

DESIGN AND FABRICATION OF AN INTEGRATED SLA 3D-PRINTED VENTURI VACUUM GRIPPER

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ABSTRACT

This paper presents the design, fabrication and integrated 3d printed venturi vacuum gripper for an Industrial robotic pick-and-place operations require lightweight, high-response, and energy-efficient end-effectors to improve dynamic performance and productivity. Conventional gripping systems employing pneumatic cylinder-based mechanical grippers and external vacuum generators increase end-effector mass, system complexity, response time, and maintenance requirements. SLA 3D-printed Venturi vacuum gripper developed as an optimized alternative to traditional gripping mechanisms. The proposed system integrates vacuum generation, suction interface, and structural mounting into a single monolithic body using the Venturi effect, eliminating moving components and external vacuum units. Analytical modelling based on Bernoulli's principle and continuity equations was used to size the Venturi geometry. The gripper was fabricated using Tough (ABS-like) SLA photopolymer resin and validated through structural simulation and experimental testing on an Epson T6 six-axis industrial robot. Experimental results demonstrated approximately 80% reduction in end-effector weight, improved vacuum response time, enhanced robot acceleration, reduced cycle time, and nearly 90% reduction in manufacturing cost compared to the existing pneumatic system

KEYWORDS

Venturi Vacuum Gripper, Additive Manufacturing, SLA 3D Printing, Robotic End-Effector, Industrial Automation.

1. INTRODUCTION

Robotic automation has become a critical component of modern manufacturing systems, especially in high-speed assembly, packaging, and material-handling operations. Although advancements in robotic manipulators have improved precision and speed, overall system performance is strongly influenced by the design of the end-effector. These systems introduce excessive mass at the robot wrist, reducing acceleration capability and increasing cycle time. Increased mechanical complexity also results in higher maintenance requirements and energy consumption.

With the advancement of additive manufacturing and fluidic design optimization, it is now possible to integrate multiple functional components into a single monolithic structure. This research proposes a fully integrated 3D-printed Venturi-based vacuum gripper designed to reduce weight, improve response time, and simplify system architecture for industrial robotic applications.

2. LITERATURE REVIEW

Vacuum-based gripping systems utilizing the Venturi principle have gained significant attention in industrial automation due to their fast response, simple structure, and minimal moving components. The operating principle of these systems is based on the pressure drop created when compressed air passes through a converging–diverging nozzle, generating suction at the side port according to Bernoulli’s principle and conservation of momentum. Classical fluid mechanics texts explain that the pressure–velocity relationship in such devices depends strongly on nozzle geometry, throat diameter, and diffuser design, which influence flow acceleration, pressure recovery, and overall efficiency [1]–[3].

Previous research has shown that the geometry of the Venturi nozzle plays a crucial role in determining the vacuum generation efficiency and air consumption. Optimization studies have demonstrated that appropriate selection of throat diameter and diffuser angle can significantly improve vacuum performance while reducing compressed air usage. For instance, Li et al. reported that optimized Venturi configurations could improve vacuum recovery efficiency by up to 30% compared with conventional designs [6]. Furthermore, computational fluid dynamics (CFD) simulations have been widely used to analyze flow behavior within Venturi devices, allowing researchers to study velocity distribution, pressure gradients, and turbulence characteristics in detail. Chen et al. demonstrated through CFD analysis that geometric optimization of Venturi nozzles can enhance flow uniformity and improve vacuum stability [7].

Additive manufacturing has recently emerged as a promising approach for fabricating compact and lightweight pneumatic devices with complex internal geometries. Compared to traditional machining, additive manufacturing allows the integration of internal flow channels, reduction in part count, and greater design flexibility [4]. Reviews of additive manufacturing technologies highlight their ability to produce functional components with embedded features that would be difficult or impossible to manufacture using conventional processes [5]. These capabilities are particularly beneficial for Venturi-based vacuum systems, where internal channel design strongly affects flow performance and system efficiency.

In robotic manipulation and automated handling applications, vacuum grippers are commonly preferred for handling flat, non-porous objects such as glass sheets, electronic components, and metal plates. Comparative studies between vacuum and mechanical gripping systems have indicated that vacuum grippers offer advantages such as faster actuation, reduced mechanical complexity, and lower maintenance requirements [8]. In modern automated manufacturing environments, these systems are widely integrated with robotic manipulators and pick-and-place equipment to improve productivity and reliability [9], [10].

Despite these advantages, several challenges remain in the design and fabrication of compact Venturi-based vacuum generators using additive manufacturing. Leakage through porous printed structures, optimization of internal flow channels, and maintaining structural integrity under pneumatic loading conditions are critical concerns. The present study addresses these challenges through analytical design of a Venturi-based vacuum generator, fabrication using

stereolithography (SLA) additive manufacturing, structural validation, and experimental benchmarking against a conventional pneumatic gripping system.

3. OBJECTIVE AND METHODOLOGY

3.1 Objectives

The primary objective of this project is to design, fabricate, and validate an integrated SLA 3D-printed Venturi vacuum gripper for industrial robotic pick-and-place applications, aimed at reducing end-effector weight, system complexity, and manufacturing cost while maintaining sufficient holding performance and structural integrity:

- To design a Venturi-based vacuum gripper using fluid mechanics principles.
- To fabricate an integrated monolithic gripper using SLA 3D printing technology.
- To reduce end-effector weight compared to conventional pneumatic gripping systems.
- To eliminate external vacuum generators and simplify system design.

3.2 Methodology

The methodology of this project began with identifying the limitations of the existing pneumatic cylinder-based gripping system used in industrial robotic applications. Excessive weight, higher inertia, and dependence on external vacuum generators were recognized as the primary drawbacks affecting robot performance and efficiency.

