technological transformation bottlenecks through cross-industry cooperation, establishing unified data standards and communication protocols, and improving data security and intellectual property protection mechanisms, the cost-effectiveness model can be optimized, lowering entry barriers, and strengthening interdisciplinary talent training in “geology-engineering-data science”. This will foster a virtuous cycle of technological innovation and business implementation, effectively overcoming operational limitations in extreme environments. It is foreseeable that intelligent MWD technology will become the core technology for implementing the “deep earth and deep sea” strategy, ultimately driving a historic upgrade of the entire drilling engineering system from the traditional “experience-driven” model to the modern “data-driven” and “intelligence-driven” models, providing critical technological support for the high-quality, sustainable development of the global energy industry.

CRediT authorship contribution statement

Zhi-Wei Cai: Writing – original draft, Validation, Methodology, Data curation. **Ran-Lei Zhao:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Zi-Ming Huang:** Methodology, Investigation. **Yu-Peng Qiao:** Supervision, Funding acquisition, Conceptualization. **Qing-You Yue:** Validation, Supervision. **Cun-Lei Li:** Resources, Funding acquisition. **Qiu-Shi Zhang:** Funding acquisition, Conceptualization. **Hang Wen:** Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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