Design and Development of an Automatic Oil Injection Fixture Device for Hydraulic Shock Absorbers

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Abstract. As a critical component of rail trains, the hydraulic shock absorber currently relies on manual operation for the oil filling process, which presents issues such as low efficiency and high labor intensity. This paper adopts an integrated approach of digital modeling design and verification analysis to develop a fixture device for the oil filling process in the hydraulic shock absorber assembly line. This device, operated via a collaborative robot,s enables full automation of the entire process, including feature recognition, oil gun docking, and piston rod grasping. It replaces manual labor and offers advantages such as simple operation, high stability, and a high degree of automation.

Keywords: Intelligent oil injection; Robot fixture; Quick-change docking; Automation.

1. Introduction

Production line automation is an inevitable trend in industrial production and assembly. Currently, there are well-established practical cases of automated assembly lines for hydraulic shock absorbers, but the automation level of the oil filling process remains relatively low. The oil filling process for hydraulic shock absorbers still largely relies on manual operation. This involves securing the inner tube of the shock absorber, removing the piston rod above the oil filling port, extracting it, then manually holding the oil gun to locate the oil filling port, inserting the oil gun, waiting for the oil level to reach the top, and finally withdrawing the oil gun and returning it to its rack [1]. This entire process has shortcomings such as operational inconvenience and poor sealing [2].

Automated refueling technology is currently applied in processes like refueling at gas stations, where robotic arms are used to handle the fuel nozzle for automated vehicle refueling. However, there are no highly automated applications of this kind in the rail transportation industry yet. The core of the automated oil filling process lies in robotic motion control and the transmission of coordinate information. The key to the robot's actions is the end-of-arm tooling (EOAT) device. Therefore, the crucial step in achieving automated oil filling for hydraulic shock absorbers is to design an EOAT device capable of performing all the required operational steps.

To address the above issues, this paper designs a robotic EOAT mechanism that can achieve the automated oil filling process for hydraulic shock absorbers under the drive of a robot. This fixture can quickly replace the oil gun, identify the features of the oil filling port, and grasp the piston rod, thereby replacing manual oil filling and realizing the automation of the oil filling process for hydraulic shock absorbers.

2. Introduction to the Hydraulic Shock Absorber Oil Injection Process

As one of the core components of the bogie in rail trains, the performance of hydraulic shock absorbers directly affects the smoothness, safety, and ride comfort of train operation [3]. Such shock absorbers typically consist of key components such as an outer cylinder, piston rod, piston valve, and internal oil chamber. Their working principle involves generating damping through the flow of hydraulic oil within the chamber, thereby absorbing and dissipating vibration energy produced during vehicle operation.

Different models and types of hydraulic shock absorbers exhibit significant variations in design parameters, specifically in terms of oil volume, the structural position of the oil filling port, and the required quality of the oil to be injected. This diversity imposes high demands on the flexibility and accuracy of automated oil filling operations. In the practical automated oil filling process, a high-precision 3D vision system is first employed to identify and locate the features of the shock absorber's oil filling port. The system acquires precise 3D coordinate information of the oil filling port via cameras and determines the type of oil gun to be used based on this information. Subsequently, an industrial robot, guided by the coordinates provided by the vision system, controls the end-of-arm tooling to automatically grasp the corresponding oil gun from a dedicated rack using a quick-change device. During operation, the robot accurately moves and docks the oil gun with the oil filling port. Once the filling conditions meet the set requirements, the system activates a metering pump to inject the shock absorber oil—of a predetermined type and precise quantity—into the oil chamber, ensuring consistency and accuracy in each filling operation. After the oil filling process is completed, the robot controls the oil gun to withdraw smoothly. Immediately following this, to initially seal the oil filling port and prevent oil leakage, the robot quickly performs the subsequent action—pressing the piston rod into place to achieve initial sealing, thereby preparing the component for the next process or transfer. The entire process highlights the advanced manufacturing characteristics of intelligence, high precision, and integration.

