

DEVELOPMENT OF DIGITAL SERVO SYSTEM EMPLOYING ADVANCED CLOSED LOOP OPERATION

A Thesis

*Submitted in partial fulfilment of the requirement for the Degree of
Master in Electrical Engineering
(Electrical Engineering Department)*

By

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DECLARATION OF ORIGINALITY AND COMPLIANCE
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I hereby declare that this thesis entitled “**Development of digital servo system employing advanced closed loop operation**” contains literature survey and original research work by the undersigned candidate, as part of his Degree of Master in Electrical Engineering. All information here have been obtained and presented in accordance with academic rules and ethical conduct. It is hereby declared that, as required by these rules and conduct, all materials and results that are not original to this work have been properly cited and referenced.

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PREFACE

The evolution of digital control systems has been a cornerstone in the development of advanced automation and robotics. One critical advancement in this domain is the use of digital servo systems, which enable precise and efficient control over mechanical movements in a variety of applications, ranging from industrial machinery to autonomous vehicles. The thesis titled "Development of Digital Servo System Employing Advanced Closed-Loop Operation" addresses this innovation, focusing on the design and implementation of a sophisticated digital servo system that leverages advanced closed-loop control for superior accuracy and responsiveness.

The primary objective of this thesis is to explore the application of a digital servo system with enhanced closed-loop operation, examining how modern control techniques, including PID control and other adaptive algorithms, can be used to achieve greater precision in position and speed control. The project investigates how closed-loop feedback enables real-time adjustments, ensuring the system's stability and adaptability in response to variable load conditions and external disturbances. Additionally, it examines how components such as microcontrollers, encoders, and motor drivers work in unison to establish a reliable control system that can meet the rigorous demands of contemporary engineering applications.

Central to this thesis is the integration of a closed-loop system with advanced digital feedback mechanisms, which contrasts with traditional open-loop systems that lack the adaptability needed in dynamic environments. By incorporating real-time feedback, this digital servo system is designed to monitor and adjust the position and speed of a motor with high accuracy, achieving improved performance metrics such as lower error margins, faster response times, and greater robustness under load variations. This research includes a comprehensive evaluation of various control algorithms, with a specific focus on proportional-integral-derivative (PID) control, which has become the industry standard for servo applications.

In a practical context, the thesis addresses the selection, calibration, and integration of hardware and software components, including the implementation of microcontrollers like Arduino, motor drivers, encoders, and other sensors. Each element plays a crucial role in enhancing the system's precision and reliability. The research methodology

encompasses both theoretical modeling and empirical testing, providing a robust framework for analyzing the system's behavior under different conditions.

Ultimately, this work contributes to the body of knowledge in digital control systems, offering insights and methodologies that are valuable to researchers, engineers, and practitioners in the fields of automation, robotics, and industrial control systems. This thesis not only highlights the technical aspects of servo system design but also underscores the importance of precise control and adaptability in achieving high-performance standards in modern engineering applications.

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CHAPTER 1

INTRODUCTION TO SERVO SYSTEMS

1.1 INTRODUCTION

A servo system is a type of control system designed to regulate the position, speed, or torque of a motor to achieve precise and responsive movement. At its core, a servo system is built around the concept of *closed-loop control*, meaning it relies on continuous feedback to adjust the motor's output and meet the desired setpoint. This feedback allows the system to detect any deviation from the target and make real-time adjustments, ensuring high accuracy and stability.

Servo systems typically consist of a servo motor, a controller, and a feedback device such as an encoder or potentiometer. The controller sends commands to the motor to achieve specific positions or speeds, while the feedback device measures the actual performance and relays it back to the controller. Any discrepancies are corrected immediately by modifying the motor's actions, often using algorithms like Proportional-Integral-Derivative (PID) control for smoother and more precise adjustment.

Widely used in applications requiring precision and speed, servo systems are integral in robotics, CNC machinery, and automated manufacturing. Their versatility and accuracy make them suitable for both simple and complex tasks, from camera focus systems to advanced robotic arms.

1.2 HISTORY AND EVOLUTION OF SERVO SYSTEMS

The **history of servo systems** spans over a century and reflects the growing demand for precise motion control in technology and industry. Initially developed for naval applications, servo systems have evolved through innovations in electronics, automation, and computer science to become critical components in modern machinery, robotics, and aerospace.

Early Beginnings (Late 19th to Early 20th Century)

The concept of a servo mechanism first emerged in the late 19th century, primarily in response to the need for precise control of heavy artillery in naval warfare. Engineers developed **basic feedback systems** to automatically adjust the orientation of guns and improve accuracy. Early systems were mechanical and hydraulic in nature, involving complex gears and levers to maintain accuracy, but they laid the foundation for servo systems by introducing the principle of feedback control.

Development of Electrical Servo Systems (1920s - 1940s)

By the 1920s, servo technology advanced with the rise of electrical and electronic systems. This era saw the introduction of **electrical servomechanisms**, where motors replaced mechanical linkages. With World War II, servo technology received significant investment as the military sought more accurate control for radar, targeting systems, and early automatic pilots. During this period, **electromagnetic servos** emerged, utilizing variable voltage and current to control motor speed and position precisely.

Rise of Feedback Control Theory (1940s - 1960s)

The mid-20th century was a period of rapid theoretical development. **Feedback control theory** became formalized, led by mathematicians and engineers like Norbert Wiener, who contributed to the field of *cybernetics*, emphasizing control and communication in systems. The **Proportional-Integral-Derivative (PID) control** algorithm emerged, allowing engineers to tune servos for greater accuracy, speed, and stability. The use of servo systems

expanded beyond military applications into industrial automation, where precision control was essential in assembly lines and manufacturing processes.

Transition to Digital Servo Systems (1970s - 1980s)

With the advent of digital electronics and microprocessors in the 1970s, servo systems transitioned from analog to **digital control**. Digital servo systems allowed for more precise and complex control strategies, as they could process data in real time and handle intricate algorithms like PID control with ease. This era marked the beginning of **programmable logic controllers (PLCs)** in servo systems, which became the backbone of automated manufacturing, robotics, and CNC (Computer Numerical Control) machinery.

Modern Servo Systems and Advanced Control (1990s - Present)

The late 20th century saw advances in **brushless DC motors**, which improved reliability and efficiency in servo applications. Coupled with the rise of **high-resolution encoders** and **advanced sensors**, servo systems gained higher accuracy and responsiveness. The integration of **field-oriented control (FOC)** and **adaptive control** techniques further enhanced servo performance, especially in complex applications like robotics, where precision and adaptability were critical.

In the 2000s, the integration of **machine learning and artificial intelligence (AI)** began influencing servo systems, enabling predictive and adaptive control that could adjust to new conditions in real time. Servo systems also became part of the **Internet of Things (IoT)**, allowing remote monitoring, diagnostics, and optimization through connected networks.

Present and Future Trends

Today, servo systems are essential in robotics, electric vehicles, industrial automation, and aerospace. With ongoing advancements in AI and IoT, servo systems are becoming more autonomous, with the ability to self-optimize and predict maintenance needs. Furthermore, **miniaturization** and **energy-efficient designs** are enabling servo systems to be implemented in more compact, lightweight, and environmentally friendly applications.

In summary, the evolution of servo systems reflects a continuous pursuit of precision, speed, and efficiency. From early mechanical feedback mechanisms to today's intelligent digital servos, these systems have transformed industrial control, automation, and robotics, setting the stage for even more adaptive, connected, and capable servo systems in the future.

1.3 IMPORTANCE AND APPLICATIONS IN MODERN AUTOMATION AND ROBOTICS

Servo systems play an essential role in modern automation and robotics due to their precision, responsiveness, and adaptability. By enabling accurate control of position, speed, and torque, servo systems allow machines to execute complex, high-precision tasks that are critical in various fields, from manufacturing and healthcare to autonomous vehicles and aerospace.

1. High Precision and Accuracy

Servo systems offer exceptional precision in controlling position and speed, crucial for tasks that demand exact movements, such as robotic surgery, semiconductor manufacturing, and high-speed assembly lines. The feedback mechanism allows servos to make real-time adjustments, ensuring minimal error and precise alignment in every operation.

2. Fast Response and High-Speed Operation

In applications requiring quick and precise movements, servo systems stand out due to their fast response times. The closed-loop control in servos helps them respond almost instantaneously to changes, making them ideal for high-speed automation systems like pick-and-place machines, conveyor belt operations, and robotic arms in manufacturing.

3. Adaptability and Flexibility

Servo systems can adapt to a wide range of applications and operating conditions. By adjusting control parameters in real time, they can handle variations in load and environmental factors, making them ideal for dynamic applications like drones, mobile robots, and automotive systems where conditions can change rapidly.

4. Energy Efficiency

Servo systems are generally energy-efficient due to their ability to deliver precise power only when and where needed, reducing overall energy consumption. This is particularly beneficial in electric vehicles, renewable energy systems, and automation processes that require sustainability.

5. Enhanced Control for Complex Tasks

Servo systems allow advanced control strategies, such as proportional-integral-derivative (PID) and model predictive control (MPC), enabling complex and multi-axis movements. This control capability is essential in robotics, where tasks like welding, painting, and intricate assembly require simultaneous coordination of multiple joints and precise path control.

Applications of Servo Systems in Automation and Robotics

1. Industrial Automation

Servo systems are integral in manufacturing, where they enable precise control of robotic arms, CNC machines, and conveyor systems. They facilitate tasks such as cutting, welding, painting, and product assembly with high repeatability, enhancing both speed and quality in production lines.

