Design of a Light-Weight, Low-Cost Three-Finger End Effector

Mohammad Al Mashagbeh[1],*, Migdad Tamimi[2], and Romil Al-Adwan[1]

[1] Department of Mechatronics Engineering, University of Jordan, Amman, Jordan
[2] Department of Computer Engineering, University of Jordan, Amman, Jordan
Email: m.mashagbeh@ju.edu.jo (M.A.M.); mqd8230581@ju.edu.jo (M.T.); romil.aladwan@ju.edu.jo (R.A-A.)
*Corresponding author

***Abstract*—Robotics research has gotten a lot of attention in recent years, thanks to the growing development and commercialization of industrial and service robots. For experimental investigations, the bulk of researchers working on robot grasping and object manipulation use commercially available robot manipulators outfitted with various end effectors. However, commercially available robotic grippers are sometimes costly and difficult to customize for individual applications. This work will offer a low-cost three-finger robotic gripper platform for research and teaching applications to expand the range of robotic end effectors freely available to researchers and Industrial users. The gripper's 3D design model is given and produced utilizing a few 3D-printed components and an off-the-shelf servo actuator. 3 fingers, a gear train mechanism, and a motor drive are detailed in detail, along with an overall gripper assembly design, followed by drawings and a discussion of gripper gripping performance and prospective gripper platform adjustments.**

***Keywords*—3-Finger Gripper, design, 3D printing, gear, simulation**

I. INTRODUCTION

Picking things from one location to another, or from one location to a machine, is a vital activity in industrial automation. In this setting, the design of a suitable end effector that effectively interacts with a wide range of objects is crucial. The end-effector must enable robust picking in a range of configurations, while simplicity and cheap cost are critical facilitators of adoption. It is much desired to have versatile robotic equipment that can work in a minimally constructed setting where people are also present. This might encourage the use of anthropomorphic hands, which strive to execute human jobs well by replicating their anatomy. Indeed, highly articulated humanoid hands have been around for a while [1] and are becoming better [2]. Few are really in use because to the enormous work and cost required to calibrate, maintain, and repair such systems. Simpler end-effectors can give a level of generality unreached by most autonomous systems [3] and are suited for the automation sector, where simple gripping solutions can be helpful owing to rigorous requirements on speed, accuracy, and dependability [4]. Underactuated and compliant systems are especially popular because they require fewer actuators to control several degrees of freedom and are less complicated and often cheaper to construct [5–7].

3D printing is widely acknowledged as a beneficial and efficient technique for the low-cost production of specialized research and educational equipment. Because of the capacity to produce numerous 3D item designs from Computer-Aided Design (CAD) models in a reasonably short period of time with minimal expense and effort, [8–10]. Researchers and educators can benefit from cheaper costs, simpler equipment maintenance and repair, more spare part availability, and greater relevance and flexibility in adapting to research demands and education curriculum [11]. Academic research on robotic grasping and object handling has acquired substantial attention in recent years, owing to the growing development and commercial deployment of industrial and service robots [12–15]. Anthropomorphic hands are commonly employed in human-like grasping and object manipulation studies when recreating human hand functionality is necessary [16, 17]. Three-finger grippers with relatively basic designs, on the other hand, are enough for conducting research and teaching activities on item manipulation in industrial and service applications [18]. Examples of gripper designs include Robotiq 3-Finger Adaptive Robot Gripper [19], Pneumatic gripper MPZ [20], and Flexible, Large-Stroke 3-Finger Gripper 3FG15 [21]. The OnRobot 3FG15 gripper stands as a pinnacle of innovation in the field of robotic end-effectors. With its three-fingered design, the OnRobot 3FG15 gripper offers unparalleled flexibility and adaptability for a variety of robotic manipulation tasks. Each finger of the gripper is meticulously engineered to provide precise control over grip force and position, ensuring the secure handling of objects across diverse sizes and materials. The gripper is equipped with advanced sensors and actuators, allowing for real-time adjustments to grip strength and position, thereby enhancing efficiency and productivity in industrial automation settings. Additionally, the gripper's soft, anti-slip fingertips offer a delicate touch, minimizing the risk of damage to fragile objects while maintaining a reliable grip. The compact and lightweight nature of the OnRobot

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3FG15 gripper facilitates seamless integration with robotic systems, enabling rapid deployment and versatility on the factory floor. In summary, the OnRobot 3FG15 gripper represents a significant advancement in robotic grasping technology, offering a combination of precision, reliability, and adaptability essential for modern automated manufacturing processes.