3. Structural Design of the Automatic Oil Injection Fixture for Hydraulic Shock Absorbers

3.1 Fixture Function Analysis

The robot used in the automated oil filling process has six degrees of freedom, with a working range that can simultaneously cover both the placement position of the oil gun and the position of the oil filling port. An external 3D vision coarse positioning system identifies the features of the hydraulic shock absorber and transmits the information to the robot. The end-effector, serving as the front end of the robot, drives the flexible oil filling process under the robot's control [4].

During the automated oil filling process, the robot end-effector primarily performs three functions: first, it identifies the features of the oil filling port using a 3D camera [5]; second, it grasps the piston rod above the oil filling port with a pneumatic gripper; and finally, it uses a quick-change plate to pick up, place, and switch between different oil guns. Since the structures of different oil guns vary, corresponding adapter fixtures need to be designed based on the interface type of each oil gun, while the interface facing the quick-change plate should remain identical. This enables rapid switching between different oil guns.

3.2 Fixture Structure Composition

The structure of the automatic oil injection robotic fixture for hydraulic shock absorbers is shown in the figure below.

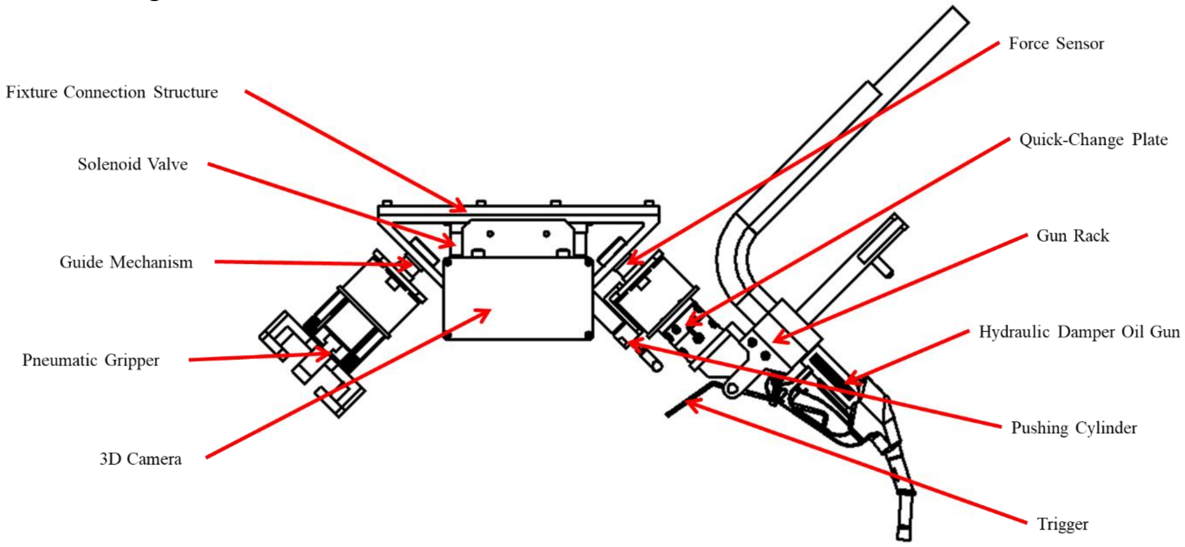

Figure 1 Automatic Oil Injection Robotic Fixture for Hydraulic Shock Absorbers

The main body of the fixture is made of high-quality 6061 aluminum alloy, offering advantages such as an aesthetically pleasing structure, high strength, and low weight [6]. The connector serves as the base of the fixture and is mounted on the front end of the robot. A 3D camera is fixed on the rear side of the connector, functioning to identify the features and positional coordinates of the oil filling port, and transmitting this coordinate information to the robot.