2. Robotics

In robotics, servo systems provide fine-tuned control of joints and actuators, enabling robots to perform delicate tasks like gripping, assembly, and welding. They're essential for creating humanoid robots and robotic arms that require high degrees of freedom and precision. Servos also help mobile robots in autonomous navigation and complex task execution.

3. Aerospace and Defense

Servo systems are used in aircraft and missile guidance systems to control flight surfaces, maintaining stability and precision in high-speed operations. In defense, servos play a role in targeting and weapon control systems, where accuracy and quick response are vital for mission success.

4. Automotive Applications

Modern vehicles utilize servo systems for various control tasks, such as electric power steering, braking systems, and electronic throttle control. Servo motors allow precise adjustments based on real-time feedback from sensors, enhancing safety, stability, and driver control.

5. Healthcare and Medical Devices

Servo systems are crucial in medical devices requiring precise control, such as robotic surgical tools, prosthetics, and rehabilitation equipment. They provide the accuracy needed for delicate procedures, improving patient outcomes and reducing the invasiveness of medical procedures.

6. Consumer Electronics

Servo systems are used in consumer electronics such as cameras (for autofocus and image stabilization), printers, and smart home devices. Their compact size and precision make them ideal for devices requiring responsive and low-power motion control.

7. Renewable Energy Systems

Servo systems are increasingly used in solar tracking systems to optimize the positioning of solar panels throughout the day. In wind turbines, they help control blade pitch for optimal energy capture, adapting to wind conditions for maximum efficiency.

8. Drones and Autonomous Vehicles

Servo systems enable the fine-tuned movement control required in drones and autonomous vehicles, allowing precise adjustments in direction, speed, and position. Servos play a crucial role in stabilizing flight, steering, and providing the responsiveness needed for safe autonomous navigation.

1.4 SCHEMATIC DIAGRAM OF SERVO SYSTEM

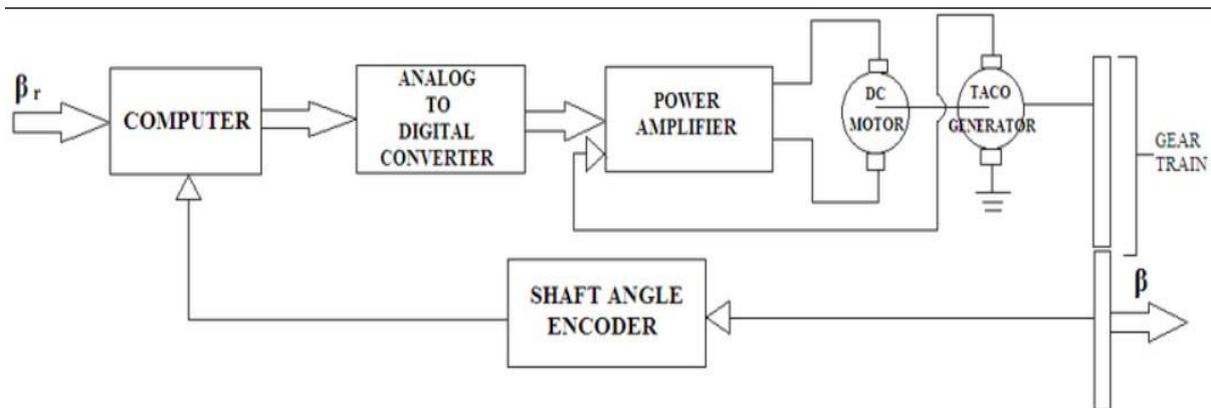


Fig 1 : schematic block of servo system

1.5 SCOPE OF THE THESIS

The scope of this thesis is broad, covering both foundational theories and practical applications in the field of advanced servo systems. By developing and implementing a digital servo system with enhanced closed-loop control, this research has the potential to improve performance standards in fields requiring precision and adaptability, setting a new benchmark in servo control technology. Through this exploration, the thesis contributes to advancing automation, robotics, and control engineering, providing valuable insights for academia and industry alike.

1.6 CONCLUSION

Servo systems have become foundational in automation and robotics, enabling a wide range of advanced applications that require precision, adaptability, and efficiency. Their role in enhancing production quality, optimizing performance, and supporting complex automation tasks highlights their importance in driving technological innovation and expanding the potential of modern robotic and automated systems.

CHAPTER 2

BASIC PRINCIPLES OF SERVO SYSTEM

2.1 CONCEPT OF FEEDBACK CONTROL

The **concept of feedback control** is fundamental to servo systems, enabling precise regulation of motion, speed, position, or torque. Feedback control works by continuously measuring the output of the system (such as the position or speed of a servo motor), comparing it to a desired setpoint, and adjusting the input to minimize any error. This closed-loop process allows for real-time corrections, ensuring the system remains stable, accurate, and responsive to changes.

Key Components of Feedback Control in Servo Systems

1. Setpoint (Desired Value)

- The setpoint is the target or desired value that the system aims to achieve. For example, this could be a specific angle, speed, or torque.

2. Sensor/Feedback Device

- Sensors, such as encoders, potentiometers, or Hall effect sensors, provide real-time data on the system's output (e.g., motor position or speed). This feedback allows the system to monitor its current state.

3. Error Calculation

- The system continuously compares the current output to the setpoint, calculating the difference, known as the **error**. Error is the signal used to determine if the system output needs adjustment. For example, if a servo motor is not at the desired position, the error signal will prompt the system to correct it.

4. Controller

- The controller, typically using algorithms like Proportional-Integral-Derivative (PID) control, processes the error and determines the necessary input adjustments to bring the output closer to the setpoint. In PID control:
 - **Proportional** control responds proportionally to the error.
 - **Integral** control addresses accumulated past errors to eliminate steady-state error.
 - **Derivative** control anticipates future error based on the rate of change.

5. Actuator (Servo Motor)

- The actuator, usually a motor, receives commands from the controller to adjust its output. For instance, if the motor is below the desired speed, the controller increases power to reach the target.

6. Correction and Stabilization

- This cycle of measuring, calculating error, adjusting input, and stabilizing repeats continuously. As the system approaches the setpoint, the error reduces, and the adjustments become smaller, stabilizing the system at the desired output.

Working Principle of Feedback Control in Servo Systems

In a **closed-loop servo system**, the feedback mechanism allows the system to self-correct based on real-time data. Here's a step-by-step example of how it operates:

1. The system receives a command to move the servo motor to a specific position.
2. The feedback device (e.g., encoder) measures the current position and sends this data back to the controller.
3. The controller compares the measured position to the desired position (setpoint) and calculates the error.
4. Based on the error, the controller adjusts the motor's input, either increasing or decreasing power or direction to minimize the error.
5. This process continues until the error is minimized to a near-zero value, meaning the motor has reached the setpoint.

Advantages of Feedback Control in Servo Systems

- **High Precision and Accuracy:** Feedback control allows servo systems to achieve precise control, which is essential in applications like robotics, CNC machining, and aerospace.
- **Dynamic Responsiveness:** The system can respond to changes, disturbances, or load variations, maintaining stability in dynamic environments.
- **Improved Stability:** Feedback control helps maintain system stability, preventing oscillations or overshooting in response to input changes.

- **Reduced Steady-State Error:** Controllers like PID reduce or eliminate steady-state error, enhancing overall performance.

Applications of Feedback Control in Servo Systems

Servo systems with feedback control are essential in fields requiring precision and adaptability:

- **Robotics:** Ensures accurate positioning of robotic arms and joints.
- **Industrial Automation:** Maintains consistent quality in tasks like welding, cutting, and assembly.
- **Aerospace and Defense:** Enables stable flight control and precise missile guidance.
- **Medical Devices:** Facilitates precise control in robotic surgery and prosthetics.

2.2 OPEN LOOP VS CLOSED LOOP CONTROL SYSTEMS

Open-Loop vs. Closed-Loop Control Systems in servo systems represent two fundamentally different approaches to controlling motion and position. Understanding the differences between these systems is essential for selecting the right control method in applications that require precision, reliability, and adaptability.

1. Open-Loop Control System in Servo Systems

In an open-loop control system, the controller sends a command to the actuator (e.g., a servo motor) without any feedback mechanism to verify if the desired output has been achieved. This control approach operates based on a pre-defined input, without considering the system's actual response or performance.

Characteristics of Open-Loop Control:

- **No Feedback:** There's no feedback from the output back to the controller, meaning the system does not self-correct.
- **Simple Design:** Open-loop systems are generally simpler and cost-effective as they require fewer components.

- **No Error Correction:** Since there's no feedback, open-loop systems cannot adjust for errors, external disturbances, or load changes.
- **Limited Accuracy:** Open-loop systems are prone to inaccuracies due to external factors (e.g., load changes or environmental conditions).

Applications:

Open-loop control is commonly used in applications where high precision and adaptability are not critical. Examples include basic positioning systems, certain low-cost hobbyist robots, and simple timers or motors operating at constant speeds.

Example:

In an open-loop servo system, a motor may be commanded to move to a position based on a specified input voltage or signal, without measuring if the motor actually reaches the intended position. Thus, if external disturbances or load changes occur, the motor's position could differ from the expected outcome.

2. Closed-Loop Control System in Servo Systems

In a closed-loop control system, also known as a feedback control system, the system continuously monitors the output through feedback devices (such as encoders or sensors) and compares it to the desired setpoint. Any difference (or error) between the actual output and the setpoint prompts the controller to adjust the input until the error is minimized.

Characteristics of Closed-Loop Control:

- **Real-Time Feedback:** Closed-loop systems use sensors to continuously monitor the system's output and provide feedback.
- **Error Correction:** The system self-corrects by adjusting input to reduce any detected errors.
- **Enhanced Accuracy and Precision:** Closed-loop control enables precise adjustments, making it suitable for applications requiring high accuracy.
- **Adaptability:** Closed-loop systems can adapt to changes in load, disturbances, and other external factors, maintaining desired performance.