The Robotiq 3-Finger Adaptive Robot Gripper is a flexible robotic end-effector that can handle items of various forms, sizes, and weights. It has three individually controlled fingers that can adapt to the geometry of objects, allowing for accurate and secure grabbing in a variety of manufacturing and industrial environments. The gripper uses compliant joints and sensors to detect item properties and modify its grasp accordingly, increasing its flexibility and dependability when performing complicated tasks. Its simple programming interface and interoperability with multiple robot platforms make it a popular choice for automation applications that need dexterous manipulation. Overall, the Robotiq 3-Finger Adaptive Robot Gripper provides a reliable solution for nimble and flexible robotic manipulation activities.

This study uses a design and proposes a low-cost 3D-printed three-finger robotic gripper, comparable to the 3FG15 industrial gripper, to expand the range of robotic end effectors freely available to researchers and industrial users. The proposed gripper platform design is easily customizable and extendable for use in a variety of research and educational projects; the driving mechanism used in the 3FG15 will be studied and replaced with a better one; and metal gripper parts will be studied and replaced with 3D-printed ones. The gripper's 3D model was produced with Autodesk Inventor CAD software.

The following is how the paper is organized. Section II discusses the three-finger robotic gripper's design and prototype assembly, which includes the finger, gear train, motor, and housing. Section III presents the simulation, and results of the gripper prototype, which is followed by discussion and conclusion in Sections IV and V, respectively.

II. DESIGN AND PROTOTYPING

A. Finger Design

As discussed before, the goal of this paper is to develop a gripper with the lowest possible cost and weight. We have made the most of off-the-shelf components and modified the gripper structure for low-cost 3D printing prototyping in order to meet this demand. Simultaneously, the intended design ought to guarantee identical cylindrical object grasping functionality and identical gripper adaptive gripping capability as 3FG15. In this work, the base and the tip were kept the same as the 3FG15, the link between them was modified to ensure the robustness of the model. Based on the same idea, Autodesk Inventor CAD was used to develop the finger link, which is shown in Fig. 1.

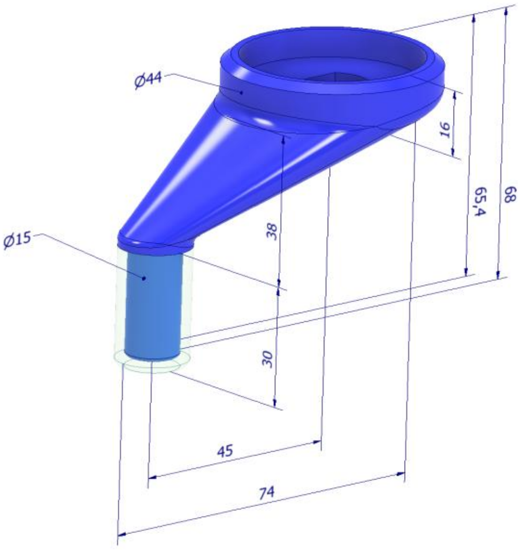


Fig. 1. 3D depicted finger's three-dimensional design (units in mm).

The surfaces of the finger are basic enough that the printer support material can be physically removed without much effort. The shape of the body was modified in order to replace the metal one of the 3FG15 finger with a 3D printed material.

B. Gear Train Design

Through the use of a gear train transmission system, a single actuator powers the gripper's three fingers. Fig. 2 displays the actuation's 3D representations. The worm gear that is directly attached is driven by a servo actuator that is fastened to the body. The worm gives the worm wheel, which is attached to a planetary gear train by means of the main shaft, rotating motion. The planetary gears are immediately attached to all three fingers, which are driven concurrently from their starting positions. The complex mechanism described in the datasheet for the 3FG15 gripper will be replaced by this configuration, which uses a worm gear to ensure that the finger actuation mechanism cannot be reversed. It's also possible to change the actuator and set up custom gear train speed/torque ratio depending on the needed outcome without modifying the overall gripper design.

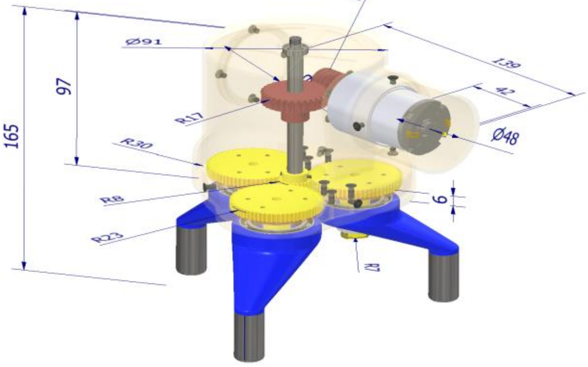


Fig. 2. 3D design of the gear train (units in mm).