A 5/3-way solenoid valve is installed on the front side of the connector, primarily responsible for controlling the actions of pneumatic components, such as the opening and closing of the pneumatic gripper and the engagement/release of the quick-change plate. Its placement near the pneumatic components ensures control stability and responsive agility. A three-finger pneumatic gripper, is fixed on the left side of the connector. Its main function is to grip the piston rod. The gripper is equipped with an upper guiding mechanism and a force sensor mounted on its side [7]. This sensor functions as follows: when placing the piston rod, the end effector stops upon contacting the oil port and encountering resistance. The robot then continues to push the connector forward over a short stroke. Once the sensor contacts the stopper surface and registers a reading—a detectable force threshold can be set manually—the robot halts its motion if the threshold is exceeded [8].

The quick-change connection between the oil gun and the robot is accomplished using a quick-change plate. A LINGHANG LTC series quick-change plate is selected for this purpose. The robot-side part of the plate is fixed on the right side of the fixture, while the mating part is fixed on the top of the adapter fixture for the oil gun. This setup enables the rapid switching of different oil guns and ensures the simultaneous connection of pneumatic circuits through the integrated pneumatic ports on the quick-change plate. A push cylinder is installed at the bottom of the quick-change plate, which functions to actuate the trigger on the adapter, thereby activating the oil gun.

3.3 Analysis of Device Workflow

The workflow for the automated oil filling of hydraulic shock absorbers, driven by the robot and its end-effector, is as follows: 1. The hydraulic shock absorber is first secured in the oil filling station by a manipulator or pneumatic device. An external 3D vision coarse positioning system captures an image to identify the shock absorber's features and transmits the coordinate information of these features to the robot [9]. 2. The 3D vision system on the robot's end-effector then captures a detailed image to identify the oil filling port. It transmits the precise coordinates of the port to the robot, which converts this data into its own coordinate system. 3. The robot moves the end-effector into position and uses the pneumatic gripper to grasp and lift the piston rod located atop the shock absorber. 4.The robot then moves the end-effector so that its 3D camera can locate the quick-change plate position. It uses the quick-change mechanism to pick up the corresponding oil gun from its rack. 5.The robot precisely inserts the oil gun into the filling port. A signal is sent to a pneumatic cylinder, which extends a push rod to depress the oil gun's trigger, initiating the oil filling process. 6.Once the filling process is complete, the pneumatic cylinder retracts the push rod. The robot withdraws the oil gun, returns it to its rack, and disengages the quick-change plate. 7.The robot then moves the grasped piston rod back into position. When the force sensor detects that the applied force has reached a pre-set threshold, the pneumatic gripper releases the piston rod. Finally, the robot returns to its home position, completing the entire oil filling cycle.

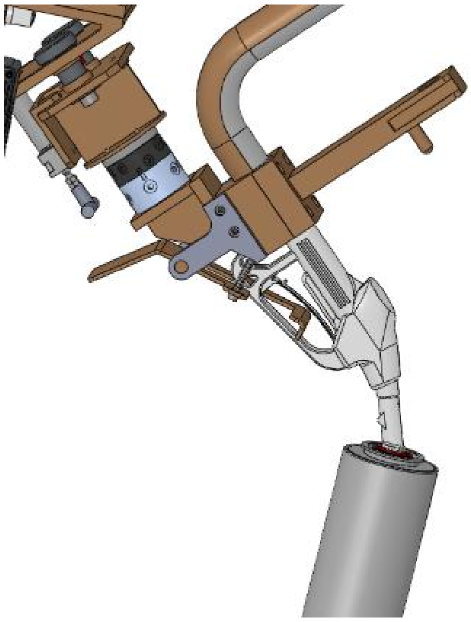

Figure 2 Partial Schematic Diagram of the Automatic Oil Injection Process for Hydraulic Shock Absorbers

4. Selection and Verification of Key Structural Components

In robotic automated oil filling systems, load matching and structural strength are critical factors for ensuring stable operation. The robot's rated load capacity directly determines the maximum total weight of the end-effector and its attached components. The system discussed in this paper is designed based on the robot's load capacity of 20kg. Actual weighing confirms that the total weight of the fixture device (including the oil gun) is 12.46kg, which is significantly below the robot's maximum load. This not only fully meets the load requirement but also provides a substantial safety margin for dynamic loads during robot movement. Similarly, the quick-change plate, serving as the interface between the robot and the end-of-arm tooling, has a load capacity of 10kg. The actual combined weight of the installed gun holder and oil gun is 4.82kg, which also falls within the safe range, ensuring structural rigidity and motion stability during both the gun grasping process and the oil filling operation.

