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Analysis and Regulation of Mechatronic Systems in Advanced Mobile Machines

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Abstract: In modern mobile machines, mechatronic systems have been integrated, enabling: a) the automation and robotization of machine tasks, b) the regulation of drive system parameters, and c) the transfer and processing of signals pertaining to machine management and monitoring. This study presents an in-depth analysis of mechatronic systems responsible for drive system regulation, transmission automation, and robotization of mobile machine manipulators. Criteria and objectives for regulation and automation are delineated, based on which application software has been developed. Through these mechatronic systems, efficient, ergonomic, and ecologically sound operations of mobile machines are facilitated.

Keywords: Mechatronic system; Mobile machines; Automation; Robotization; Drive system regulation

1 Introduction

In diverse economic sectors, mobile machines—spanning construction, mining, transport, agricultural, and communal domains—are utilized extensively, particularly in earthmoving and intermittent transportation tasks [1]. Over the past decade, owing to their pivotal role in economic development and large-scale investment projects, mobile machines integrated with mechatronic systems have been developed. These advancements are attributed to intensive research outcomes and have facilitated: a) the automation (robotization) of machine operations, b) the efficient, energetic, and ecological regulation of drive system parameters, and c) the transmission and processing of signals for machine control and monitoring.

Mechatronic control systems in these machines predominantly comprise (Figure 1): a) electronic components, including sensors, potentiometers, and microcontrollers, and b) hydrostatic components, which encompass regulators for diesel motors, hydraulic pumps, hydraulic motors, and drive system actuators [1]. Signals from kinematic chains and the drive system, gathered by sensors, in tandem with operator command signals relayed via potentiometers, typically serve as analog input signals for the microcontroller. Within the microcontroller, these analog signals are first transformed to digital signals, subsequently processed via dedicated software, and then reverted to output analog signals. These output signals guide regulators, which modulate and oversee the machine's drive system components: diesel motors, hydraulic pumps, and actuators [1]. Moreover, the microcontroller interfaces with a monitoring system for real-time parameter tracking, as well as external devices, such as control panels or computers equipped with diagnostic and system parameter-setting software. Communication within this mechatronic system is facilitated by the CAN Bus (Controller Area Network) wires [1].

A fundamental aspect of mechatronic systems lies in sensors' ability to capture and transduce physical system state quantities into corresponding analog signals. Depending on the specific physical quantity detected, various sensors are employed: stroke, displacement, angle, angular velocity, force, pressure, temperature, and others [2]. Potentiometers, designed as levers, buttons, switches, and control distributors, translate operator inputs into respective electrical analog signals. Control distributors specifically function as potentiometers, deriving power from an external source, typically a 0-5V or 0-10V battery. Their operational mechanism involves registering a stroke by a position sensor, which corresponds proportionally to the control lever's rotation angle and the consequent output analog signal [2].

Microcontrollers, pivotal for the programmed control of mechatronic systems, vary based on their capacity, denoted by the volume of input and output signals they manage, and the power of the embedded microprocessor.

Specialized microcontrollers have been designed to withstand mobile machines' demanding conditions—ensuring resilience against temperature fluctuations, ensuring hermetic sealing, and offering resistance to shocks, vibrations, and electromagnetic interference. These microcontrollers not only supply input voltage to sensors and potentiometers but also retrieve analog signals from them [1].

Achievements within mechatronic control systems for mobile machines include automatic regulation of motion transmissions, automation (robotization) of manipulative functions, and consistent diagnostic and system parameter monitoring aligned with ergonomic standards and requirements. To cater to mobile machine operational demands, software packages—or programmed cards—have been developed, equipping the mechatronic control systems' microcontrollers. Global manufacturers, including Bosch Rexroth [2] and Kawaaki [3], have introduced components like integrative hydrostatic-mechatronic drive systems for a diverse range of mobile machine sizes. Regulation software packages for these hydrostatic-mechatronic systems have been crafted, adhering to functional, energy conservation, ecological, and ergonomic criteria. Additionally, they offer adaptability based on users' requirements. Extant research on the mechatronic control system of mobile machines has predominantly focused on energy efficiency, the evolution of hybrid drive systems [4, 5], dynamic mathematical model creation for robotized machine manipulators [6, 7], and machine operation automation [8, 9].