The gear train design has a minimum amount of small size parts because of potential constraints in generating strong and precise miniature parts that may be brought on by the printing material qualities and/or low resolution of an inexpensive desktop 3D printer. On the other hand, if different gears are needed, it is simple to swap out the current gears for them. If necessary, a more robust gear train with fewer gears can be designed using off-the-shelf metal gear components, more sophisticated additive manufacturing machinery, or both.

C. Gripper Assembly Design and Housing

The three-finger robotic gripper presented here is made up of three 1-DOF fingers, a base, a planetary gear train set, a worm gear train set, and an actuator. The fingers are connected in a circular fashion, 120 degrees apart. As shown in Fig. 2, this permits the planetary gears of the fingers to be driven by a single actuator via the actuating worm. This finger positioning is preferred for holding cylindrical items of various diameters.

The proposed robotic gripper's CAD model and 3D-printed assembled prototype are shown in Fig. 2. The main prototype constructions will be made of Acrylonitrile Butadiene Styrene (ABS) plastic. ABS is a sturdy, long-lasting production-grade thermoplastic utilized in a variety of sectors, and it is an excellent material for conceptual prototyping [22]. As an actuator for the robotic gripper prototype, a JGB37-520 12 V 110RPM Encoder Motor with wheel Kit [23] is utilized, which avoids the need for sophisticated electrical circuits and encoders for motor position control. Controlling the motor is simple thanks to the two-channel encoder, which allows for simple integration of the gripper with other robotic setups. At 12 V power supply voltage, the motor's output torque is 0.98 Nm and 110 rpm rotational speed.

Fig. 3 depicts an exploded assembly perspective of the gripper design. The actuator is bolted to a motor bracket, which is positioned at the bottom on a triangular circular-shaped base. Bearings connect the fingers and planetary gears to the base, the worm to the motor shaft, and the worm gear and planetary sun to the main shaft, which is connected to the base and main cover by additional bearings. A series of bolts connects the maintenance and motor covers to the main cover. Depending on the robotic arm utilized, mounting holes for the gripper can be made in a CAD software or easily drilled. To reduce slippery, a rubber shroud can be used for the tip of the finger. The gripper's overall weight in its current configuration is roughly 618 g, which is around half the weight of the 3FG15 gripper.

Table I shows the bill of materials for the gripper. It comprises a list of gripper elements together with their quantities and costs in order to determine the entire cost of the gripper prototype. Rough calculations reveal that the whole cost of the gripper prototype should not surpass USD 300, making gripper manufacture very appealing in terms of cost when compared to similar commercial grippers that cost several thousand USD. The cost of 3D-printed parts is computed based on their weight. All parts in Table I are based on the prices in the local markets. Actuator, screws, nuts, pins, and bearings are readily accessible for purchase locally or on manufacturer websites.

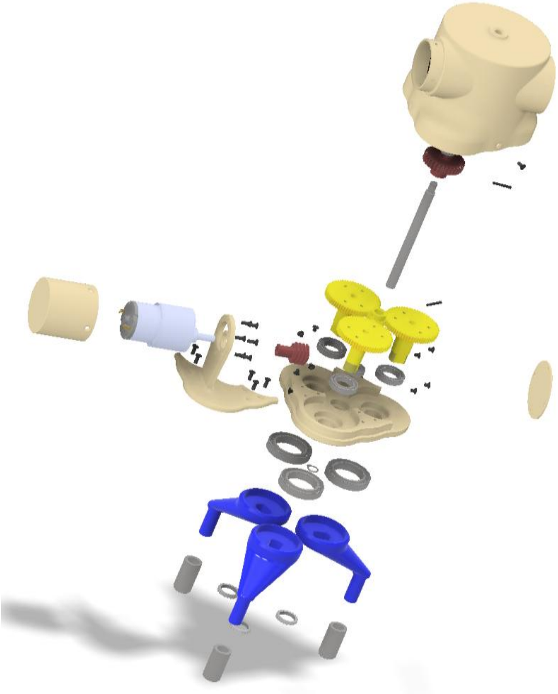


Fig. 3. Exploded view of the 3-finger gripper.