Applications:

Closed-loop control is essential in applications requiring precision, stability, and real-time adaptability, such as robotics, CNC machinery, aerospace, and industrial automation.

Example:

In a closed-loop servo system, if a motor is commanded to move to a specific position, the feedback device will monitor the actual position and relay it back to the controller. If there's any discrepancy between the actual and desired positions, the controller adjusts the motor's input until the error is minimized, ensuring that the motor accurately reaches and maintains the target position.

Comparison: Open-Loop vs. Closed-Loop Control in Servo Systems

Feature	Open-Loop Control	Closed-Loop Control
Feedback	None	Real-time feedback from sensors
Error Correction	No error correction	Actively corrects errors
System Complexity	Simple, fewer components	More complex with additional sensors
Accuracy and Precision	Limited due to lack of feedback	High precision due to continuous feedback
Adaptability	Poor; cannot adjust to disturbances	High; adapts to load and external factors
Cost	Lower due to simpler design	Higher due to additional components
Applications	Low-precision tasks	High-precision, critical applications

Advantages and Limitations

- Advantages of Open-Loop Control:
 - Simplicity and lower cost make it suitable for basic, low-precision tasks.
 - Easier to design and implement, with fewer components needed.
- Limitations of Open-Loop Control:
 - Inability to self-correct makes it unsuitable for precision tasks.
 - Poor performance under varying load or external disturbances.
- Advantages of Closed-Loop Control:
 - **High accuracy and responsiveness make it ideal for precision applications.**
 - **Self-correction allows it to maintain stability and adapt to changes.**
- Limitations of Closed-Loop Control:
 - **More complex and costly due to additional components and feedback systems.**
 - **Requires more tuning and calibration to achieve optimal performance.**

2.3 ROLE OF SERVO SYSTEM IN PRECISION CONTROL

Servo systems play a pivotal role in precision control, which is essential for applications where accuracy, responsiveness, and stability are paramount. By utilizing advanced feedback mechanisms and control algorithms, servo systems ensure that desired positions, speeds, and torques are achieved with minimal error. This precision control capability is foundational in industries such as robotics, aerospace, manufacturing, and medical devices.

Key Roles of Servo Systems in Precision Control

1. Accurate Positioning

- Servo systems excel at precise positioning, enabling devices and machinery to move to exact locations with minimal error. Through continuous feedback, the system monitors the current position and corrects any deviation from the target position in real-time.
- Applications like robotic arms, CNC machines, and assembly line automation rely heavily on servo systems to achieve micron-level positioning accuracy, ensuring high-quality production standards.

2. Stable Speed Control

- Precise speed control is essential in tasks where constant motion is required, such as conveyor systems, electric vehicles, and robotic grippers. Servo systems maintain consistent speeds by adjusting input power in response to load variations or disturbances, preventing fluctuations.
- This stability is crucial in applications like textile machinery, where uniform speed ensures product quality and consistency, and in robotics, where stable motion aids in safe and reliable operation.

3. Dynamic Responsiveness

- Servo systems are designed to respond quickly to changing commands or external forces. Using feedback loops and advanced algorithms like PID (Proportional-Integral-Derivative) control, they can adapt in real-time to ensure minimal lag and rapid adjustments.
- In surgical robots and aerospace controls, this quick responsiveness enables precise control of delicate and complex operations, enhancing both safety and effectiveness.

4. Error Minimization and Correction

- With feedback control, servo systems continuously monitor the actual output (e.g., position or speed) against the desired setpoint, allowing them to detect and correct any discrepancies immediately. This closed-loop control minimizes errors, especially in high-precision environments.

- For instance, in semiconductor manufacturing, servo systems ensure that wafers are positioned with nanometer precision, reducing the risk of defects caused by positioning errors.

5. Controlled Torque for Variable Loads

- Servo systems can manage torque precisely, which is particularly useful when operating under variable loads. By adjusting torque in response to feedback, they maintain stability and control without losing accuracy.
- In electric vehicles and robotic arms, torque control is crucial for maintaining smooth and stable operation, especially when lifting heavy or delicate objects.

6. Flexibility in Multi-Axis Coordination

- **Servo systems can synchronize multiple axes with high accuracy, which is essential in complex systems like 3D printers, robotic manipulators, and CNC machines. By coordinating the movements of multiple servos, the system ensures that each axis operates precisely, producing smooth, coordinated motion.**
- **In robotic welding, for example, multi-axis servo control allows for accurate and repeatable welding paths, even in complex geometries, thereby improving quality and reducing rework.**

7. Enhanced Repeatability

- **Precision control isn't just about hitting the target once; it's about doing it consistently. Servo systems provide high repeatability, allowing machines to perform the same operation with the same level of accuracy each time.**
- **This feature is crucial in automated manufacturing, where repeated precision in tasks like assembly, drilling, and cutting ensures uniformity across products, enhancing quality control.**

Applications Highlighting the Role of Servo Systems in Precision Control

- **Medical Devices:** In robotic surgery, servo systems allow for precise control of surgical tools, enabling highly controlled and minimally invasive procedures. The servo system's precision ensures accuracy and reduces the risk of error.
- **Aerospace and Defense:** In aircraft and missile guidance systems, servo systems manage precise control of flight surfaces and weapon targeting. This precision is vital for maintaining stability in high-speed, high-stakes environments.
- **Automated Manufacturing:** Servo systems enable high-speed, precise assembly, welding, and material handling in automated production lines. This precision improves throughput and reduces waste, resulting in higher quality products.
- **Robotics:** For robotic arms and mobile robots, servo systems provide the precise movement needed to manipulate objects, navigate spaces, and perform tasks requiring fine motor control.
- **Optics and Imaging:** In applications like autofocus in cameras and telescopes, servo systems control the movement of lenses to achieve sharp focus, ensuring high-quality imaging.

2.4 CONCLUSION

Feedback control is the core principle enabling servo systems to achieve reliable, precise, and stable performance in a wide range of applications. By continuously monitoring and adjusting output based on real-time feedback, servo systems maintain accuracy and respond effectively to varying demands. This ability to self-correct makes feedback control essential for modern automation and robotic systems, where precision is critical.

In servo systems, open-loop control is best suited for simpler, low-accuracy tasks where real-time adjustment isn't critical, while closed-loop control is essential in applications demanding high precision, adaptability, and stability. Closed-loop systems provide significant advantages in modern automation, robotics, and high-performance machinery, making them the preferred choice in complex and dynamic environments.

The role of servo systems in precision control is central to the advancements in automation, robotics, and high-tech industries. By ensuring accuracy, stability, and responsiveness, servo systems enable precise control in complex tasks and demanding environments. They help achieve consistent quality, enhance system efficiency, and enable innovations across fields that require rigorous control standards, making them indispensable for modern precision applications.

CHAPTER 3

TYPES OF SERVO SYSTEMS

3.1 AC VS DC SERVO SYSTEMS

AC vs. DC Servo Systems are two types of servo motor systems that differ primarily in how they operate and are applied. Both types play a key role in precision control and are used in a variety of applications, but each has distinct characteristics, advantages, and drawbacks.

Overview of AC and DC Servo Systems

Feature	AC Servo Systems	DC Servo Systems
Power Source	Alternating Current (AC)	Direct Current (DC)
Motor Type	Synchronous or Induction motor	Brushed or Brushless DC

Feature	AC Servo Systems	DC Servo Systems
Control Complexity	More complex control circuitry	Simpler control circuitry
Efficiency	Higher efficiency at higher speeds	Efficient at low to moderate speeds
Torque Characteristics	High torque at higher speeds	High torque at low speeds
Maintenance	Generally lower due to lack of brushes	Higher maintenance in brushed types due to brushes
Applications	High-precision, high-speed applications (e.g., robotics, CNC machines)	Low to moderate speed applications (e.g., small robotics, position control)
Cost	Typically more expensive	Generally more affordable
Durability	Longer lifespan, robust in harsh environments	Moderate lifespan, sensitive to load changes

AC Servo Systems

AC servo motors are driven by alternating current and are typically of the synchronous or induction type. They're known for high-speed applications and are often used in more demanding environments.

- Advantages:
 - Capable of operating at high speeds with minimal losses, making them ideal for high-speed and high-precision tasks.
 - Lower maintenance due to the absence of brushes in synchronous or induction motors.
 - Durable and reliable in harsh or demanding industrial conditions.
- Disadvantages:
 - Control systems are more complex and costly due to the need for specialized drives and circuitry.
 - Generally higher initial cost due to motor complexity.
- Applications: Used in robotics, CNC machines, factory automation, and aerospace applications requiring high speed, precision, and endurance.

DC Servo Systems

DC servo motors operate on direct current and are generally simpler in construction. They come in two types: brushed and brushless DC motors. DC servo motors are preferred for applications requiring steady torque at low to moderate speeds.

- Advantages:
 - Simple control circuitry makes them easier to operate and more cost-effective for basic applications.
 - High starting torque, making them ideal for applications needing quick, responsive movements at low speeds.
 - Brushless DC servos (BLDC) offer a longer lifespan and require less maintenance than brushed types.
- Disadvantages:
 - Brushed DC servos require regular maintenance due to brush wear, which limits their lifespan and performance in some applications.

- Less efficient at high speeds compared to AC servo motors.
- Applications: Used in low to moderate-speed applications such as small robotics, conveyor systems, servo-controlled valves, and other positioning applications.