The subsequent sections delve into an analysis of mechatronic systems concerning drive system regulation, motion transmission automation, and robotization of principal mobile machines, including hydraulic excavators, loaders, and track loaders.

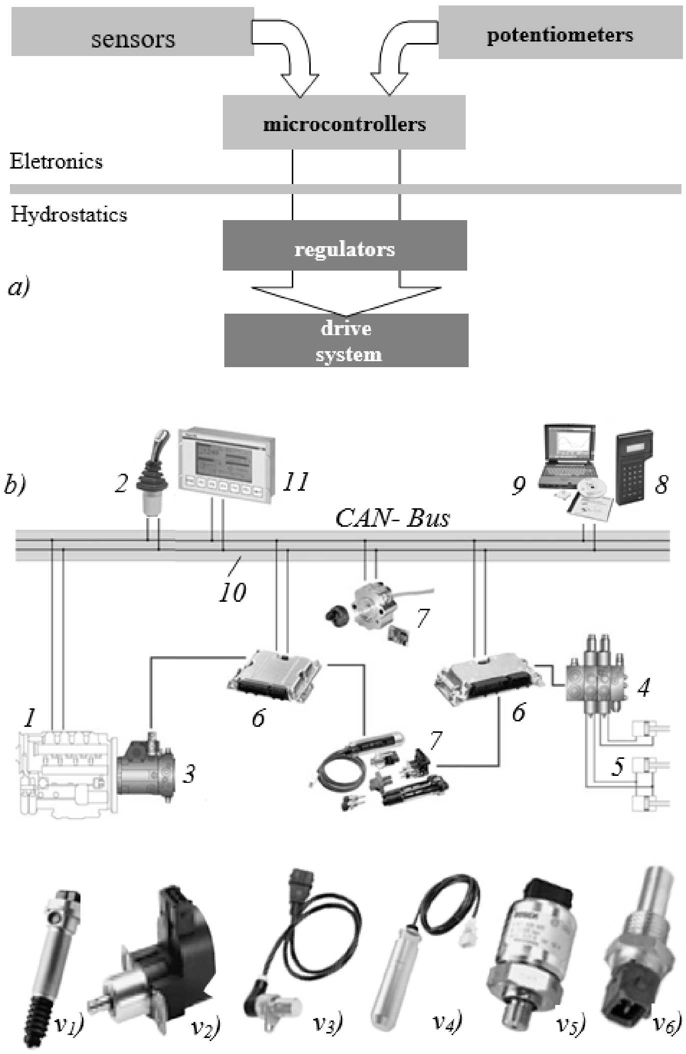

Figure 1. Mechatronic control system of mobile machines

2 Drive System Regulation

In contemporary mobile machines, a hydrostatic drive system is predominantly employed, encompassing a diesel engine 1 as shown in Figure 2, and a hydraulic pump 3. This pump, whether in an open or closed hydraulic loop, delivers hydraulic fluid via a distributor 4 to hydraulic cylinders 5.1 and hydraulic motors 5.2 that facilitate kinematic chain drives. A mechatronic system, integrated with a microcontroller 6, is interconnected through CAN wires to sensors that measure diesel engine revolutions (7.1) and temperature (7.2). Additionally, pressure sensors 7.3 in the extension duct of the hydraulic pumps, as well as sensors 7.4 gauging the motion speed of the hydraulic cylinder and hydraulic motor revolutions, are also integrated.

As the machine operates, the microcontroller processes input values representing the state of the drive, external characteristics of the diesel engine, and regulatory criteria for the hydraulic pump. Based on this data, regulation signals are subsequently transmitted via CAN wires. These signals determine the synchronous operation of both the diesel engine and the hydraulic pump, effectively governing the machine's entire drive system. It should be noted that the external characteristic of the diesel engine is typically defined in terms of its torque relative to its rotational speed. Similarly, the hydraulic pump's regulation criteria are expressed as a function of its pressure and displacement.

