

Research Article

Tracking and Analysing Error in Feedback Linearized Motion Trajectory of Hydraulic Actuator Based on the Internet of Things

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In the current era of technology, the Internet of Things (IoT) is gaining more importance as compared to the rest of the technologies because of its tremendous improvement and application in various areas including tracking and error controlling of physical devices. Controlling physical equipment from afar has become necessary in today’s practice. This type of operation needs a robust infrastructure that connects various types of equipment, such as sensors, actuators, plants, and so on, with controllers located in remote locations, either centralized or decentralized, via a communication channel. The variety of platforms makes it difficult to integrate all of these components; nevertheless, the usage of the IoT effectively offers communication across several devices and platforms. However, the drive joints of the traditional hydraulic actuator arm mostly take the form of a combination of a motor and a reducer, resulting in a very small load-to-weight ratio and the power-to-volume ratio of the traditional hydraulic actuator arm. In addition, the load-bearing ratio is one of the important indicators to measure the performance of industrial robots. In response to this problem, this paper studies the combined advantages of hydraulic transmission, a six-degree-of-freedom hydraulic actuator based on a vane-type hydraulic swing cylinder as a joint. According to the performance requirements of the butterfly valve, the hydraulic actuator components, such as hydraulic cylinders, AC servo motors, and hydraulic pumps, have been selected and designed. Furthermore, the calculation and construction of hydraulic pipelines and integrated valve blocks have been accomplished, as has the selection summary of various actuator components. Considering joint flexibility, this research work carries out trajectory planning in joint space, during which it resolves the optimal value of each joint angle under the condition of joint flexibility and obtains a smoother joint motion parameter curve by relying on the layered structure of the IoT framework. The simulation results show that this method can ensure that the acceleration at the start and end time is 0, and it can avoid the vibration of the hydraulic actuator arm at the start and stop.

1. Introduction

These days, the usage of physical devices in many areas is increasing at an extraordinary speed. Even a single system is made up of several subsystems that each contains several interconnected components. These devices are linked to a medium of communication based on the IoT idea, for which cyber-physical technologies and networked control mechanisms are two more preferred terminology. Currently, the IoT play a significant role in several fields that improve the lives we lead. Transportation, industrial automation, universal healthcare, and emergency management in disaster management circumstances are among the domains. It offers a means for physical things to communicate data and coordinate choices. The fundamental technologies like ubiquitous and pervasive computers, embedded systems, communications technology, Internet protocols, and programs are used to achieve the IoT. In the Internet of Things (IoT) paradigm, items are network-connected to transmit and receive information. Hardware resources, computational platforms, and communications equipment are all integrated into the architecture. These three crucial components are vastly different from one another. The integration of multiple devices with that computer system and communication channel is the most difficult due to heterogeneity in system-level features and local attributes of elements [1]. Interactions between various systems have an impact on their performance, such as tracking and mistake
analysis. The coupled physical’s dynamics, calculation, and disciplines of communication must be adequately understood before putting out the whole framework to track and evaluate the feedback linearized motion trajectory of the hydraulic actuator.

The trajectory planning of the hydraulic actuator manipulator refers to the motion trajectory of the hydraulic actuator manipulator arm in the joint space and Cartesian space and its generation based on the kinematics and dynamics of the hydraulic actuator manipulator [2]. The trajectory planning of the hydraulic actuator manipulator is divided into joint space planning and Cartesian space trajectory planning [3]. The former refers to the change law of the motion parameters of every joint of the hydraulic actuator controller during the movement process, and the latter refers to the movement of the termination effector of the hydraulic actuator controller. In the case of certain known conditions, the running time is different, and the corresponding motion parameters are also different, but it is necessary to ensure that the obtained change curve of the motion parameter must be continuously smooth [4]. Proper trajectory planning may assure the steady functioning of the hydraulically performed manipulator, decreasing impact and wear on components and extending service life [5]. Compared with the motor transmission, hydraulic transmission has outstanding advantages such as large load, compact structure, and stable transmission under the same power, and its load-weight ratio has significant advantages [6–8]. At the same time, the output power can be controlled by adjusting its system pressure.