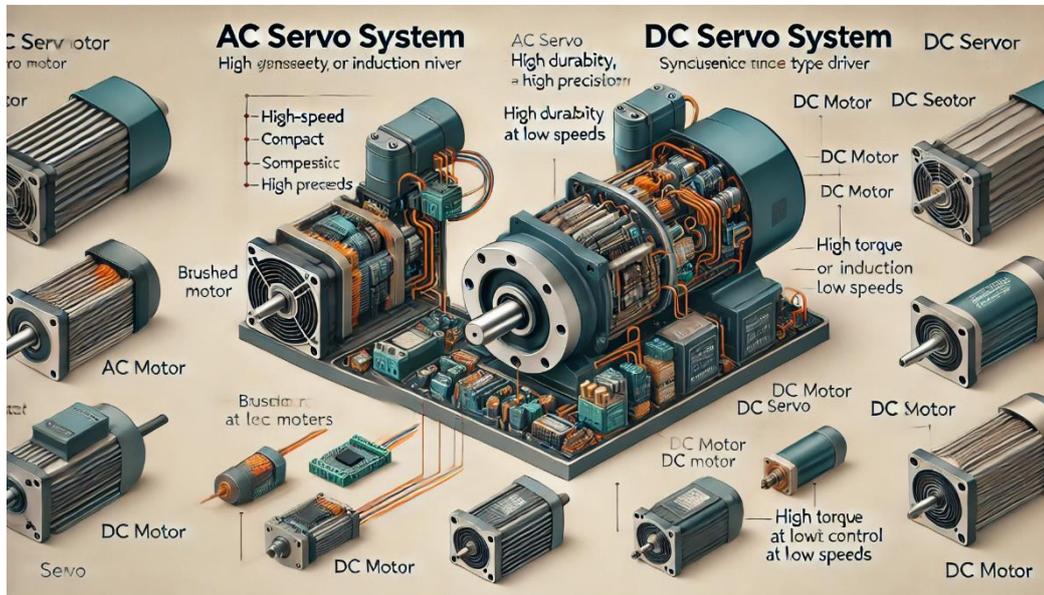


Fig 2 : Compariosn of AC and DC servo system

3.2 ANALOG AND DIGITAL SERVO SYSTEMS

Analog and Digital Servo Systems are two types of servo control systems that differ in how they process and transmit control signals to achieve desired movement. Each has distinct characteristics, advantages, and specific applications, and the choice between them often depends on the precision and response speed required.

Overview of Analog vs. Digital Servo Systems

Feature	Analog Servo System	Digital Servo System
Signal Type	Continuous, pulse-width modulated (PWM) signal	High-frequency pulse signals (often with PWM)
Response Time	Slower, with gradual response	Faster, with quicker

Feature	Analog Servo System	Digital Servo System
		response and more precise control
Frequency	Low-frequency signal, typically 50-60 Hz	High-frequency signal, often up to 300 Hz or higher
Control Precision	Lower, due to slower processing and limited accuracy	Higher, due to faster processing and precise updates
Torque Holding power	Lower holding power when stationary	Higher holding power and torque, even at standstill
Power Consumption	Generally lower, conserving energy	Higher power consumption due to more frequent updates
Cost	Typically more affordable	Higher cost due to more complex electronics
Applications	Basic applications like hobby-grade RC cars	High-performance tasks in robotics, CNC, and drones

Analog Servo Systems

Analog servos operate by receiving a continuous PWM signal, which directly controls the motor. The width of the PWM signal correlates to the position or speed of the servo.

Characteristics:

- **Signal Processing:** An analog servo receives one pulse about every 20 milliseconds. This lower frequency means it responds slower to input changes, making it less suitable for applications requiring high-speed adjustments.

- **Torque:** Analog servos typically produce lower torque and have less holding power at a stationary position, as they receive fewer signals to correct their position.
- **Power Efficiency:** Since it processes fewer signals, an analog servo consumes less power, making it more efficient for low-energy applications.

Applications:

Analog servos are commonly found in applications where high-speed, precise responses aren't critical. They are often used in:

- Hobby-grade remote-controlled (RC) vehicles
- Model airplanes
- Simple robotic arms

Digital Servo Systems

Digital servos utilize a microprocessor that processes high-frequency pulses. This allows them to make rapid adjustments, providing faster response times and greater accuracy.

Characteristics:

- **Signal Processing:** Digital servos receive signals at a much higher frequency, often up to 300 pulses per second or more, enabling them to react quickly to input changes. The high-frequency signal allows for precise and rapid position adjustments.
- **Torque:** Digital servos maintain higher torque and holding power even when stationary, as they receive constant, frequent updates to correct for any positional drift.
- **Performance and Precision:** Digital servos achieve precise control and rapid response, making them ideal for high-performance applications that require stability and accuracy.

Applications:

Due to their fast response and precise control, digital servos are preferred in advanced applications such as:

- Robotics and drones

- Industrial automation systems
- High-precision CNC machinery
- High-end RC vehicles and aircraft

Comparison: Analog vs. Digital Servo Systems

Feature	Analog Servo	Digital Servo
Response Speed	Slower, due to low-frequency signal	Faster, with high-frequency signal processing
Holding Torque	Lower torque at stationary positions	Higher holding torque, even at standstill
Control Precision	Limited accuracy and gradual adjustments	High precision and rapid adjustments
Applications	Basic or hobby-grade applications	High-performance, industrial, and precision tasks

Advantages and Limitations

- **Advantages of Analog Servos:**
 - Cost-effective, making them ideal for simpler or budget-sensitive projects.
 - Lower power consumption, beneficial for battery-operated devices.
 - Suitable for applications where high speed and precision are not critical.
- **Limitations of Analog Servos:**
 - Slower response time due to lower signal frequency.
 - Lower holding torque and less stability in stationary positions.
 - Limited control precision, making them less ideal for complex tasks.
- **Advantages of Digital Servos:**
 - High response speed and precision due to high-frequency signal processing.
 - Increased holding torque, providing better stability and control.

- Ideal for applications requiring high accuracy and fast adjustments.
- **Limitations of Digital Servos:**
 - Higher cost due to complex electronics and faster processing.
 - Increased power consumption, which may reduce battery life in mobile applications.

3.3 LINEAR VS ROTARY SERVO SYSTEM

Linear vs. Rotary Servo Systems represent two distinct types of servo systems, each designed to fulfill specific motion control requirements. The primary difference lies in the type of movement they generate: **linear** servos provide straight-line motion, while **rotary** servos provide circular or rotational motion. These differences make each type suited to particular applications in fields like robotics, automation, and manufacturing.

Overview of Linear and Rotary Servo Systems

Feature	Linear Servo System	Rotary Servo System
Motion Type	Linear (straight-line)	Rotary (circular or rotational)
Primary Use	Applications requiring linear positioning	Applications requiring angular positioning
Common Actuator Type	Linear actuator or rod-style servo	Traditional rotary motor
Precision	High precision for straight-line positioning	High precision for angular positioning
Space Efficiency	Typically requires more space for stroke length	Compact design, suitable for smaller spaces
Applications	CNC cutting machines, linear actuators	Robotics, conveyor belts, automated machinery

Feature	Linear Servo System	Rotary Servo System
Examples	Automated doors, medical devices, sliding RC cars, drones, robotic systems	arms

Linear Servo Systems

Linear servos convert rotational motion into straight-line motion. These servos often use a lead screw, ball screw, or linear actuator mechanism to achieve precise linear positioning.

Characteristics:

- **Movement:** Provides a straight-line motion along a fixed path, ideal for applications requiring linear displacement.
- **Design:** Usually bulkier due to the need for components like lead screws or actuator rods.
- **Precision:** Offers high precision in linear positioning and can maintain consistent speed and accuracy over a specific stroke length.

Applications:

- **CNC Machines:** Linear servos control the straight-line movements required in CNC machining for precise cutting, drilling, and shaping.
 - **Medical Devices:** Linear actuators in medical devices provide precise, repeatable linear motion in equipment like imaging devices.
 - **Automation:** Used in applications such as automated sliding doors, conveyor systems, and packaging machinery.
-

Rotary Servo Systems

Rotary servos provide rotational or angular motion, making them ideal for applications that require circular movement, such as rotating parts or components. They are the more traditional and commonly used servo type.

Characteristics:

- **Movement:** Provides circular or rotational motion within a specified range (e.g., 0-180 degrees or continuous rotation).
- **Design:** Compact, with most components contained within a single motor unit, making it space-efficient.
- **Precision:** High precision in rotational positioning, making them suitable for applications that require consistent angular displacement.

Applications:

- **Robotics:** Rotary servos control the angular motion in robotic arms, joints, and other robotic mechanisms.
- **Automated Machinery:** In conveyor systems, rotary servos drive the rotating belts or wheels.
- **RC and Drones:** Rotary servos provide precise angular control in remote-controlled vehicles, drones, and other hobbyist devices.