The regulation signals that are received play a pivotal role in modulating the diesel engine's fuel injection and fan operation, specifically for cooling. Concurrently, these signals also regulate the specific flow—essentially the working volume—of the hydraulic pump. Thus, regardless of the variations in load and operational conditions, the hydraulic pumps are designed to harness the maximum available power from the diesel engine without risking an overload.

2.1 Regulation of Hydraulic Pump Drive

In mobile machines, varied loads and operational conditions necessitate a drive system equipped with multiple hydraulic pumps and actuators. To address this need, a mechatronic control and regulation system has been developed. This system allows for selective engagement, facilitated by a potentiometer 2 as shown in Figure 2, enabling synchronized operation of the diesel engine and hydraulic pump. Regulation adheres to the criterion of maintaining hydraulic power constant, as expressed by:

$$N_e = N_h = p \cdot Q = \text{ constant} \tag{1}$$

where, N_e represents the power of the diesel engine and N_h denotes the hydraulic pump power, with $p \cdot Q$ indicating pressure and flow rate, respectively.

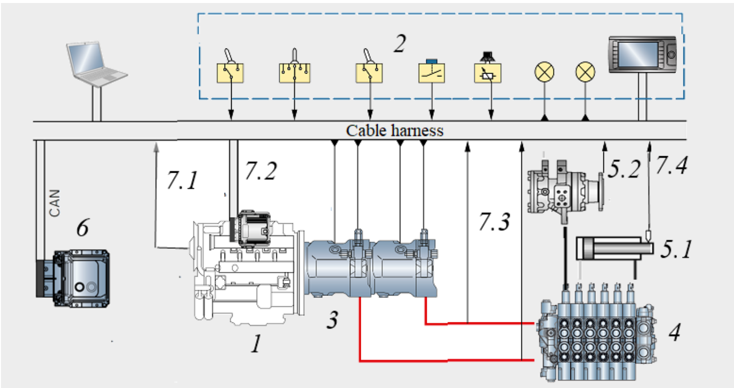

Figure 2. Mechatronic system of regulation of the drive system

In this configuration, the diesel engine 1 (Figure 3) powers both the primary double hydraulic pump 3 and the secondary hydraulic pump 3.2 through the interplay of an elastic coupling 2 and a power distributor 2.1. The principal double hydraulic pump is equipped with a collective power regulation and an associated regulator 3.1 exhibiting ideal hyperbolic characteristics (flow and pressure dependency in alignment with Eq. (1)). An additional feature of this regulator is its capability to modify the hydraulic pump's regulation range, a task executed via microcontroller 9. Input signals are received by this microcontroller from a sensor 4, which measures revolution count, a sensor 5 monitoring the fuel injection command, and a sensor 6 assessing the diesel engine's temperature. There is also a switch 10, which determines the power allocation the main hydraulic pump derives from the diesel engine. The electro-hydraulic valve 7, governed by the current I sourced from the microcontroller, modulates the pressure of the auxiliary hydraulic pump 3.2 to match the control pressure p_st.