An analytical design approach was then adopted to develop a Venturi-based vacuum generation mechanism. Fundamental fluid mechanics principles, including Bernoulli's equation and the continuity equation, were applied to determine the required pressure differential and airflow velocity to achieve sufficient holding force.

Based on the analytical calculations, a detailed 3D CAD model of the integrated gripper was developed. The design incorporated a converging nozzle, throat section, diffuser region, and suction chamber within a single compact structure to ensure functional integration.

Material selection was performed considering strength, durability, and airtight properties. Tough ABS-like SLA photopolymer resin was chosen, and the component was fabricated using stereolithography (SLA) 3D printing technology to achieve precise internal geometries. Structural validation was carried out using finite element analysis to evaluate stress distribution and factor of safety under operating pressure conditions. Finally, experimental validation was conducted on an industrial robot to measure vacuum pressure, holding force, and dynamic pick-and-place performance, and the results were compared with the conventional system.

4. EXPERIMENTAL SETUP

The experimental validation of the developed Venturi vacuum gripper was carried out using an industrial robotic platform. An Epson T6 six-axis articulated robot was used to evaluate the real-time pick-and-place performance of the integrated gripper. The setup included a regulated compressed air supply system capable of delivering air pressure in the range of 3 to 6 bar. Vacuum pressure sensors and digital gauges were connected to measure suction performance accurately.

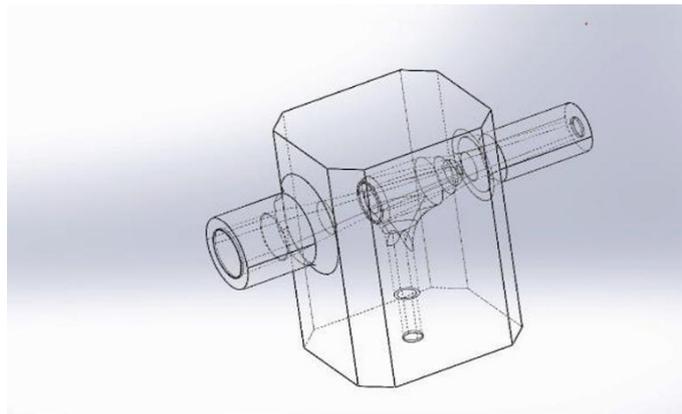
Vacuum generation tests were conducted by varying the supply pressure and recording the corresponding vacuum pressure developed at the suction port. Holding force capability was evaluated using standard test components with known weights. The response time of vacuum generation and release was also observed during repeated gripping cycles.

Dynamic performance testing was performed under actual pick-and-place conditions. Multiple trials were conducted to ensure repeatability, and the obtained results were compared with the existing pneumatic cylinder-based gripping system to assess improvements in weight, efficiency, and cycle time.

5. RESULTS AND DISCUSSION

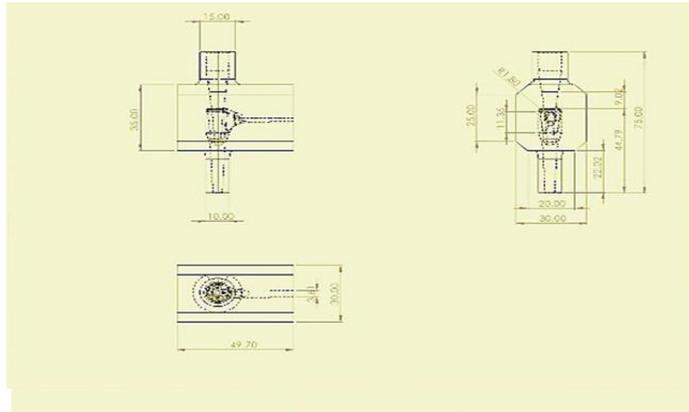
At an input pressure of 5 bar, the system achieved an average vacuum pressure of approximately 40 kPa. This negative pressure was sufficient to create strong suction at the gripping surface and maintain stable attachment throughout the handling process.

Based on the measured pressure differential and suction cup area, the generated holding force was approximately 50 N, which was significantly higher than the required holding force of around 21 N for lifting the test components weighing about 0.72 kg (four components of 0.18 kg each).



3D Model of Venturi Effect Gripper

Structural analysis results indicated a maximum stress of nearly 1.2 MPa, which is well below the allowable strength of the SLA Tough resin. The calculated factor of safety was greater than 15, the conventional pneumatic gripper assembly weighed approximately, 2.5 kg, whereas the proposed integrated gripper weighed only 0.5 kg, resulting in nearly 80% weight reduction.



Three Views of Model

Dynamic testing showed improved acceleration and smoother robot motion. The reduced mass contributed to a noticeable decrease in cycle time and improved operational efficiency during repeated pick-and-place operations. The elimination of external vacuum generators and pneumatic cylinders reduced overall manufacturing cost by approximately 90%, making the proposed system both economically and technically advantageous for industrial applications.

6. CONCLUSION

The design and fabrication of an integrated SLA 3D-printed Venturi vacuum gripper successfully demonstrated that additive manufacturing can enable lightweight, high-performance robotic end-effectors. The monolithic design eliminated mechanical complexity, reduced weight by 80%, improved vacuum response time, enhanced robot acceleration, and reduced system cost by nearly 90%. Structural validation confirmed safe operation under pneumatic pressure. The results validate the effectiveness of integrating fluidic design and additive manufacturing for next-generation industrial robotic tooling.

7. FUTURE SCOPE

- Future research may focus on:
- CFD-based multi-objective optimization of Ventur geometry Integration of vacuum pressure sensors within printed body
- Hybrid materials for improved thermal and chemical resistance Scaling for multi-port industrial automation systems
- Long-term durability testing under continuous industrial cycles.

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