Comparison: Linear vs. Rotary Servo Systems

Feature	Linear Servo	Rotary Servo
Motion Type	Straight-line	Circular or angular
Design Complexity	Often requires additional components (e.g., lead screws)	Compact, with integrated components
Control Precision	High precision for linear displacement	High precision for angular movement
Applications	CNC machines, medical devices, conveyor systems	Robotics, automated machinery, RC

Feature

Linear Servo

Rotary Servo

vehicles

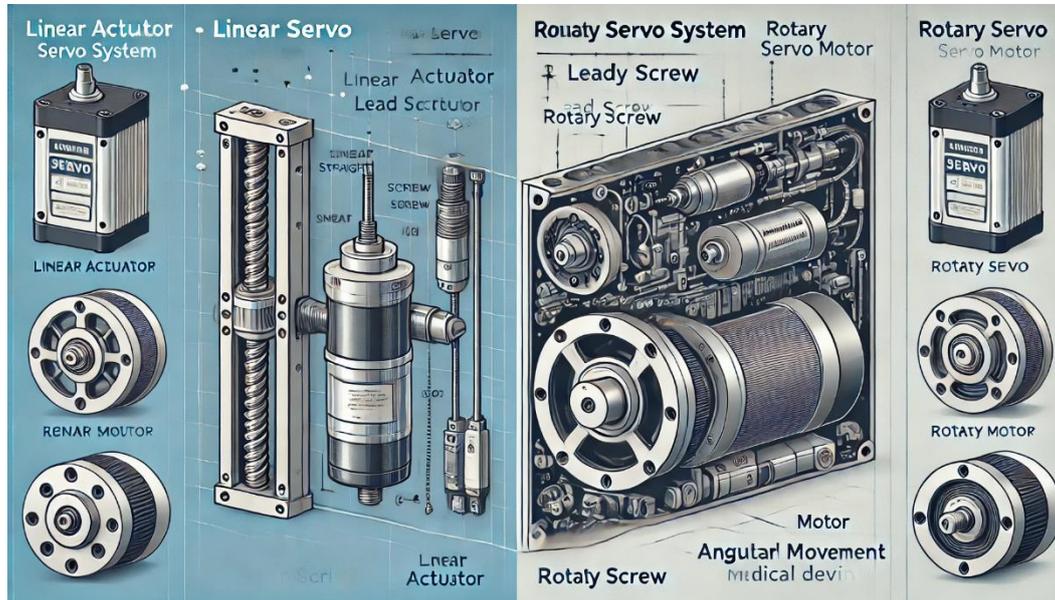


Fig 3 : Linear Vs Rotary Servo System

CHAPTER 4

COMPONENTS OF SERVO SYSTEM

4.1 SERVO MOTORS (DC , AC OR STEPPER MOTORS)

Servo motors come in different types based on their power source and design, each offering distinct advantages suited for specific applications. Here's an overview of **DC, AC, and Stepper Servo Motors**, along with an explanation of each type.

4.1.1 DC SERVO MOTOR

DC servo motors are driven by direct current and are known for their simplicity and ease of control. They're often used in applications where quick response and control over low-speed torque are important.

Characteristics:

- **Power Source:** Operates on direct current (DC).
- **Control:** Easier to control with simple circuitry.

- **Torque:** Provides high torque at low speeds.
- **Maintenance:** Brushed DC motors require regular maintenance, while brushless DC motors offer longer life with less maintenance.

Applications:

- Used in small robotics, conveyor belts, and low to moderate-speed applications.



Fig 4 : DC SERVO MOTOR

4.1.2 AC SERVO MOTORS

AC servo motors run on alternating current and are generally used in high-precision applications that require fast and accurate responses. They're preferred for high-speed applications due to their efficiency.

Characteristics:

- **Power Source:** Operates on alternating current (AC).
- **Efficiency:** High efficiency at high speeds, making them suitable for demanding applications.
- **Durability:** Typically more robust and lower maintenance due to lack of brushes.
- **Control Complexity:** Requires more complex control circuits than DC motors.

Applications:

- Ideal for industrial automation, CNC machines, and robotics where high speed and precision are needed.



Fig 5 : AC SERVO MOTOR

4.1.3 STEPPER MOTOR

Stepper motors provide precise control by moving in fixed increments or "steps," making them ideal for applications requiring accurate positioning without the need for a feedback loop.

Characteristics:

- **Control:** Moves in precise, fixed steps; no feedback loop is typically required.
- **Positioning:** Known for high accuracy in positioning.
- **Torque:** Provides high torque at low speeds.
- **Power Source:** Can be driven by DC but typically requires a specialized driver for controlled stepping.

Applications:

- Used in 3D printers, CNC machines, and applications requiring precise incremental motion.



Fig 6 : STEPPER MOTOR

4.2 MICROCONTROLLERS

Microcontrollers are small computing devices that are widely used in embedded systems, providing an all-in-one solution with a processor, memory, and I/O peripherals. They are popular in applications where automated control and processing are required, from home appliances to industrial machines and robotics. One of the most widely recognized microcontrollers is the **Arduino Uno**, a beginner-friendly, versatile board that has become popular for prototyping and educational purposes.

Overview of Arduino Uno

The **Arduino Uno** is an open-source microcontroller board based on the **ATmega328P** microcontroller. It offers a simple platform to interface with various sensors, actuators, and other hardware through coding, making it an ideal choice for both hobbyists and engineers.

Key Features of Arduino Uno

1. **Processor:** ATmega328P, an 8-bit microcontroller with a clock speed of 16 MHz.
2. **Memory:**
 - Flash Memory: 32 KB for storing code.
 - SRAM: 2 KB for variables and runtime data.

- EEPROM: 1 KB for long-term storage (non-volatile).
- 3. **Power Supply:** Operates on either a USB connection (5V) or an external power supply (7-12V).
- 4. **I/O Pins:**
 - 14 digital pins (6 of which can provide PWM output).
 - 6 analog input pins for reading sensors.
- 5. **Communication:** Built-in support for serial communication (UART), along with I2C and SPI, which allows easy interfacing with sensors, displays, and other microcontrollers.
- 6. **Programming:** C/C++ based programming environment via the Arduino IDE.

Example Applications of Arduino Uno

1. Temperature Monitoring and Control System

- **Description:** Using a temperature sensor like the **DHT11** or **LM35**, Arduino Uno can measure ambient temperature and humidity.
- **Working:** The microcontroller reads data from the sensor through one of its analog pins and can be programmed to trigger actions, such as turning on a fan or sending an alert if the temperature exceeds a set threshold.
- **Components:**
 - Temperature sensor (DHT11 or LM35).
 - Relay module to control a fan or other appliances.
 - Display module, such as an LCD, to show temperature readings.

2. Obstacle-Avoiding Robot

- **Description:** Arduino Uno can serve as the brain of an obstacle-avoiding robot, which uses ultrasonic sensors to detect and navigate around obstacles.
- **Working:** The Arduino reads data from an **ultrasonic sensor** to measure the distance from objects. Based on this information, it controls motors through an **L298N motor driver** to change direction whenever it detects an obstacle.
- **Components:**
 - Ultrasonic sensor (HC-SR04).
 - L298N motor driver module to control DC motors.
 - DC motors for movement.

3. Home Automation System

- **Description:** Arduino Uno can be used to create a basic home automation system to control appliances remotely.

- **Working:** With the addition of a **Bluetooth module (HC-05)** or a **Wi-Fi module (ESP8266)**, the Arduino can receive commands from a smartphone app. These commands can control lights, fans, or other appliances via relays connected to the Arduino's digital pins.
- **Components:**
 - Relay module to switch household appliances.
 - Bluetooth or Wi-Fi module for wireless communication.
 - Smartphone or computer interface for sending commands.

4. Weather Station

- **Description:** A weather station can monitor temperature, humidity, atmospheric pressure, and even sunlight using various sensors.
- **Working:** Using sensors like **BMP180** for barometric pressure, **DHT11** for temperature and humidity, and an **LDR** (Light Dependent Resistor) for light intensity, the Arduino Uno collects and logs environmental data. This data can be displayed on an LCD screen or sent wirelessly to a computer.
- **Components:**
 - BMP180 for barometric pressure.
 - DHT11 for temperature and humidity.
 - LDR for light intensity.
 - LCD display to show readings.

Advantages of Using Arduino Uno

1. **Ease of Use:** The Arduino environment is simple, and its extensive documentation and community support make it easy to learn.
2. **Open-Source:** Both the hardware and software are open-source, allowing for easy customization and adaptation.
3. **Cost-Effective:** Arduino Uno and its components are relatively affordable.
4. **Flexible and Expandable:** A variety of shields and modules can be connected to expand its functionality.
5. **Cross-Platform:** The Arduino IDE is compatible with Windows, macOS, and Linux, making it accessible to a wide range of users.

Comparison with Other Microcontrollers

While the Arduino Uno is great for prototyping, there are other microcontrollers (e.g., **ESP32**, **STM32**, **Raspberry Pi Pico**) that may offer more power, memory, or specific

features like Wi-Fi and Bluetooth. However, Arduino's simplicity and flexibility make it a popular choice for both beginner projects and advanced embedded applications.



Fig 7 : ARDUINO UNO

4.3 FEEDBACK DEVICES (HALL EFFECT ENCODER)

A **Hall Effect Encoder** is a type of encoder that uses the Hall effect principle to measure and detect rotational or linear movement. Hall Effect Encoders are widely used in applications that require accurate position and speed measurements, especially in environments where optical encoders may not perform well due to dust, moisture, or temperature extremes.

Understanding the Hall Effect

The **Hall effect** is a phenomenon where a voltage (known as the Hall voltage) is generated perpendicular to an electric current in a conductor when it is placed in a magnetic field. This voltage can be measured and used to detect the presence and position of a magnetic field, which forms the basis for Hall effect sensors.

How a Hall Effect Encoder Works

In a Hall Effect Encoder, a **magnet** is attached to a rotating shaft, and **Hall effect sensors** are positioned to detect the magnetic field as it changes with the rotation of the shaft. Each Hall effect sensor generates a voltage signal when it detects a change in the magnetic field, which can be processed to determine rotational position, direction, and speed.

Components of a Hall Effect Encoder:

1. **Magnetic Wheel or Disk:** The magnet is usually embedded in or attached to a wheel or disk that rotates along with the motor's shaft.
2. **Hall Effect Sensors:** Small devices that generate voltage when they detect changes in the magnetic field.
3. **Signal Processing Circuitry:** This circuitry processes the signals from the sensors and provides output signals that correspond to the position or speed of the rotation.