In addition to the above, the trajectory planning of the hydraulic actuator manipulator is based on the kinematics of the hydraulic actuator manipulator to generate the motion trajectory of the hydraulic actuator manipulator [9, 10]. For different optimization goals, domestic and foreign scholars have done a lot of research on the trajectory planning of the hydraulic actuator manipulator [11–13]. Relevant scholars have studied the vibration suppression and joint torque minimization of redundant flexible hydraulic execution manipulator trajectory planning. Most of them are proposed using its redundant characteristics for self-motion planning, which not only guarantees the minimization of joint torque but also achieves a good vibration suppression effect [14, 15]. For the research of the rigid-flexible two-link hydraulic actuator manipulator, the researchers proposed to use cubic spline function as the motion trajectory of the hydraulic actuator manipulator joint and use particle swarm optimization (PSO) to optimize the maximum amplitude of the residual vibration at the end [16–18]. Experiments, using simulation, demonstrate the reasonableness of the suggested technique. A two-link flexible hydraulic actuator manipulator has been presented by other researchers [19–21]. An evolutionary method is used to reduce the energy usage of the hydraulic actuator manipulation under the two predetermined joint trajectories [22]. The Hamilton concept is employed to create a model, and the optimizing of joint torque along a trajectory is modeled and judged on the least energy usage, demonstrating the efficacy of the suggested technique [23]. Researchers established a model of the optimal problem with dual boundary value constraints through the Pontryagin principle, obtained the optimal vibration suppression trajectory of the flexible arm system in PTP control, and solved its maximum load [24].

However, due to the small amount of internal leakage of the pendulum cylinder itself and the movement inertia of the pendulum cylinder rotor, the pendulum cylinder produces a rotation angle error [25]. At the same time, the hydraulic control system also has problems such as response lag. Under the combined action of these factors, the joint rotation angle of the hydraulic actuator arm exists. Errors cause the hydraulic actuator arm to have joint flexibility. The joint flexibility eventually leads to a definite error in the end effector of the hydraulic actuator, which determines that the hydraulic actuator lack accuracy compared with the traditional hydraulic actuator [26]. Therefore, the use of the hydraulic actuator is biased. It is suitable for occasions that do not require too high precision, such as handling and palletizing. At the same time, some methods are used to reduce the influence of the joint flexibility of the hydraulic actuator arm on the overall hydraulic actuator arm and decrease the error of the end effector of the hydraulic actuator arm. Therefore, it is necessary to study the influence of joint flexibility on the kinematics characteristics of hydraulic actuators. At the same time, considering the influence of joint flexibility factors, it is particularly important to carry out trajectory planning and kinematic error research on hydraulic actuators.

The key innovations of this research work are listed as follows:

1. This paper derived the error distribution of the hydraulic actuator arm’s end effector with the flexibility of the joints examined in this work. The cubic triangular Bezier spline is used to design the trajectory in joint space to assure the smooth mark and link of the joint motion parameter curve. Simultaneously, the issue of rapid joint angular speeding up is handled by raising the degree of the cubic triangular curve of Bezier spline, and its logic is validated by simulation.

2. This paper establishes the kinematics design of elastic joint hydraulic actuator manipulators considering the influence of joint flexibility based on rigid kinematics. We perform our experimental work using MATLAB and obtain the motion error dispersal of the end effector of the hydraulic actuator arm under the given joint motion law.

3. Our findings demonstrate that the kinematics design of the flexible hydraulic actuator arm is accurate. The kinematics simulation is carried out using MATLAB, and the curve of each joint angle is generally smooth, confirming the reasonableness of the hydraulic actuator arm’s structural design.

The remainder of this study effort is structured in the following order: Section 2 provides information and techniques for the Internet of Things-based feedback linearized motion trajectory of the hydraulic actuator tracking and
Based on the minimal goal function values ing under the prior instruction packets. Communication inconsistency, the actuator remains operating to the controller. If the packets are corrupted or lost owing to the network sends packets of data from sensors to remote controllers and from those controllers to actuators. These packets are susceptible to timing latencies and packet loss rates. Figure 1 depicts a schematic of a wirelessly communicated closed network comprising sensors, controllers, and actuators. The fundamental idea of the communication system from [27] has been used in this study, with a few alterations.