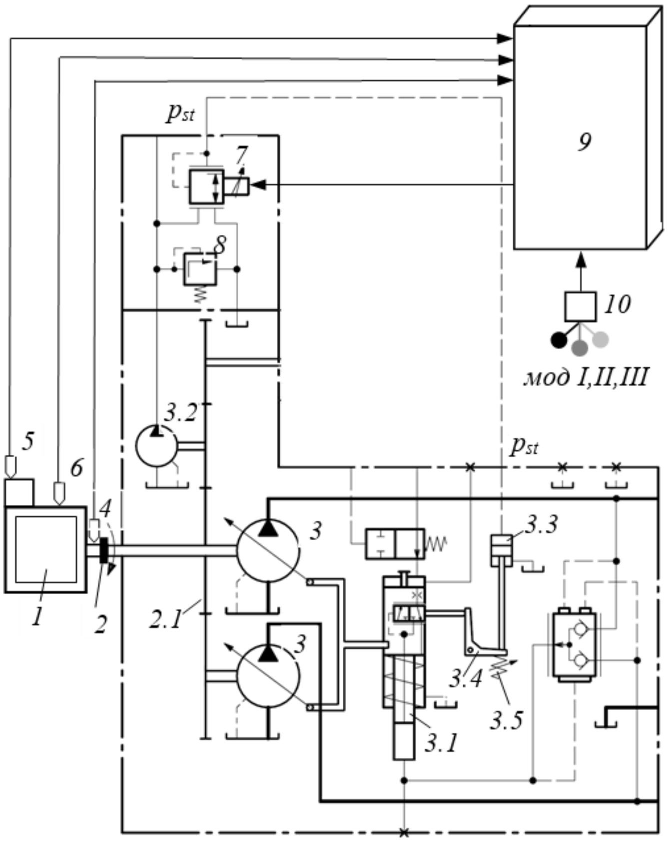

Figure 3. Hydraulic pump regulation system

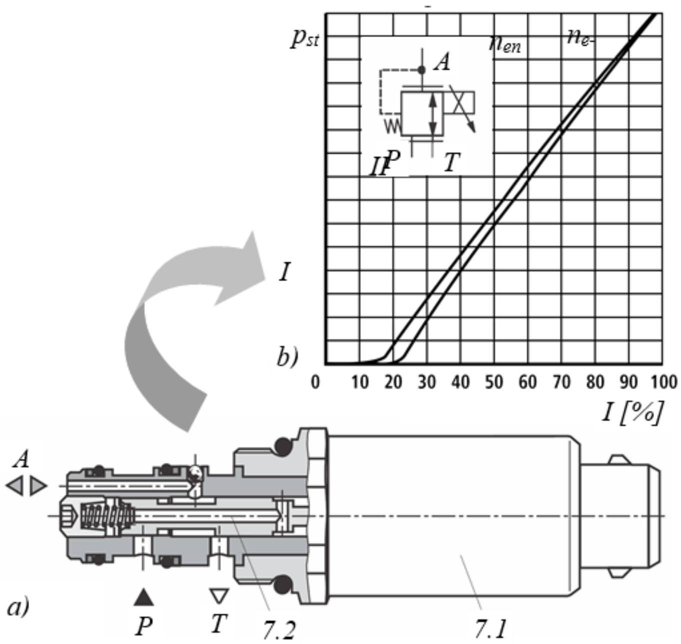

Figure 4. Characteristic of the electro-hydraulic valve

The pressure level within the auxiliary hydraulic pump is meticulously maintained via the safety valve 8. In this setup, input signals representing the system state are processed by the microcontroller utilizing specialized software, leading to the generation of an output electrical signal characterized by a specific current I strength.

The electro-hydraulic valve 7, as depicted in subgraph (a) of Figure 4, incorporates a housing (7.1) encompassing a pump (P), a reservoir (T), and a working line (A). Positioned within is a piston (7.2) which, when acted upon by the force exerted from the electromagnet 7.3, ensures the control pressure pst in the working line (A) remains proportional to the strength I of the current supplied to said electromagnet, as demonstrated in the diagram in subgraph (b) of Figure 4.

The consequential action of this control pressure p_st from the electro-hydraulic valve on the hydraulic pump's regulator (3.1) is facilitated via the piston within cylinder 3.3. This piston interacts directly with the arm of a two-armed lever (3.4) integral to the regulator. The force derived from the control pressure acting upon the face of the cylinder piston (3.3) is counteracted by the force emanating from spring 3.5, impacting the two-armed lever 3.4. As a result, an augmentation in the control pressure p_st - or equivalently, an enhancement in the output current I from the microcontroller - leads to a reduction in the initiating regulation pressure p_p of the hydraulic pump (as visualized in Figure 5). This, in turn, modulates the hydraulic power under regulation.

Consequently, an approximately constant pressure p_k is sustained at the culmination of the hydraulic pump's regulation. The switch 10 provides the option to select between three to six distinct power tiers that the hydraulic pump derives from the diesel engine. Most commonly, three selective modes are utilized:

I) for taxing operational conditions, utilizing 100% of the available engine power (Figure 5),

II) for moderate conditions, employing 75% of the engine's power,

III) for lighter tasks, harnessing just 50% of the engine's power capacity.

Through such an arrangement, optimal diesel engine power usage is achieved, leading to diminished fuel consumption, noise reduction, and enhanced adaptability to the varying loads and operational conditions of the machinery.