Types of Hall Effect Encoders

1. **Incremental Hall Effect Encoders:** These encoders generate a series of pulses as the magnetic wheel rotates. The pulses can be counted to calculate the relative position, speed, and direction.
 - **Quadrature Encoders:** Use two Hall sensors (A and B channels) placed 90 degrees apart to generate two pulse trains. By comparing these pulse trains, the direction of rotation can also be determined.
2. **Absolute Hall Effect Encoders:** These provide a unique position value for each position of the rotating shaft, allowing the exact angle or position to be known even after power loss. Absolute encoders typically have multiple Hall sensors positioned in a specific pattern to achieve absolute position encoding.

Advantages of Hall Effect Encoders

1. **Robustness:** Hall Effect Encoders are less susceptible to environmental contaminants like dust, oil, and moisture, which makes them suitable for industrial environments.
2. **Non-Contact Sensing:** The Hall effect sensor does not need to physically touch the magnet, which reduces wear and tear, resulting in a longer lifespan.
3. **Wide Range of Applications:** These encoders work well across a range of speeds and offer good accuracy in low to medium-speed applications.
4. **Magnetic Field Immunity:** Hall effect sensors are generally immune to stray magnetic fields, which can make them more reliable in noisy environments.

Applications of Hall Effect Encoders

- **DC and Servo Motors:** Hall Effect Encoders are commonly used in closed-loop control systems to provide feedback on motor position and speed.
- **Automotive Applications:** Used in throttle position sensors, anti-lock braking systems (ABS), and other rotational sensing applications.

- **Robotics:** Hall Effect Encoders are used in robotics for precise movement control, especially in joints and rotating parts.
- **Industrial Automation:** They provide precise position feedback for conveyor belts, packaging machines, and other automated systems.

Key Parameters in Hall Effect Encoders

1. **Resolution:** The number of pulses per revolution (PPR) or counts per revolution (CPR) the encoder can produce. Higher resolution allows for more precise control and measurement.
2. **Accuracy:** The degree of error in measuring the position or speed, often affected by the alignment of the magnet and sensors.
3. **Speed Range:** Hall Effect Encoders can operate across a broad range of speeds, but their maximum speed rating depends on the type of sensor and signal processing circuit.
4. **Output Signals:** Incremental Hall Effect Encoders typically output pulse signals, while absolute encoders may output a digital code representing the angle of rotation.

Example: Hall Effect Encoder with an Arduino

1. **Setup:** Attach the Hall Effect Encoder to a DC motor's shaft, with the Hall sensors positioned to detect changes in the magnetic field.
2. **Programming:** Using an Arduino, the encoder's output signals (e.g., A and B channels in an incremental encoder) can be read to calculate the motor's speed, position, and direction.
3. **PID Control:** In a closed-loop control system, the encoder's feedback is used in a **PID controller** algorithm on the Arduino to adjust the motor speed, ensuring precise control.

4.3.1 OE-28 HALL EFFECT ENCODER

The **OE-28 Hall Effect Encoder** is a compact, robust encoder model used primarily in applications requiring precision and durability in feedback systems. Like other Hall effect

encoders, it utilizes the Hall effect principle, providing a digital output based on magnetic field variations, which can be used to calculate the rotational position and speed of a motor shaft. This model is well-suited for industrial, automotive, and robotic applications due to its robust build and reliable performance.

Key Features of the OE-28 Hall Effect Encoder

1. **Resolution and Precision:** The OE-28 encoder is known for its high resolution, typically measured in **pulses per revolution (PPR)**. This high PPR capability provides precise feedback, making it ideal for closed-loop control systems requiring accurate position and speed measurement.
2. **Incremental Encoder:** The OE-28 is generally an incremental encoder, meaning it outputs a specific number of pulses per rotation without giving an absolute position value. However, by counting pulses and interpreting the quadrature signals, you can achieve accurate tracking of movement, speed, and direction.
3. **Quadrature Output:** It usually comes with two output channels, A and B, which are set 90 degrees out of phase. This quadrature configuration allows for:
 - **Direction Detection:** By comparing the order of pulses in channels A and B, the encoder can determine the direction of rotation.
 - **Increased Resolution:** Using both channels allows for higher resolution as each pulse can represent a quarter-step, enabling precise position measurement.
4. **Magnetic Immunity:** Being a Hall effect-based encoder, the OE-28 is resilient to dust, dirt, oil, and moisture, making it suitable for harsh environments where optical encoders might fail. It also withstands various operating temperatures and is immune to external light interference.
5. **Output Signal:** The encoder provides **TTL (Transistor-Transistor Logic)** output signals, which are compatible with digital circuits, including microcontrollers like Arduino, PLCs, and industrial controllers. TTL signals are fast and reliable, ensuring quick response times, which is important in real-time applications.

Applications of the OE-28 Hall Effect Encoder

- **Robotic Motion Control:** The OE-28 encoder is commonly used in robotics for controlling precise movements of joints and rotational parts.
- **Automotive and Aerospace:** Suitable for applications that require high durability, such as throttle control, steering systems, and anti-lock braking systems.
- **Industrial Automation:** Used in conveyor systems, assembly lines, and other automated equipment requiring speed and position control.

Advantages of the OE-28 Hall Effect Encoder

1. **Reliability:** The OE-28 offers long operational life due to its non-contact sensing method, which eliminates mechanical wear, unlike mechanical encoders.
2. **Environmental Robustness:** Performs well in dusty, oily, or wet environments, which are common in industrial settings.
3. **Compact Design:** Its compact size allows it to fit into smaller machines, making it versatile for space-constrained applications.

Using the OE-28 Hall Effect Encoder with an Arduino

To use the OE-28 with an Arduino in a typical control application, you would connect the encoder's channels A and B to two digital pins on the Arduino and write code to read the pulses for speed and position tracking. The Arduino can then use this feedback in a **PID control algorithm** to adjust motor speed or maintain position accuracy.



Fig 8: HALL EFFECT ENCODER

4.4 POWER SUPPLY AND DRIVE CIRCUITRY

The **power supply and drive circuitry** are fundamental components of a servo system, providing the necessary energy and control to operate the servo motor with precision. Both elements are critical in delivering consistent, reliable performance, particularly in applications where precise positioning, speed, and torque control are essential.

1. Power Supply in Servo Systems

The **power supply** provides the electrical energy required to drive the servo motor. Servo systems may use various types of motors, including **DC servo motors**, **AC servo motors**, or **stepper motors**, each with different power requirements.

Key Considerations in Servo Power Supply:

1. Voltage and Current Ratings:

- The power supply should match the voltage and current ratings of the servo motor to ensure optimal performance.
- **DC servo motors** often require a low voltage DC supply (e.g., 12V, 24V).
- **AC servo motors** may require higher AC voltage, depending on the application and motor size.

2. Power Stability:

- Servo systems, especially those in precision control, need a stable and noise-free power supply.
- Variations in power can lead to erratic motor performance, affecting position accuracy and overall system stability.

3. Current Capacity:

- Servo motors can draw significant current, especially under load or during start-up.

- The power supply must handle peak current demands to avoid shutdowns or drops in motor performance.

4. **Filtering and Noise Reduction:**

- Power supplies for sensitive servo systems often include filtering components, like capacitors or inductors, to reduce electrical noise that could interfere with the motor's performance.

2. **Drive Circuitry in Servo Systems**

The **drive circuitry**, often called a **servo drive** or **motor driver**, interprets control signals from a controller (e.g., microcontroller, PLC) and delivers appropriately conditioned power to the servo motor to control its movement.

Key Functions of Drive Circuitry:

1. **Signal Amplification and Power Conversion:**

- The servo drive amplifies control signals to levels suitable for the motor and converts these signals into high-power outputs for the motor.
- **AC drives** convert low-power control signals into high-power AC voltages.
- **DC drives** amplify low-power control signals into high-power DC voltages, suitable for DC motors.

2. **Position, Speed, and Torque Control:**

- Servo drives interpret control signals to regulate the motor's position, speed, and torque according to the requirements of the application.
- In closed-loop systems, the drive receives feedback from sensors (e.g., encoders, tachometers) to adjust motor output in real time, maintaining precise control.

3. **PWM (Pulse Width Modulation) Control:**

- In many DC servo systems, **PWM** is used to control motor speed by varying the width of voltage pulses sent to the motor.
- PWM effectively manages power delivery, allowing for efficient and smooth control over motor speed and torque.

4. **Protection and Safety:**

- Drive circuitry typically includes protection mechanisms against overcurrent, overheating, and undervoltage to safeguard the motor and the drive itself from damage.
- Some advanced servo drives include built-in diagnostics to monitor the motor's performance and detect potential faults.

5. **Feedback Integration:**

- In closed-loop servo systems, the drive circuitry receives feedback from sensors (e.g., Hall effect encoders, potentiometers) to adjust motor operations dynamically.
- This feedback loop allows the drive to make real-time adjustments to maintain accuracy and stability in position, speed, or torque control.

Example: Servo Drive Circuit for DC Servo Motor

For a **DC servo motor** with an Arduino-based control system, a typical setup might include:

- **Power Supply:** A 12V DC power source, providing the necessary voltage and current to the motor.
- **Motor Driver:** An H-bridge driver (e.g., L298N) to control the motor's direction and speed using PWM signals from the Arduino.
- **Feedback Sensor:** A Hall effect encoder or potentiometer to provide position or speed feedback.

The Arduino sends control signals to the H-bridge, which adjusts the motor's direction and speed based on the desired position or speed setpoints. The feedback from the encoder is processed in a **PID (Proportional-Integral-Derivative) controller** within the Arduino, which fine-tunes the motor operation to reach and maintain the target position or speed.