While the six-degree-of-freedom movement of the robot body provides the primary spatial positioning capability, completing the precise oil filling action relies on a series of auxiliary pneumatic components. Specifically, a three-finger pneumatic gripper is used in the system to clamp the piston rod. This gripper can provide a clamping force of 187N. The maximum weight of the piston rod to be clamped is 2.69kg, resulting in a gravitational force of only approximately 26.4N, which is far less than the clamping force. Therefore, the clamping process is safe and reliable, with no risk of slippage.

On the other hand, triggering the oil gun's trigger is the key action for completing the oil filling, and its power is supplied by a push cylinder with a bore diameter of 16mm. Under standard atmospheric working pressure, this cylinder provides a theoretical output force of 18.1N. Additionally, the system is equipped with two springs, each with an elastic coefficient (K) of 1.7N/mm, which act as auxiliary force-applying elements. When the oil gun trigger is in the engaged state, each spring is compressed by 4.5mm, providing a support force of 7.65N per spring, resulting in a combined elastic force of 15.3N from both springs. In practice, a minimum operational force of 20N is required to successfully activate the oil gun trigger.

Force analysis further reveals that the component of the cylinder's output force acting in the direction of the trigger's movement is 9.05N. Thus, the combined force from the springs and the cylinder's thrust can reach 24.35N. Furthermore, the additional resistance posed by the mass of the push component itself (0.21kg), with a gravitational force of approximately 2.1N, must be considered. Therefore, the actual operational force required is the sum of the force needed to overcome the trigger's activation threshold and the gravity of the push component, totaling 22.1N. The currently provided combined force of 24.35N still exceeds this value, indicating that the combined design of the cylinder and springs can reliably achieve the trigger pushing function.

In summary, this automated oil filling system is not only rational and reliable in terms of load distribution, meeting the performance limits of the robot and quick-change plate, but also ensures the feasibility and stability of key pneumatic actuator actions through detailed mechanical calculations. This provides a solid foundation for the efficient and accurate execution of the automated oil filling task.

5. Conclusion

This paper focuses on the research and design of a robotic end-effector structure for the automated oil filling of hydraulic shock absorbers. Aimed at achieving an intelligent and high-efficiency oil filling process, the design integrates multiple technical aspects including functional analysis, mechanical design, and control systems. Starting from the overall functional requirements of the fixture system, the paper identifies its core tasks, such as grasping, positioning, and oil filling, and subsequently elaborates in detail on the mechanical composition of the fixture. This includes components like the quick-change device, actuating cylinders, force sensing unit, and the oil gun integration module.

Regarding the workflow, the system utilizes vision guidance to position the robot relative to the workpiece, employs the quick-change mechanism to automatically pick and place the oil gun, and executes integrated, metered oil filling to accomplish the precise oil delivery task. The research also includes detailed static analysis and stress verification of key load-bearing components—such as the pneumatic gripper, push cylinder, and connection structures—ensuring their reliability and durability under working loads.

The notable advantages of this fixture structure lie in its simple yet highly practical design, combining a high degree of automation with excellent integrability, which aligns with the core demands for intelligence and efficiency in modern mechanical systems. Its successful application can not only achieve complete automation of the shock absorber oil filling process, effectively reducing the assembly line's reliance on manual labor, but also significantly mitigate quality fluctuations and safety risks associated with manual operations. This contributes positively to enhancing the assembly quality of key components in the rail transportation sector and advancing production line technology [10].

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