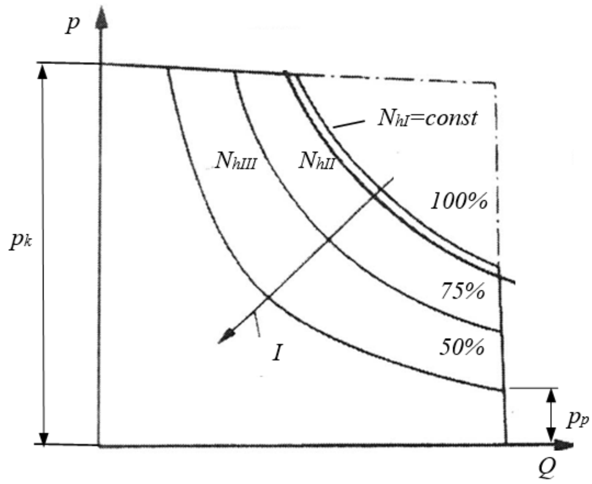

Figure 5. Flow control diagram of the hydraulic pump

3 Automation in Motion Transmissions

Mobile machines are categorized by their tracked or wheeled support mechanisms and moving members. Those equipped with tracked moving mechanisms typically possess a single pair of tracks and are characterized by hydrostatic movement transmission; examples of such configurations include tracked tractors, finishers, and loaders. In these machines, identical and autonomous drives are observed. These drives operate in a closed hydrostatic circuit where hydraulic pump 3 (Figure 6) is activated by diesel engine 1. Concurrently, the hydraulic motor 5, seamlessly integrated with a planetary reducer, is directly linked to the track sprocket via its output shaft.

Central to the drive is a mechatronic system, equipped with a microcontroller 6. Through the CAN Bus, this microcontroller is interfaced with several components: the diesel engine's electronic control unit (ECU) 7.1, the hydraulic pump's electric regulators 7.2, the hydraulic motor's regulators 7.3, sensors (7.4) that gauge revolutions and pressure levels of the hydraulic motor, and potentiometers such as an electric joystick 2 and an inch hydraulic brake pedal.

During machine operations, input signals, derived from the state of the transmission as gauged by sensors, in conjunction with set values acquired via potentiometers, are processed by the microcontroller. Utilizing its intrinsic software, this microcontroller computes regulation signals which are then dispatched to the regulators of the various transmission components through the CAN Bus.

Such a sophisticated setup facilitates multi-functional, ergonomic control over the machine's movements. Specifically, linear motion (either forward or reverse) is initiated when the joystick 2 is toggled forward or backward. Meanwhile, curvilinear directional movements with a predetermined radius can be achieved by shifting the joystick either to the left or right.

Regulation Eq. (2) captures the relationship inherent in this system:

$$N_e = N_h = p \cdot Q = M_h \cdot \omega_h = F \cdot v = \text{ constant} \tag{2}$$

where, M_h, and ω_h represent the torque and angular velocities of the hydraulic motor, respectively. F and v correspond to the machine's traction force and movement speed.

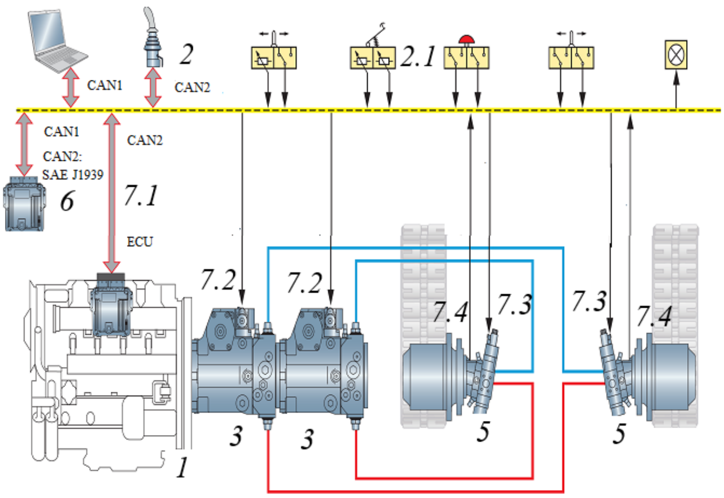

Figure 6. Schematic representation of a tracked mobile machine's movement transmission

Hydraulic halting or "braking" of the machine is manipulated through the position of the inch pedal 2.1. This process, devoid of traditional friction brakes, operates by dynamically adjusting the specific flow rates of the hydraulic pump and motor based on regulation signals.