2.1.1. Sensors. In the first phase of each sampling interval, the sensors submit measuring packets and other needed packets to the controller. The sensors then fall into a sleep state for the remainder of the sampling moment. The packets from the sensors are received by the controller, which calculates the necessary actions based on the state data. The optimization problem value is calculated using the data and control actions from all projected states. It then awaits the next sample interval. For a certain interval, the actuator actions stay constant. During the most recent sample interval, the actuators acquire instruction packets. When the appropriate packets are properly received, the actuator returns the acknowledgments to the controller. If the packets are corrupted or lost owing to communication inconsistency, the actuator remains operating under the prior instruction packets.

2.1.2. Controllers. Based on the minimal goal function values obtained at each sampling instant of the relevant control intervals, the controller determines the needed control actions for the previous period of analysis. It transmits them towards the actuators and waits for confirmation.

2.1.3. Actuators. The actuators are time-driven because they depend on information supplied from the controller at frequent sampling instants. The most recent time-stamped control packet is utilized to control the plant. Failed packets include corrupted packets and packets that arrive at the actuators in the wrong order and are in the wrong state. The duration of each sample period is set, while the durations of the control intervals vary. The framework competes for the shortest possible length of every control interval. The longer the duration of every control interval, the improved the controller’s judgment for actuator operations. The operations of the actuators are determined by the proportional value of an objective function. Because the sensors, controllers, and actuators are well synced, each of them executes its functions as expected during the sample intervals. The duties are assigned to each device on a network.

2.2. Analysis of Hydraulic System Control Scheme. The hydraulic system of the hydraulic actuator refers to the direct-drive volume control hydraulic circuit, and on this basis, an optimized design is made for the working conditions of the hydraulic butterfly valve. The hydraulic system of the actuator consists of an AC servo motor, a two-way quantitative hydraulic pump, a rack, a pinion hydraulic cylinder, a hydraulic integrated valve block, a displacement sensor, a controller, and other hydraulic components. All components in the hydraulic system adopt a modular, miniaturized, and integrated design, and oil is closed and independent from the outside.

The entire hydraulic system adopts a fully enclosed internal circulating hydraulic circuit, which can avoid dust and impurities in the working environment from being mixed into the contaminated hydraulic oil. The hydraulic oil in the actuator can be kept clean for a long time and requires almost no maintenance. The hydraulic pump adopts the same amount of oil to be pumped in and pumped out. There is no servo control valve in the hydraulic circuit and no additional heat loss is generated, so it can ensure high mechanical efficiency. The hydraulic system of the hydraulic actuator consists of 4 main pump units, namely, the main valve block unit, the actuator, the hand pump unit, and the butterfly valve load unit. The main pump units, the main valve block unit, the actuator, and the hand pump unit are all connected by hydraulic pipelines to realize the transmission of oil. The actuator and the butterfly valve load unit transmit torque through a mechanical connection. The main pump unit consists of 4 parts, namely, AC servo motor 1 (hereinafter referred to as motor 1), two-way quantitative hydraulic pump 2, one-way valve 3, and pressure oil tank 4. The coupling is connected with the power output shaft of motor 1 and the power input shaft of pump 2, so that motor 1 can drive pump 2 to work. The pressure oil tank 4 is connected in parallel with pump 2 and connects the first check valve 3.1 and the second check valve 3.2 to provide hydraulic oil for the oil circuit. The main valve block unit is composed of 4 parts, which are the first dual hydraulic control check valve 5.1, the second dual hydraulic control check valve 5.2, the first relief valve 6.1, and the second relief valve 6.2. The main valve block unit plays a role in controlling oil flow and safe unloading in the hydraulic circuit. The actuator is a hydraulic cylinder 7. The high-pressure oil in the circuit enters the hydraulic cylinder to drive the piston. The piston in hydraulic cylinder 7 drives the butterfly valve 8 to open and close through a series of mechanical transmissions. The hand pump unit consists of a manual reversing valve 9 and a manual emergency pump 10. When an emergency occurs during operation, if there is a power failure or hydraulic circuit leakage, the manual emergency pump 10 can be operated to pump oil into the hydraulic cylinder 7 to realize the butterfly valve 8 work. The manual reversing valve 9 can control the flow direction of the oil circuit to control the opening and closing of the butterfly valve 8.