TABLE I. BILL OF MATERIALS FOR THE OPEN-SOURCE 3D-PRINTED GRIPPER

Item	Part Number	Weight [g]	QTY	Cost [USD]
1	Gripper Base	71.5	1	15.6
2	Main cover	80.4	1	31
3	Motor Bracket	18.3	1	5.4
4	Motor Cover	16	1	5.4
5	Maintenance Cover	3.0	1	1.0
6	Main Shaft	40.8	1	7.2
7	Spur Gear1	1.2	1	0.8
8	Spur Gear2	13.2	3	2.8
9	Worm	3.0	1	1.7
10	Worm Gear	6.8	1	1.5
11	Finger	31.2	3	7
12	Finger Jacket	24.9	3	15.5
13	Nut	1.0	3	0.2
14	JGB37-520 Motor	147.0	1	31.7
15	Bearing 71805	19.0	3	57.0
16	Bearing 61802-2RZ	7.0	3	41.0
17	Bearing 628/8-2RS1	4.0	1	10.0
18	Bearing 618/6	2.0	1	9.0
19	ANSI B27.7-8, R(1)	1.0	2	0.4
20	ISO 2339-B-2×16	1.0	2	0.1
21	ISO 7046-1-M3×8	1	12	0.3
22	ISO 7046-1-M3×6	1	3	0.3
23	ISO 7046-1-M3×4	1	8	0.3
-	Total	618	57	245

D. Component Dimensions and Key Parameters

To enhance reproducibility and allow other researchers to accurately replicate the three-finger gripper design, Table II provides the dimensions and key parameters for each primary component in the assembly. These specifications include essential details such as the material, dimensions, and weight of each part, facilitating adaptation and potential modifications for various research or industrial applications.

TABLE II. DIMENSIONS AND KEY PARAMETERS OF GRIPPER COMPONENTS

Component	Dimensions (mm)	Material	Key Parameters
Gripper Base	112×106×21	ABS Plastic	Mass: 71.5 g
Main Cover	125×120×92	ABS Plastic	Mass: 80.4 g
Motor Bracket	74×81×69	ABS Plastic	Mass: 18 g
Motor Cover	48×42	ABS Plastic	Mass: 16 g
Maintenance Cover	50×1.5	ABS Plastic	Mass: 3 g
Finger	44×74×65.4	ABS Plastic	Mass: 31.2 g
Worm Gear	34×18	ABS Plastic	Torque Ratio: 1.068 Nm
Worm	18×25.5	ABS Plastic	Torque Ratio: 1.068 Nm
Spur Gear 1	16.4×11.5	ABS Plastic	Gear Module: 1.2
Spur Gear 2	46×38	ABS Plastic	Gear Module: 1.2
Main Shaft	109×8	Mild Steel	Mass: 40.8 g
Actuator Motor	Model No. JGB37-520	Metal, Plastic	Torque: 0.98 Nm, Speed: 110 rpm
Gear Train	Customized Gear Ratios	-	Ratio: 3:1 for planetary gears
Finger Jacket	15×10×30	Aluminum 6061	Yield Strength: 275 MPa

III. RESULT AND SIMULATION

A. *Analysis*

According to the datasheet for the 3FG15 gripper, the maximum gripping force is 240 N, which will be the aim for this job. Based on the geometrical dimensions of the finger, which has an arm length of 44.5 mm, this yields a torque of 10.68 Nm per finger. Therefore, the total torque required to drive the gears is the sum of each torque per finger, which is 32.04 Nm. To obtain this level of torque, the gear ratios of the planetary and worm gear sets were investigated. As a result, the planetary gear ratio must be 3:1, resulting in a 30:1 ratio, and the required torque to drive the worm gear is 1.068 Nm, which is compatible with our chosen motor's maximum torque of 0.98 Nm. The main design was built based on these assumptions and calculations. As shown in Table III, which is taken from the inventor design calculator, the torque, speed, and efficiency (η) of the two trains are compatible with the needed input and output. Since we are not seeking a fast response actuator, these results are fit for the design.