Example: Servo Drive Circuit for AC Servo Motor

For an **AC servo motor**, the drive circuitry is typically more complex, involving specialized **servo drives** capable of handling AC voltage and precise control.

- **Power Supply:** AC supply, often at 220V or 380V, depending on the motor rating.

- **AC Servo Drive:** A specialized servo drive converts AC input power to variable frequency and voltage, controlling the AC motor's speed and torque.
- **Control Interface:** The drive receives commands from a central controller (e.g., PLC, CNC controller) to set the desired position or speed.
- **Feedback:** Position feedback from an encoder on the motor shaft is fed into the drive, which adjusts power delivery to correct any deviations from the target.

CHAPTER 5

CONTROL METHODS IN SERVO SYSTEM

5.1 PROPORTIONAL INTEGRAL DERIVATIVE CONTROL

Proportional-Integral-Derivative (PID) control is a widely used feedback control technique in servo systems, which helps achieve precise positioning or speed control by continuously adjusting control inputs to correct errors. Here's how PID control is applied in a servo system:

1. Components of PID Control

- **Proportional (P):** This term provides an output that is proportional to the current error. If the error is large, the proportional response is also large, which enables quick correction. The proportional gain (K_p) determines the strength of this correction. However, using the proportional term alone can lead to steady-state error and overshoot.
- **Integral (I):** This term accounts for the accumulation of past errors, essentially summing them up over time. The integral gain (K_i) is used to reduce steady-state

error, making sure the system converges on the desired setpoint. However, too much integral action can lead to slow response times and can cause oscillations or instability.

- **Derivative (D):** This term predicts the future trend of the error based on its rate of change, adding a damping effect to the control system. The derivative gain (K_d) helps to prevent overshoot and settle the system faster, making the control smoother. Overuse of the derivative term, though, can lead to noise amplification in the system.

2. How PID Control Works in a Servo System

- The servo motor in a closed-loop system reads its current position or speed (often with a sensor like a Hall effect encoder) and compares it with the desired target (the setpoint).
- The PID controller calculates the error (difference between the setpoint and the current reading) and adjusts the motor's voltage or pulse width to reduce this error.
- Each term of the PID controller (P, I, and D) affects the motor's control signal. The proportional term quickly reacts to current error, the integral term corrects long-term cumulative error, and the derivative term stabilizes the response by anticipating the change in error.
- The result is a smooth, accurate response, achieving the setpoint with minimal overshoot and settling time.

3. PID Tuning in Servo Systems

- Tuning K_p , K_i and K_d values is critical for optimal performance. Typically, the proportional gain K_p is tuned first for quick response, followed by K_i for eliminating steady-state error, and finally K_d to reduce overshoot.
- Common tuning methods include manual tuning (trial and error), Ziegler–Nichols tuning, and software-based approaches for real-time adjustment.

4. Applications in Servo Systems

- **Position Control:** PID controllers in servo motors are often used to achieve precise angular positioning, as seen in robotic arms, CNC machines, and camera gimbals.

- **Speed Control:** In some systems, maintaining a specific speed (e.g., conveyor belts, DC motor control) is more critical than precise positioning. The PID adjusts motor speed to maintain consistency under varying loads.

A well-tuned PID controller in a servo system can achieve quick, accurate, and stable control, even in the presence of external disturbances or system non-linearities.

5.2 EXPERIMENT

```
#define ENA 11

#define IN1 9

#define IN2 8

#define ENCODER_PIN 2

#define POT_PIN A0

volatile int encoderValue = 0;

double setpoint, input, output;

double Kp = 2.0, Ki = 5.0, Kd = 1.0;

double previous_error = 0, integral = 0;

void setup()
{
    pinMode(ENA, OUTPUT);

    pinMode(IN1, OUTPUT);

    pinMode(IN2, OUTPUT);

    pinMode(ENCODER_PIN, INPUT_PULLUP);
```

```

attachInterrupt(digitalPinToInterrupt(ENCODER_PIN), readEncoder, RISING);

Serial.begin(9600);
}

void loop()
{
// Motor Direction Control (Forward)

digitalWrite(IN1, HIGH);

digitalWrite(IN2, LOW);

// Reading the potentiometer value for speed control setpoint

int potValue = analogRead(POT_PIN);

setpoint = map(potValue, 0, 1023, 0, 300); // Map pot value to RPM setpoint

// Calculating RPM from encoder counts

int current_value = encoderValue;

encoderValue = 0; // Reset encoder value for the next interval

input = current_value;

// PID calculations

double error = setpoint - input;

integral += error;

```

```

double derivative = error - previous_error;

output = Kp * error + Ki * integral + Kd * derivative;

previous_error = error;

// Constrain output to valid PWM range

output = constrain(output, 0, 255);

// Set motor speed using PWM

analogWrite(ENA, output);

// Print the setpoint, actual RPM, and PID output for debugging

Serial.print("Setpoint: ");

Serial.print(setpoint);

Serial.print(" | RPM: ");

Serial.print(input);

Serial.print(" | PID Output (PWM): ");

Serial.println(output);

delay(1000); // Wait 1 second before the next iteration
}

void readEncoder()

{

encoderValue++;

```

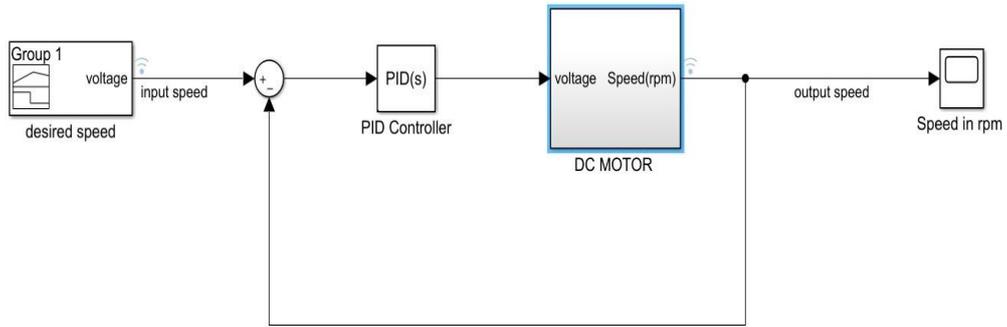


Fig 9 : Block Diagram of the servo system

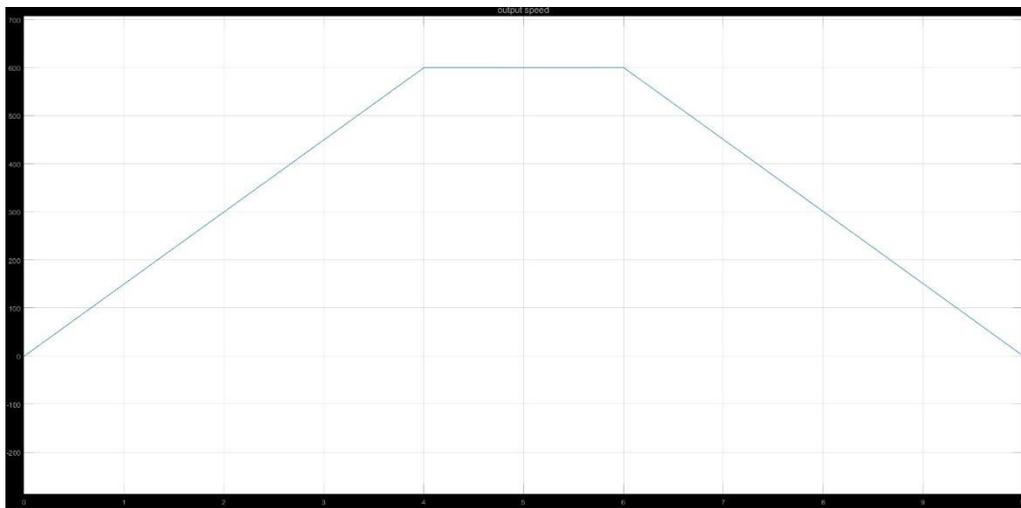


Fig 10 : graph of output speed

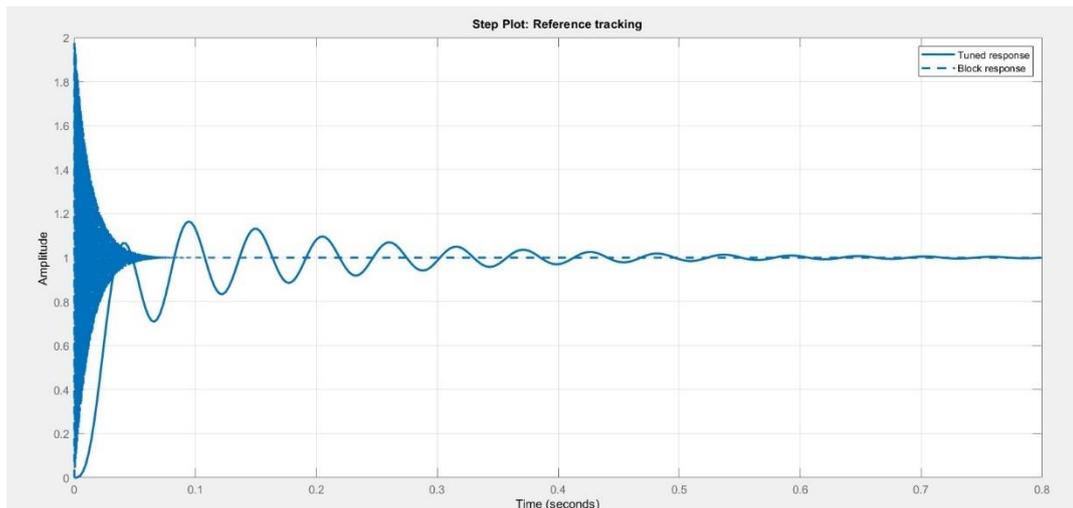


Fig 11 : plot of the system with pid control

CHAPTER 6

CONCLUSION AND FUTURE DIRECTION

6.1 CONCLUSION

The implementation of a digital servo system with advanced closed-loop control has transformed modern automation by providing high precision, adaptability, and robustness. As control technology advances, the digital servo system's ability to integrate with smart, AI-driven environments will further enhance efficiency, opening new possibilities in automation and smart manufacturing.