The traditional hydraulic servo valve-controlled actuator adopts an open-loop control system. The control method of the hydraulic actuator studied in this paper is a closed-loop
control system. The open-loop control no longer affects the input signal after the signal is output, and the closed-loop control will affect the input signal all the time until the target displacement position is reached. The control block diagram of the hydraulic actuator is shown in Figure 2.

Figure 2 shows the closed-loop control process of the hydraulic actuator. The command signal outputs the target displacement. After the controller receives the displacement signal, it drives the AC servo motor to work. The AC servo motor controls the two-way quantitative hydraulic pump by changing the speed and steering, outputting the pressure and direction of the oil, and indirectly controlling the movement speed and direction of the piston of the hydraulic cylinder. The displacement of the piston of the hydraulic cylinder is measured by an angle (or displacement) sensor installed at the connection between the hydraulic cylinder and the butterfly valve. The angle (or displacement) sensor can continuously measure the feedback signal of the hydraulic cylinder displacement and transmit the signal to the controller. The target displacement signal and the position feedback signal are compared and amplified in the controller to obtain the displacement deviation. When the deviation exceeds the set value, the controller sends a signal, and the AC servo motor continues to work until the butterfly valve reaches the predetermined position. The closed-loop control system of hydraulic actuators still needs to develop specific intelligent control methods.

2.3. Structural Design of the Actuator. The AC servo motor 9 and the bidirectional quantitative hydraulic pump 1 are connected by a coupling, and the two parts are externally installed with a metal shell. For the complex working environment, the installed metal shell can protect against collision, dust, and water. The bidirectional quantitative hydraulic pump is equipped with a charge oil tank, which is installed in the metal shell of the hydraulic pump. The metal shell, servo motor, and hydraulic pump are connected and fixed with shell 2 by bolts. Housing 2 is hollow on the interior and has an integrated hydraulic valve block. The hydraulic system oil circuit is included in the hydraulic valve block’s integrated board. This design can minimize noise generated by pipeline vibration induced by changes in oil pressure. At one end of housing 2, a hydraulic cylinder 7 is placed. The hydraulic oil port of hydraulic cylinder 7 corresponds to the oil port of the integrated plate of the hydraulic valve block in housing 2, which can realize the communication of oil. The upper part of the hydraulic cylinder 7 is equipped with an angle sensor 6 and the lower part is connected with a butterfly valve 10. We install a hand pump 8 on the other end of the hydraulic cylinder 7 for emergency use. The above constitutes the external structure of the hydraulic actuator.

The structural design of the hydraulic butterfly valve actuator also includes the control structure design. The control structure consists of 4 parts, which are the controller 5, the display 4, the control switch 3, and the angle sensor 6. Control switch 3, the angle sensor 6, and controller 5 are connected by a circuit, and the function of control switch 3 is to open and close the circuit of controller 5. Both display 4 and control switch 3 are fixed on the outer surface of one side of housing 2. Controller 5 is fixed inside housing 2, and its function is to receive and process the displacement signal and control the operation of the AC servo motor to achieve precise control of the rotation angle of the butterfly valve. Controller 5 is equipped with a communication interface based on the field CAN bus, which can communicate with the upper and lower computers. In short, the control structure of the hydraulic actuator can not only achieve precise control of the butterfly valve but also receive and send displacement signals to achieve remote monitoring and control.

2.4. Selection and Analysis of Main Components. This section explains and analyses the main components of our selected model for tracking and error analysis of the feedback linearized motion trajectory of the hydraulic actuator based on
the Internet of Things. This section first explains the selected hydraulic cylinder that has been chosen for our proposed model, and then, it calculates the efficiency of the AC servo motor.

