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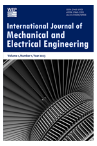

Design of an Auxiliary Manipulator for Threaded Hole Machining in Narrow Spaces

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ABSTRACT

In mechanical manufacturing and daily maintenance, it is often necessary to process threaded holes on large components in narrow spaces such as pipes or corners. Traditional machine tools cannot operate due to spatial constraints, while handheld devices struggle to guarantee accuracy. This study designs an auxiliary machining system based on robotic arm technology to address the challenge of threaded hole machining in confined spaces. The manipulator integrates a magnetic base, a feed mechanism, angle and height adjustment devices, a laser positioning system, and a drilling power unit. The rotary cutting motion is achieved by a DC motor driving a gear reducer; the feed motion is accomplished via a manually operated rack and pinion mechanism; and positioning is realized by two linear infrared lasers arranged at a 90° cross angle. This paper focuses on presenting the overall scheme, key mechanism designs, and working principles of the manipulator. It also includes the design and calculation of the rack and pinion transmission for the feed mechanism. Finite element analysis was performed on critical load-bearing components (e.g., the handle) using SolidWorks software to verify structural safety. The design features a small size, high flexibility, and convenient operation, making it suitable for various narrow space scenarios and capable of significantly improving machining efficiency and precision.

KEYWORDS

Drilling Device; Feed Mechanism; Manipulator Design; Auxiliary Machining.

1. INTRODUCTION

As a foundational industry of the national economy, the development level of mechanical manufacturing is directly related to a country's industrial strength [1]. Threaded hole machining, one of the most common processes in mechanical manufacturing, is widely used in the assembly and connection of various equipment [2]. However, in engineering practice, situations often arise where threaded holes need to be machined inside pipes, in cabinet corners, or within gaps of complex components—collectively referred to as narrow spaces. Traditional large drilling machines or machining centers are too bulky and immobile to operate in such spaces [3]. While conventional handheld electric drills or impact drills are flexible, they rely entirely on manual operation, making it difficult to ensure hole perpendicularity, positional accuracy, and consistency in batch processing. This is particularly challenging in confined spaces with obstructed vision and limited arm movement, where machining difficulty and labor intensity are significantly increased, potentially even leading to safety incidents [4].

To address the aforementioned challenges, industrial robot or manipulator technology demonstrates unique advantages. Manipulators are programmable, offer high precision and flexibility, and can operate in hazardous or constrained environments, having found mature applications in fields such as welding, spraying, and handling [5]. In recent years, research on specialized manipulators for specific scenarios has gradually increased. For example, Xie Junxian et al. designed a manipulator for handling bagged goods in narrow spaces [6]; Ma Xinhe et al. researched a hydraulically controlled manipulator-type water drill system [7]. These studies provide valuable references for mechanized operations under specific working conditions. However, there are relatively few reports on the research and design of integrated, portable auxiliary manipulator systems specifically aimed at high-precision threaded hole machining in narrow spaces[8].

Based on this, this study proposes and designs an auxiliary manipulator for threaded hole machining in narrow spaces. The design aims to integrate the precision control of small machine tools with the flexible portability of handheld tools. Through modular design, it incorporates magnetic adsorption fixation, multi-degree-of-freedom pose adjustment, laser vision-assisted positioning, and a combined manual/powered feed and cutting system. This addresses problems such as difficult positioning, challenging operation, and low accuracy when machining threaded holes in confined spaces. This paper first elaborates on the overall design scheme and working principles of the manipulator, then provides detailed design analysis of its key mechanisms. Finally, the structural reliability of critical components is verified through finite element analysis, aiming to provide a feasible technical solution for engineering applications in related fields.

2. OVERALL SCHEME DESIGN

The auxiliary manipulator for threaded hole machining is a specialized device designed for hole machining in narrow spaces commonly encountered in mechanical manufacturing, such as pipes or corners. Its primary objectives are to solve problems like inconvenient operation and difficulty in ensuring accuracy caused by spatial limitations. This design aims for a small volume, light weight, convenient operation, and good rigidity and stability. The manipulator mainly consists of the following functional modules: a magnetic base, a feed device, an operating handle, adjustment devices, a reducer, a drill bit, and a laser positioning system.

2.1. Complete Equipment Design Scheme

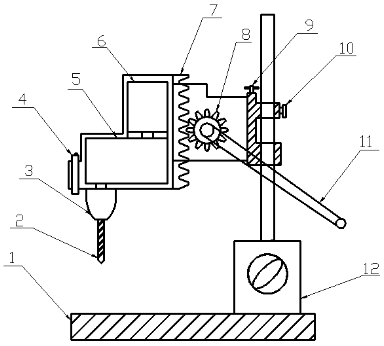

Figure 1. Schematic diagram of the auxiliary manipulator for threaded hole machining in narrow spaces (1-Workpiece to be processed; 2-Drill bit; 3-Drill chuck; 4-Laser locator; 5-Reducer; 6-Motor; 7-Rack; 8-Pinion; 9-Fixing pin; 10-Positioning pin; 11-Handle; 12-Magnetic base)

The overall layout of the manipulator is shown in Figure 1. The required rotary cutting motion for drilling is transmitted from the motor (6) through the gear reducer (5) to the drill chuck (3) and drill bit (2). The feed motion is achieved by manually rotating the handle (11), which drives the pinion (8) meshing with the rack (7) fixed on the side of the reducer housing. This moves the entire drilling unit linearly along the guide slide, controlling the drilling depth. The main body of the manipulator is fixed to the workpiece (1) surface via a magnetic base (12), facilitating movement and positioning.