Lastly, the microcontroller, considering inputs such as the hydrostatic transmission system's oil temperature and the diesel engine's temperature and speed, generates control signals. These signals ensure that the operation of the diesel engine adheres to prevailing environmental standards and safeguards against potential overloads.

3.1 Regulation of Hydraulic Motor's Rotational Speed

In machine motion transmissions, a closed-circuit hydrostatic drive system enables the desired continuous variation in the number of revolutions n (subgraph (b) of Figure 7) of the hydraulic motor's output shaft. This is achieved irrespective of the rotational speed of the diesel engine and the load exerted on the system. This hydrostatic drive system comprises a hydraulic motor 4 (subgraph (a) of Figure 7) with a constant specific flow, and a hydraulic pump 3 with a variable specific flow. Both components are powered by diesel engine 1 and are governed by a mechatronic control system.

Central to this control mechanism is the microcontroller 6, which is equipped with specialized software. Input signals, derived from the rotational speed sensor 7.4 located on the hydraulic motor's output shaft, and from potentiometer 2 (utilized for setting the desired rotational speed via a control lever), are processed by the microcontroller. The microcontroller, through its embedded software, computes the output signals destined for the hydraulic pump regulator 7.2 and the fuel injection pump regulator 7.1 of the diesel engine.

The difference between the signals produced by sensor 7.4 and potentiometer 2, or in other words, the disparity between the actual and the desired rotational speeds of the hydraulic motor, dictate the regulation signals generated by the microcontroller. These signals modulate the fuel injection rates, and by extension, the diesel engine's rotational speed, as well as the specific flow rate of the hydraulic pump. Consequently, the desired number of revolutions n (subgraph (b) of Figure 3) of the hydraulic motor is achieved, ranging from its minimum to its maximum value. This occurs in both rotational directions, R and V, contingent on the orientation of the control handle and the current strength I of potentiometer 2.

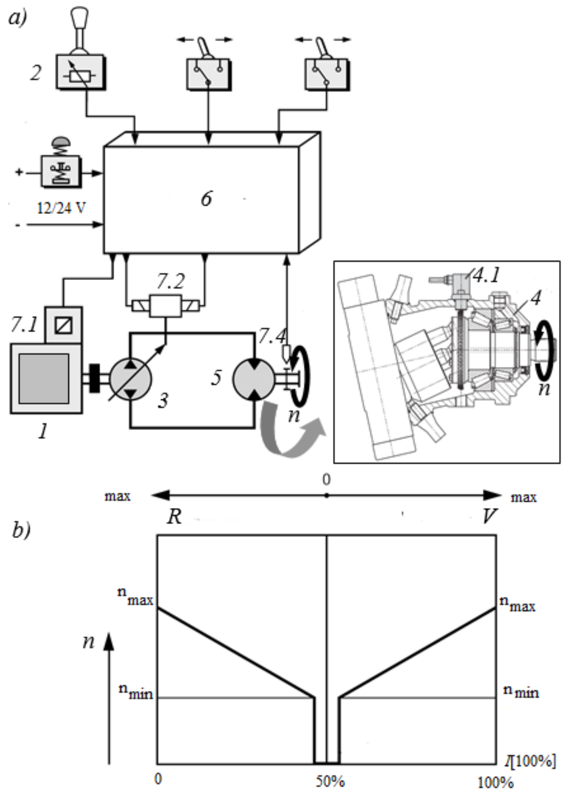

Figure 7. Schematic representation of the hydraulic motor's rotational speed regulation

3.2 Gear Ratio Modification

Mobile machinery such as loaders and cranes often utilize hydrostatic-mechanical transmissions to enable higher movement speeds. These transmissions primarily comprise a hydraulic pump (3 in Figure 8), driven by a diesel engine (1), which supplies two hydraulic motors (5 and 5.1) connected to the input shafts of a gearbox (8) in a closed hydrostatic circuit. The output shafts of the gearbox are connected to the drive bridges (9) via cardan shafts, with the wheels (10) of the machine's moving mechanism attached to the lateral reducers.