2.4.1. Hydraulic Cylinder. The hydraulic cylinder is the power output device of the hydraulic actuator and is one of the key components. The hydraulic cylinder can convert hydraulic energy into mechanical energy through a series of mechanical transmissions to realize the butterfly valve drive. Piston hydraulic cylinders can be divided into single rod hydraulic cylinders and double rod hydraulic cylinders according to the extension of the piston rod at the end cover. In this paper, the double-barrel hydraulic cylinder is selected, and the double-barrel hydraulic cylinder has a better stable performance of power output under the working environment.

The maximum output torque $T$ required by the butterfly valve is $3000 \text{Nm}$. Considering that the output voltage is unstable under the working environment, the oil pressure of the hydraulic pump may also be unstable. To ensure that the hydraulic cylinder can withstand higher oil pressure, the maximum pressure of the initially selected hydraulic cylinder is $16 \text{MPa}$ (rated oil pressure is $10–13 \text{MPa}$). Referring to the hydraulic manual, the force balance equation of the hydraulic cylinder is calculated as follows:

$$ P_1 - P_2 = \frac{2(T - 1)}{AD_0}. $$

(1)

In the above equation, $P_1$ represents the pressure of the oil inlet cavity and $P_2$ is the pressure of the oil return cavity. Similarly, $A$ represents the diameter of the piston and cylinder and $D_0$ is the index circle diameter of the gear. The area of the piston is calculated as follows:

$$ A = \pi (0.25D)^2. $$

(2)

In the above equation, $D$ represents the outer diameter of the piston (inner diameter of the cylinder).

2.4.2. AC Servo Motor. An AC servo motor is a type of servomotor that employs alternating current electrical input to create physical output in the shape of accurate angular velocity. AC servomotors are 2 different electric motors with several design differences. The output power of an AC servomotor can range from one watt to several hundred watts. The operational frequency band is between 50 and 400 Hz. It gives the feedback system closed-loop control since it uses a sort of encoder to offer feedback on speed and location.

Given the piston diameter $D_1$ of the hydraulic cylinder, the piston stroke $S$, the piston full stroke flow $V$, and the rated pressure $P_s$ of the hydraulic pump. The time required for the hydraulic cylinder to drive the butterfly valve to open and close once is $7 \text{s}$. The flow rate $q$ of the hydraulic cylinder per unit of time can be calculated as follows:

$$ q = \pi D_1 S / 7. $$

(4)

Therefore, the required power of the AC servo motor can be calculated using the following equation:
In the above equation, \( \eta \) represents the overall efficiency of the pump (such as \( \eta = 0.82 \)).

The AC servo motor selects the model 110ST-M04030. The motor can be a small inertia permanent magnet synchronous motor to meet the performance requirements of hydraulic actuators with high positioning accuracy and fast response speed.

### 2.5. Design of Piping and Hydraulic Valve Block

#### 2.5.1. Piping Design

The hydraulic actuator has servo valve blocks and hydraulic lines built in. This design solution not only eliminates tube vibration and pressure loss but also significantly increases the hydraulic actuator’s operating efficiency and operational stability. The following equation can be used to find the pipe diameter.

\[
d = 2 \frac{(q/\pi \theta)^{1/2}}{\eta}\cdot
\]

In the above equation, \( q \) is the oil flow rate in the pipeline, and \( \theta \) is the allowable flow rate in the pipeline.

#### 2.5.2. Summary of Selection of Hydraulic Valve Block Components

Other components can be selected using the above selection and design of hydraulic cylinders, AC servo motors, and hydraulic pumps. Table 2 provides a summary of the actuator component selection process.

### 2.6. Feedback Linearization Algorithm

The input-state linearization structure cancels the nonlinear phase in the state equation through the state feedback of the system and converts the nonlinear state equation into a linearly controlled state equation. At this time, it is required that the nonlinear state equation can be written as the following structure:

\[
\dot{x} = Ax - By(x - 1) + u\alpha(x).
\]

In the above equation, \( A \) represents a square matrix of order \( n \), \( B \) is an \( n \times m \) matrix, \((A, B)\) is controllable for all \( x \), and the matrix \( \gamma(x) \) is not singular. The term "state feedback" describes the requirement that the feedback control rule is a linear combination of just the state vector (velocity and position). There are various alternative control rules after state feedback is selected as the nature of the control force. One option is to employ pole positioning. In structural control, pole positioning entails finding appropriate modal damping proportions and vibration frequency. The state feedback of the suggested model can be calculated using the following equation:

\[
u = \alpha(x - 1) - \eta \beta(x + 1).
\]