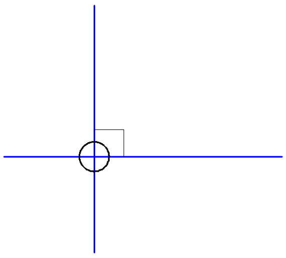

Figure 2. Schematic diagram of the laser positioning system

To adapt to machining requirements at different angles within narrow spaces, the manipulator incorporates an angle adjustment mechanism. This allows the drilling unit to rotate around the X-axis within a range of ±60° and be secured with threaded pins. Simultaneously, a height adjustment mechanism, which slides on a column, enables changing the position of the drilling unit along the Z-axis, achieving a minimum working space of 300 mm. The positioning function is realized by two linear infrared lasers (4) fixed on the manipulator. They are installed at a 90° angle, and the intersection point of their laser beams indicates the center of the hole to be machined, as shown in Figure 2. This positioning system remains collimated as the manipulator's posture is adjusted, ensuring machining accuracy.

2.2. Key Mechanism Design

2.2.1. Feed Mechanism Design

The feeding mechanism employs a rack and pinion transmission system, with its 3D model presented in Figure 3. The front arm of the drilling unit is designed with a movable guide rail, which facilitates precise linear movement along the Z-axis while providing essential structural support. Mechanical limit blocks are installed at both the upper and lower ends of the rail to strictly define the travel range and prevent over-travel, thereby ensuring operational safety. This integrated design of transmission, guidance, and limiting mechanisms not only guarantees smooth motion and positioning accuracy but also incorporates multiple safety features to mitigate operational risks, meeting the reliability requirements for industrial production environments.

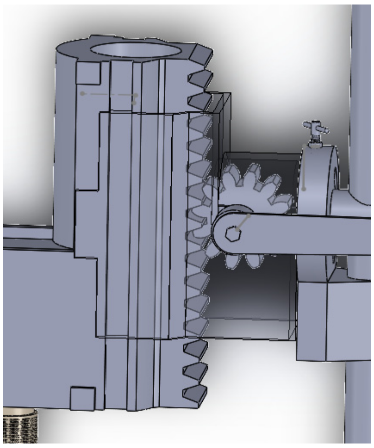

Figure 3. 3D model of the feed mechanism

2.2.2. Adjustment Mechanism Design.

The adjustment mechanism of the equipment adopts a dual-module integrated design for height and angle, with the overall structure shown in Figure 4. Height adjustment is achieved by sliding the manipulator housing along the column, incorporating a low-friction linear guide system to ensure smooth vertical movement. After positioning, a quick-release locking mechanism is engaged, where a hardened steel positioning pin interlocks with a series of pre-machined locating holes on the column, providing rigid fixation under load and guaranteeing repeatable positioning accuracy. The angle adjustment module consists of a stationary support disk and an indexable rotating disk. By operating a manual lever-actuated release mechanism, the rotating disk—along with the drill bit assembly—can be continuously adjusted within a 120° range (as illustrated in Figure 5). Mechanical stops are installed at both rotational limits to prevent over-travel. This two-stage adjustment system forms a compact and highly adaptable positioning solution, significantly enhancing the manipulator's operational flexibility and accessibility in complex spaces while also improving overall process efficiency and application versatility.

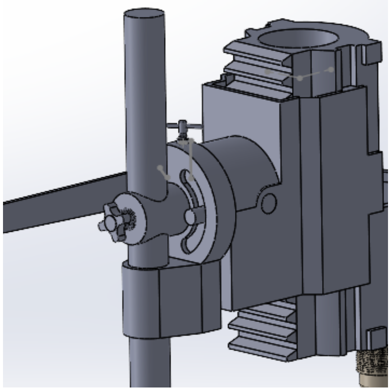

Figure 4. 3D model of the adjustment mechanism

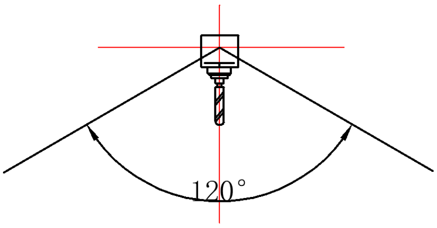

Figure 5. Schematic diagram of drill bit rotation angles (±60°)

3. MOTOR SELECTION AND TRANSMISSION SCHEME

To achieve the required rotary cutting motion for the drill bit, it is necessary to select the drive motor and transmission scheme.