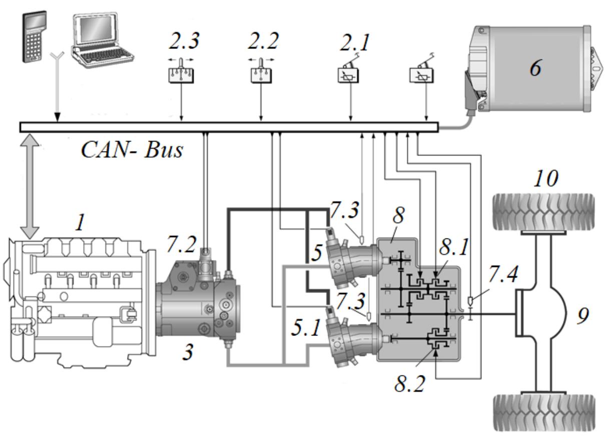

Figure 8. Gear ratio modification in transmission

An integral part of this transmission system is a mechatronic management system for gear ratio modification (8) during load-induced machine movement. This system communicates input signals via a Controller Area Network (CAN) Bus to a microcontroller (6). These signals are derived from various sensors: the revolution number of the diesel engine (7.1), the revolution number of hydraulic motors (7.3) related to both 5 and 5.1, and the gearbox output shaft (7.4). Moreover, signals are also received from potentiometers like the fuel supply pedal for the diesel engine

(2.1), levers for changing the transmission gear (2.3), and the machine movement direction control (2.2).

As output variables, the microcontroller (6) provides electrical signals to control the couplings of the gearbox (8.1 and 8.2) and an electrical signal for the hydraulic pump's regulator (7.2). This mechanism allows for synchronized engagement of the couplings and flow regulation of the hydraulic pump (3) under gearbox load, thereby enabling a continuous and jerkless gear ratio change (8) in the transmission. This change is dependent on the machine's condition and the state of the transmission drive, ensuring operator convenience.

4 Automation and Robotisation of Mobile Machinery Manipulators

Efforts to increase productivity, enhance safety, and improve operator comfort have led to the development of automation or robotisation systems for mobile machines, particularly hydraulic excavators and loaders [10]. The automation systems integral to these machines can be divided into two primary components: hydrostatic and mechatronic.

The hydrostatic component encompasses the diesel engine-powered hydraulic pump 3 in Figure 9, which feeds the machine manipulator's drive mechanisms, namely, hydraulic cylinders and hydraulic motors, via the distributor 4 [10].

On the other hand, the mechatronic component is comprised of sensors, potentiometers, and microcontrollers [11]. For excavators, this includes inertial sensors that monitor movement in various parts: the supporting and moving mechanism 7.1 in subgraph (a) of Figure 9, rotating platform 7.2, boom 7.3, arms 7.4, and bucket 7.5. These sensors measure linear and angular accelerations of the members. In the case of loaders, similar inertial sensors are used to monitor the movement of the support and moving mechanism 7.1 in subgraph (b) of Figure 9, the boom 7.3, and the tool (bucket) 7.3. Additionally, the system employs sensors to measure pressure in the working lines of the machine manipulator mechanisms, which are installed in the distributor section 4.

The mechatronic component also includes manual 2.1 and foot 2.2 control joysticks as potentiometers, and microcontrollers 6.1 and 6.2 for regulating the diesel engine and hydraulic pump, and for controlling the machine manipulator, respectively. These controllers operate based on software founded on kinematic and dynamic machine models.