Among them,

\[
\beta(x) = \gamma^{-1}(x - 1)\cdot \alpha(x).
\]

We get the linear equation of state as per above equation.

\[
\dot{x} = Ax - B(v + 1).
\]

We design the virtual input quantity \( v \) (if \( v = -Kx \)); then, the total nonlinear state feedback control law can be calculated as follows:

\[
u = Kx\alpha(x) - \beta(x - 1).
\]

From the above equations, it is clear that input-state linearization has higher requirements on the structure of the system state equation. Even if the state equation is not directly satisfied, it should be able to meet the structural requirements through variable substitution. In addition, this method achieves linearization between the input and the system state. When the output is nonlinear, the closed-loop system is still nonlinear, and the linear system theory cannot be used to design the system controller. Figure 3 shows the structure diagram of input-output linearization.

The input-output linearization structure diagram of the system is shown in Figure 3. That is, the linearization of a system as a whole is realized between the input quantity and the output quantity, allowing the state of the internal system to have a nonlinear phase. This method is mainly realized by selecting appropriate coordinate transformation and state feedback.

It can be seen from the figure that input-state linearization refers to linearization between external input and system state, while input-output linearization is linearization
between input and output. The two are not the same, but there is also a close connection between the two. For an n-order system, only part of the state is linearized when the relative order of the system is \( r < n \). However, when the relative order is \( r = n \), then it proves that all states are also linearized. Therefore, if an n-order system is input-output linearizable and the relative order is \( r = n \), then it must be input-state linearizable, that is, input-state linearization is input-output linearization when the relative order of the function is \( n \).

We can see from the preceding analysis that the specific methods of feedback linearization are similarly classified into two categories. For analysis, we use a single-input single-output nonlinear system as an example. When \( r = n \), we select the following coordinate transformation:

\[
\begin{align*}
    &v \cdot a(x) - \beta(x + 1) \\
    &x = u \cdot f(x) - g(x + 1)
\end{align*}
\]

At this stage, the closed-loop system is linear and controllable, and the system’s state feedback control law may be derived from the following equation:

\[
u = -vL_f h(x) \bullet L_f^{-1} h(x + 1).
\]

In the above equations, when \( r < n \), first we carry out the coordinate transformation to obtain \( r \) new state quantities. For the other \( n - r \) states, we construct a new coordinate transformation for them, so that there is no input quantity in the state equation.

### 3. Simulation, Experiment, and Analysis

#### 3.1. Kinematics Simulation of the Hydraulic Actuator Manipulator

Kinematic analysis is used to characterize the time course of alterations in the orientation and position of body segments, as well as the geometries of motion in measures of displacements, speeds, and accelerations, despite considering the kinetics of motion production. Thermal imaging systems that capture the 3D location of markers put on the body surface can be used to collect kinematics information. Data are collected at regular periods. Calibration is required for kinematic devices to offer consistency throughout recording sessions. We use the `jtraj` statement in MATLAB to simulate the kinematics of the hydraulically executed manipulator as given in the following equation:

![Figure 3: Input-output linearization structure diagram.](image-url)
In the equation, \( q \) represents the joint trajectory from the initial state \( q_A \) to the final state \( q_B \), \( q_d \) and \( q_{dd} \) respectively, represent the speed and acceleration of the joint angle, and \( t \) represents the movement time.

The end effector of the hydraulic actuator manipulator built in this work is defined to move from point \( A \) to point \( B \) as an example for simulation. Figures 4 and 5, respectively, show the motion trajectory and displacement curve of the end effector of the hydraulic actuator arm. It can be seen that the coordinate curve changes smoothly, that is, it can reach the predetermined position smoothly.