3.1. Motor Selection

Considering the constraints of equipment size and the demand for high transmission efficiency within confined spaces, as well as aligning with the typical operational speed range of electric drills (approximately 0–1300 r/min), this design adopts the NICHIBO MOTOR-997 DC motor as the power source. This motor is characterized by its compact dimensions and high power density, with a rated power of 469 W and a rated speed of up to 19,500 r/min. To adapt the motor’s high rotational speed to the suitable range for drilling operations while ensuring sufficient output torque, a matched two-stage cylindrical gear reducer is integrated. This reduction system effectively steps down the motor speed and amplifies torque, thereby meeting the operational requirements of the drill bit under typical working conditions.

3.2. Overview of The Transmission System

The transmission system primarily consists of the motor, reducer, and output shaft. The output shaft of the motor is directly coupled to the input shaft of the reducer. Through internal multi-stage gear pairs within the reducer, the high-speed input is converted into lower-speed, higher-torque output. The output shaft of the reducer subsequently drives the drill chuck and drill bit into rotation. The reducer is designed with a compact structure to comply with the overall miniaturization objectives of the manipulator. The layout of the entire rotary transmission chain is rationally arranged to ensure high transmission efficiency, smooth operation, and minimal spatial footprint, thereby supporting stable and reliable drilling performance in narrow and complex working environments.

4. FEED MECHANISM DESIGN OF THE MANIPULATOR

The feed motion employs a manual rack and pinion transmission to convert human hand operation into the linear feed of the drill bit.

4.1. Rack and Pinion Design

Materials Selection:The pinion is constructed from 40Cr alloy steel (quenched and tempered, hardness 280 HBS), while the rack is made of 45 steel (quenched and tempered, hardness 240 HBS).

Design Input:Assuming the operator applies a force of 1000 N on a lever arm with a length of 200 mm, the resulting input torque is calculated to be 200 N·m.

Design Process:Design calculations were performed separately based on surface contact fatigue strength and root bending fatigue strength. The final determined parameters include a module of m = 4 mm and a pinion tooth count of z = 12. Key geometric dimensions are provided in Table 1 (pinion data) and Table 2 (rack data).

Strength Verification:Calculations confirm that both the contact stress and bending stress remain below the allowable stresses of the respective materials, verifying that the design meets all required safety standards.

Table 1. Main Geometric Dimensions of the Pinion (m=4 mm, z=12)

Parameter	Symbol	Calculated Value (mm)	Adopted Value (mm)
Pitch Diameter	d	48	48
Addendum	h_a	4	4
Dedendum	h_f	5	5
Tooth Height	h	9	9
Circular Pitch	p	12.57	12.57

Table 2. Main Geometric Dimensions of the Rack (m=4 mm)

Parameter	Symbol	Calculated Value (mm)	Adopted Value (mm)
Pitch	p	12.57	12.57
Space Width	e	6.28	6.28
Tooth Thickness	s	6.28	6.28
Addendum	h_a	4	4
Dedendum	h_f	5	5

4.2. Finite Element Analysis of Critical Components

To ensure structural reliability, static finite element analysis was performed on the main load-bearing components using SolidWorks Simulation. Taking the feed handle as a representative case, which is fabricated from 45 steel and subjected to a 1000 N operational load, the simulation results (Figure 6) indicate that the maximum equivalent von Mises stress is 2.857 MPa. This value is significantly lower than the material's yield strength of 335 MPa. The analysis confirms that the handle structure possesses sufficient strength margin and fully complies with the design safety requirements.

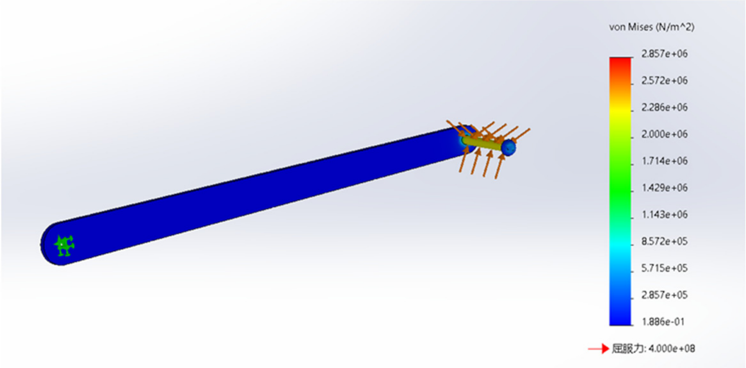

Figure 6. Finite element stress contour plot of the manipulator handle

5. CONCLUSION

This paper addresses the challenge of threaded hole machining in narrow spaces by designing an integrated and modular auxiliary manipulator system. The overall scheme design was completed, and the working principles of its magnetic fixation, multi-degree-of-freedom pose adjustment, laser vision-assisted positioning, and combined manual/powered feed and cutting system were elaborated in detail. The core transmission components (rack and pinion) of the feed mechanism were designed and their strength was calculated. The safety of critical load-bearing parts was verified using finite element analysis. This manipulator combines the precision of machine tools with the flexibility of handheld tools. Through its compact structure and user-friendly operational design, it enables rapid and precise threaded hole machining in confined spaces. This design provides an effective solution for mechanical machining under special working conditions and holds certain engineering application value and promotion prospects.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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