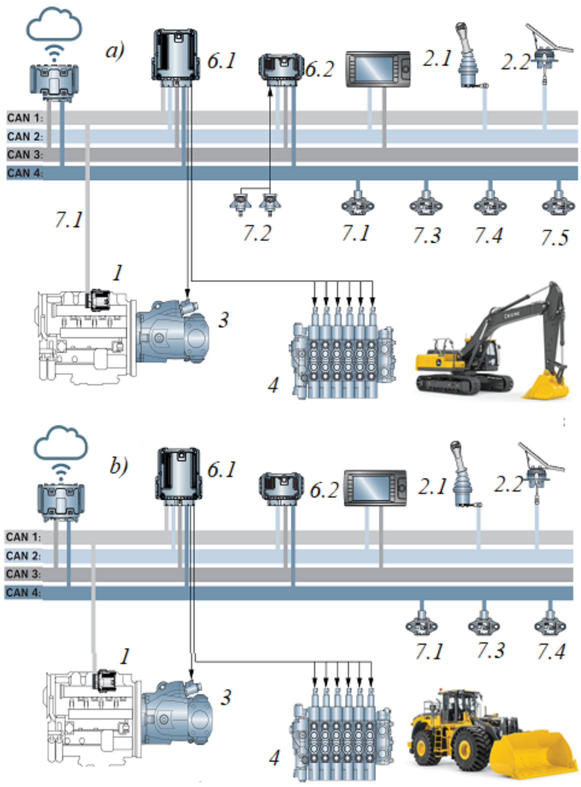

Figure 9. Systems for machine robotisation

The aforementioned sensors and potentiometers capture measured and input values, respectively. These values are processed by the microcontrollers, using the developed software, to determine the regulation signals for the hydrostatic drive system and the automation (robotisation) signals for the manipulators.

Through these processes, several operational outcomes can be achieved:

• The position and orientation of the machine's kinetic chain within the working space can be identified.

• The excavator bucket can be guided along a predetermined path at a specific angle during tasks such as leveling, digging, and large channel cleaning, through the activation of a single control joystick.

• The position of the loader's bucket or fork can be corrected to prevent spillage or load falling when lifting the boom, again with the activation of a single control joystick.

• The optimal bucket grip position can be determined after lowering the boom from the bucket's unloading position.

• The machine's stability during operation can be dynamically monitored.

• The load size caught by the tools during machine operation can be displayed on a monitor.

• Safety "virtual walls" can be established in the machine's working space, with the control system slowing or halting machine movement when the manipulator's tool is near or in contact with the virtual wall.

5 Conclusion

This study has provided an analysis of mechatronic systems in mobile machines, elucidating the structure of such systems, the control systems they necessitate, their applications in the engineering process, and the benefits they confer. Current models of diverse mobile machines are equipped with modular mechatronic control systems, designed and executed by specialized manufacturers to meet specific requirements.

Mechatronic systems, complemented by appropriate software, enable synchronized movement and manipulation, foster ecological and economical operation of the drive system, and facilitate comprehensive monitoring and optimal operator comfort in mobile machines.

This discussion has also examined various control strategies employed in mechatronic systems for mobile machines. Emphasis has been placed on how these control systems promote optimized movement, safety, and precise manipulation. Control techniques such as fuzzy logic and model predictive control have been presented as specific examples, shedding light on their respective advantages.

Further research in this field could potentially explore more advanced control techniques and their applications in different types of mobile machines. It could also delve into how machine learning and artificial intelligence can enhance the capabilities of these mechatronic systems, leading to further optimization of movement, increased safety, and more precise manipulation.

The integration of more advanced software could also be a fruitful research area, especially with regard to developing more intuitive user interfaces and automated systems for enhanced operator comfort and efficiency. The potential for mechatronic systems to contribute to the sustainable operation of mobile machines is another promising avenue for future research, particularly in light of increasing global concerns about environmental sustainability.

By continuing to advance the field of mechatronics in mobile machines, it is anticipated that significant strides will be made in enhancing the productivity, safety, and operator comfort of these machines, contributing to their broader utility in various sectors.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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Nomenclature

N_e	power of diesel engine, kW
N_h	hydraulic pump power, kW
p	pressure, MPa
Q	flow rate, $1/\mathrm{min}$
M_h	torques of the hydraulic motor, Nm
ω_h	angular velocities of the hydraulic motor, s^{-2}
F	traction force of movement of the machine, N
v	speed of movement of the machine, $\mathrm{m/s}$