6.2 MERITS OF THE PROPOSED SCHEMES

The development of digital servo systems with advanced closed-loop operation brings numerous benefits to automation, robotics, and various industrial applications. By utilizing digital processing and real-time feedback control, these systems offer increased accuracy, efficiency, and robustness. Here are the main merits:

1. High Precision and Accuracy

- Advanced closed-loop systems continuously monitor the system's output through feedback (e.g., from encoders or sensors), allowing for precise control adjustments. This accuracy is critical in applications requiring exact positioning and speed, such as CNC machines, robotic arms, and camera stabilization systems.

2. Enhanced Stability and Reduced Error

- Through real-time error correction, digital servo systems achieve stable and consistent performance, even in dynamic environments. Advanced control algorithms (like PID) help minimize overshoot and steady-state error, providing smooth operation and preventing oscillations.

3. Improved Adaptability to Load and Environmental Changes

- Digital servo systems can adjust to changes in load or external disturbances thanks to advanced control methods such as adaptive control, which modifies parameters in real time to maintain optimal performance. This adaptability makes these systems suitable for demanding, variable conditions.

4. Increased Energy Efficiency

- By accurately controlling motor power output, digital servo systems reduce unnecessary energy consumption, which is particularly beneficial in high-demand industrial applications. Digital feedback mechanisms ensure that the system only uses the power required for the task, leading to cost savings and improved environmental sustainability.

5. Faster Response Times and Reduced Latency

- Digital processing provides high-speed feedback and control adjustments, enabling quicker response times compared to analog systems. This responsiveness is essential in applications requiring rapid movement or adjustments, such as automated manufacturing lines, precision printing, and robotics.

6. Scalability and Flexibility

- Digital systems are inherently scalable, allowing easy adaptation across various applications and industries. They are also more programmable and customizable, accommodating unique control requirements without significant redesigns. This flexibility is crucial in modern applications, from micro-scale devices to large industrial machinery.

7. Enhanced Diagnostics and Maintenance Capabilities

- Digital servo systems enable real-time monitoring, diagnostics, and predictive maintenance. This capability allows for early fault detection and preventive maintenance, reducing downtime and extending equipment life. Remote monitoring also makes maintenance more convenient and less time-intensive.

8. Integration with Smart and Automated Systems

- Digital systems easily interface with Industry 4.0 and IoT technologies, allowing seamless integration with automated environments. This connectivity supports data sharing across systems, enabling advanced functions like predictive analytics, AI-driven optimizations, and centralized control in smart factories.

9. Higher Reliability and Reduced Wear and Tear

- Closed-loop control reduces unnecessary motor stress by keeping the motor within optimal operational limits, minimizing wear on components. Consequently, digital servo systems tend to be more reliable and have longer operational lifespans compared to open-loop or analog systems.

10. Improved Safety

- Digital feedback control allows for better safety mechanisms by instantly detecting and responding to abnormal conditions, such as overloads, position errors, or system faults. These systems can automatically adjust or stop the operation to prevent damage to equipment and ensure operator safety.

6.3 DEMERITS OF THE PROPOSED SCHEMES

The development of digital servo systems with advanced closed-loop operation has several advantages, but it also presents certain limitations and challenges. Here are some notable demerits:

1. **Complexity and Cost**

Advanced closed-loop digital servo systems require sophisticated hardware, sensors, and algorithms. This complexity increases both the initial development cost and the cost of components, making it more expensive than simpler, open-loop systems. For small-scale applications where high precision may not be necessary, this investment may not be justifiable.

2. **Dependency on High-Quality Sensors**

Accurate feedback in closed-loop systems depends heavily on high-quality sensors, such as encoders or tachometers, to measure position, speed, or torque. Sensor noise, drift, or failure can introduce errors in the control loop, affecting overall performance and leading to potential instability. The reliance on high-quality sensors also contributes to increased costs.

3. **Increased Computational Requirements**

Advanced control techniques, like adaptive control or model predictive control, require significant computational resources to process data in real time. This necessitates powerful digital processors, which may increase power consumption and could potentially require heat management solutions. For applications where size and power consumption are constraints, this could be a drawback.

4. **Complex Tuning and Maintenance**

Tuning a digital servo system with PID or more advanced algorithms can be complex and often requires specialized expertise. If the system includes adaptive algorithms or AI-based controllers, there may be a need for ongoing calibration or retuning. Maintenance can also be challenging due to the number of components and the system's sensitivity to sensor errors.

5. **Sensitivity to Environmental Conditions**

Environmental factors, such as temperature, humidity, and electromagnetic interference (EMI), can impact the sensors and electronics within a closed-loop digital servo system. This sensitivity can lead to degraded performance or, in some cases, cause failure in harsh environments, requiring additional protective measures.

6. **Lag and Latency Issues**

Digital systems introduce some inherent processing delay, especially in systems with complex algorithms or high-resolution sensors. Although advanced processing units

reduce this lag, it can still be a limitation in applications that require extremely fast response times, such as high-frequency industrial applications.

7. Vulnerability to Cybersecurity Threats

In applications where digital servo systems are connected to networks or rely on cloud-based analytics, there is an added risk of cybersecurity threats. Unauthorized access to control systems could lead to data breaches or even sabotage. Implementing security measures can mitigate this risk but adds to the system's complexity and cost.

8. Troubleshooting and Diagnostics Complexity

Diagnosing issues in advanced closed-loop systems is often more difficult due to the intricate interactions between hardware, sensors, and software. Specialized tools and expertise are frequently required to identify and resolve issues, which can result in longer troubleshooting times and higher maintenance costs.

6.4 FUTURE SCOPE

The future development of digital servo systems employing advanced closed-loop operations promises to bring even greater precision, efficiency, and intelligence to various industries. As technology progresses, several key areas will likely shape the next generation of digital servo systems:

1. Integration with Artificial Intelligence (AI) and Machine Learning (ML)

AI and ML algorithms can enable digital servo systems to self-optimize, learning from operational data to adjust control parameters in real time. These algorithms could predict and adapt to varying conditions, such as load changes or disturbances, with unprecedented accuracy. Predictive maintenance powered by AI will also allow servo systems to identify and mitigate potential faults before they occur, minimizing downtime and improving system reliability.

2. Enhanced Real-Time Adaptive Control Techniques

Future servo systems are expected to incorporate more sophisticated adaptive control methods, allowing them to dynamically adjust to changing environments and application needs. This includes advanced techniques like model predictive control

(MPC), self-tuning regulators, and adaptive PID control, which will improve performance in applications requiring fast, precise adjustments and complex non-linear control.

3. **Miniaturization and High-Precision Applications**

As components continue to shrink and improve in capability, servo systems will become more compact without sacrificing power or control. This miniaturization will open new applications in fields such as medical devices, biotechnology, and consumer electronics, where precise, controlled movements are essential. Nano- and micro-scale servo systems could revolutionize fields like surgical robotics and micromanipulation.

4. **Improved Energy Efficiency and Sustainable Design**

Future digital servo systems will likely focus on energy efficiency, especially with the increasing need for sustainable technology. Advanced control algorithms, regenerative braking, and optimized power management could reduce energy consumption significantly, making these systems more viable in energy-sensitive and environmentally-conscious applications. Additionally, the use of lightweight materials and energy-efficient components will enhance overall system efficiency.

5. **Integration with IoT and Industry 4.0**

As part of the Industry 4.0 revolution, digital servo systems will increasingly be networked with other industrial equipment through the Internet of Things (IoT). This connectivity will enable real-time monitoring, data sharing, and remote control, allowing seamless integration within smart manufacturing environments. Servo systems will be able to communicate and collaborate with other machines, contributing to fully automated and intelligent production processes.

6. **Improved Safety and Compliance Standards**

Advanced digital servo systems will enhance safety by incorporating more sophisticated sensors, redundancy, and fail-safe mechanisms, especially for use in critical applications like aerospace, autonomous vehicles, and medical devices. Servo systems will comply with stricter safety regulations, enabling broader adoption in regulated industries that require reliable and safe operation.

7. **Wireless and Cloud-Based Control**

In the future, we can expect the adoption of wireless and cloud-based technologies in servo systems, allowing control systems to be managed from remote locations and

monitored in the cloud. This setup will enhance flexibility, reduce the complexity of physical wiring, and provide easy scalability for large industrial installations.

8. Development of Quantum-Enhanced Servo Systems

With advancements in quantum computing and quantum-enhanced sensors, future digital servo systems could achieve unprecedented levels of accuracy and speed.

Quantum-enhanced sensors could provide more accurate feedback, while quantum computing might solve complex control problems that are difficult for classical computers, especially in high-speed and high-precision applications.

Long-Term Vision

The development of advanced digital servo systems with closed-loop operation is set to transform multiple industries, creating smarter, more responsive, and efficient control systems. These advancements will not only improve performance but will also pave the way for innovative applications in fields ranging from smart manufacturing and robotics to healthcare and energy-efficient systems.

As technology continues to evolve, digital servo systems will become an integral part of intelligent automation, contributing to smarter, more adaptable, and sustainable solutions across the global industrial landscape.

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