3.2. Joint Angle Error Compensation. In the process of trajectory planning, the starting point, ending point, and running time of the end effector of the hydraulic actuator arm are known, and the joint variables corresponding to the starting point and ending point are solved by inverse kinematics, and interpolation is performed on them. The joint angle time interpolation function \( \theta(t) \) is used to describe the motion law of each joint of the hydraulic actuator. The value of \( \theta(t) \) at \( t_0 \) and \( t_f \) corresponds to the rotation angle of the joint at the starting and ending positions, respectively. There are countless smooth curves between the start and end points, so \( \theta(t) \) can be selected according to specific constraints.

The hydraulic actuator manipulator designed in this paper has joint flexibility, so the trajectory planning of the hydraulic actuator manipulator considering joint flexibility is carried out. There is a rotation angle fault in the joint of the hydraulic actuator controller that will cause an error among the end effector and the desired point at the termination of the process of the hydraulic actuator manipulator. Therefore, this joint angle error needs to be compensated. First, we use inverse kinematics to find the theoretical value of each joint angle when the end effector reaches the desired position. The joint error is a known range, and the value is randomly selected within a given interval of the joint error and the theoretical angle of rotation is added to the joint. The actual joint angle is obtained from the error, and then, the actual joint angle is substituted into the positive kinematics equation to solve the actual position of the end effector and compared with the expected position point. The optimum joint error is the joint error that corresponds to the smallest position error. Subtracting the optimum joint fault from the joint angle yields the ideal real joint angle. Finally, the best joint angle is interpolated to calculate the change law curve of the signal parameters of each joint of the hydraulic actuator controller. The theoretical joint variable values in the joint space matching to the route points in the workstation are solved by inverse kinematics, as shown in Figure 6.

Knowing that the maximum rotation angle error of each joint is 0.5°, we randomly selected the error. The theoretical joint rotation angle plus the joint rotation angle error can get the actual joint angle, and then, the actual joint angle is substituted into the positive kinematics equation to find the corresponding end execution. In addition, we compare it with the desired point to find out the joint angle error equivalent to the minimum position error to obtain the best actual joint angle. Combining Figure 6, we write the corresponding program in MATLAB for calculation. Since the angle error of the sixth joint does not affect the location error, only the first 5 joints are studied. We take 500 position points and obtain the error dispersal illustration between the real arrival location and the expected location of the hydraulic actuator arm end effector, as shown in Figure 7. The step length of the joint error is fixed to 0.01° to decrease the quantity of calculation. Table 3 displays the optimum joint rotation angle determined.

We take the actual optimal joint path point for each joint angle of the hydraulic actuator arm and then repeat the above steps. The error distribution of the hydraulic actuator’s end effector after incorporating joint flexibility correction may be determined by programming and calculating in MATLAB, as illustrated in Figure 8.

When the findings of the figures are compared, it is clear that after joint error benefit, the extreme location error of the hydraulic actuator arm’s end effector is greatly decreased, and the range of location error is extra focused. The
Figure 5: Coordinate projection of end effector of the hydraulic actuator arm.

Figure 6: Theoretical path points of each joint (unit: rad).

Figure 7: Distribution of position error.
measurement of the complete location interval of error is decreased by around 46.5%, demonstrating the method’s viability.

4. Conclusions

The Internet of Things (IoT) infrastructure connects items to the network so that they may transmit and receive data. Physical equipment like hydraulic actuators, computing systems, and communication infrastructure are all integrated into the architecture. These three crucial components are vastly different from one another. The tracking and integration of multiple devices with that computer environment and communication channel is the most difficult problem because of variability in system-level features and the local characteristics of hydraulic actuator parts. The tracking and interactions that take place between various platforms have an impact on their performance. The interplay of physical, computer simulation, and communication disciplines must be fully defined before setting out the entire framework. Based on these issues, this study explores the realization approaches of input-output linearization and input-state linearization of nonlinear systems by evaluating the underlying differences and internal relationships between these two methods. For the hydraulic actuator, the input-output linearization approach is used, the mathematical model of the system is transformed into two linear subsystems, and controllers are created for the two linear subsystems using the pole configuration concept. The simulation findings reveal that feedback linearization control outperforms classical vector control in terms of the hydraulic actuator control effect.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares that there are no conflicts of interest.

References