TABLE III. INVENTOR GEAR TRAIN CALCULATOR RESULTS

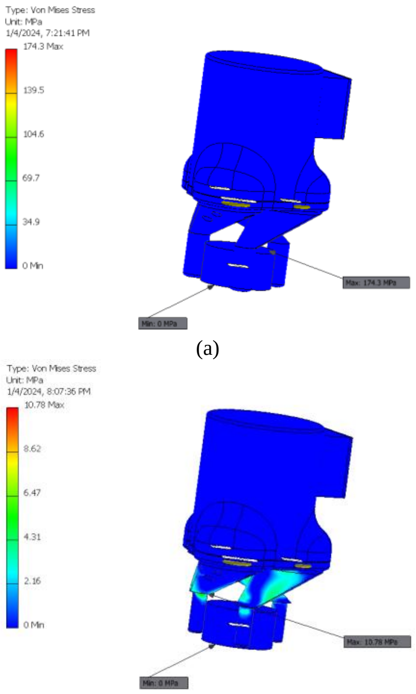
Gear Train	Power (kW)		Speed (Rpm)		Torque (Nm)		η
	Input	Output	Input	Output	Input	Output	
Worm Gear	0.011	0.004	110	3.55	0.98	11.61	0.38
Planetary Gear	0.004	0.004	3.55	1.16	11.61	34.68	0.98

B. *Simulation*

The simulation in this article focused on the finger, and because the goal of the work is to transform metal components into 3D printed ones, the first step was to reverse engineer the 3FG15 finger, and then the model was reduced into a single part to decrease cost and stress as much as feasible. The material used for this project is ABS plastic, and the model was updated depending on the results of several simulations. Finite Element Analysis (FEA) stress analysis was utilized for simulation using Autodesk Inventor software, using static analysis as the research type. Table IV provides mesh parameters, and the simulation's mesh type is tetrahedron, which is ideal for components with complicated and curved shape. The input torque for each finger is 10.68 Nm, and the sample to be grasped is a circular bar of 48 mm diameter made of mild steel [24], allowing the finger to rotate at a 45° angle (half the stroke). The results suggest that it is necessary to increase finger size in order to withstand the high pointed stresses exerted on it, and the fingertip should be coated with a metal jacket; the material chosen for the jacket is Aluminum 6061 [25], which is lighter than steel and has a high yield strength depicts the final acceptable simulation results using the Von Mises stress criteria, and as mentioned in the Fig. 4, the maximum stress on the jacket and finger is 174.30 MPa and 10.78 MPa, respectively, which is reasonable given the chosen material. Table V summarizes the mechanical properties of the materials utilized in the simulation. These results are acceptable for manufacturing, and the modifications were made within the constraints of manufacturing using 3D printing technology. The metal jacket can be easily machined in a standard workshop, and this modification will allow for the design of variant jacket geometries that meet the user's requirements.

TABLE IV. MESH SETTINGS

Avg. Element Size (fraction of model diameter)	Min. Element Size (fraction of avg. size)	Grading Factor	Max. Turn Angle	Create Curved Mesh Elements	Use part-based measure for Assembly mesh
0.1	0.05	1.5	60°	Yes	Yes



(a)

(b)

Fig. 4. Von Mises stress analysis results for (a) jacket and (b) finger.

TABLE V. MECHANICAL PROPERTIES OF THE MATERIALS USED IN SIMULATION

Mechanical Property	Aluminum 6061	ABS Plastic	Steel, Mild
Mass Density (g/cm^3)	2.7	1.06	7.85
Yield Strength (MPa)	275	20	207
Ultimate Tensile Strength (MPa)	310	29.6	345
Young's Modulus (GPa)	68.90	2.24	220.00
Poisson's Ratio	0.330	0.380	0.275
Shear Modulus (GPa)	25.9	0.8	86.3

IV. DISCUSSION

This proposed design of a 3D-printed 3-finger gripper will be simple to alter and modify based on the end-user's demands, whether it is utilized for industrial or educational applications. The grabbing mechanism was designed in a simple manner to save manufacturing costs while also providing an adaptive technique with a high grasping force, which was accomplished using the differential actuation mechanism principle [26]. The proposed design is simpler and more reliable than current underactuation grippers [27, 28], and it allows for additional modification options.

The proposed 3D-printed gripper, which is based on the 3FG1g gripper, a concept originally based on the patented oil filter wrench [29], has been modified to fit for 3D-printing technology, and this modification can be easily changed by other researchers or end-users to fit for their specific application. The finger can be sculpted in a variety of shapes to meet the required geometries, and the material can be replaced with a stiffer one, providing a wider grasping range and reducing the bulky geometry shown in the ABS plastic version. The added jacket to the tips of the fingers can be easily adjusted into a variety of shapes, but removing it is not recommended because direct contact between the workpiece and the ABS plastic will result in plastic deformation of the finger, unless the material is replaced with a 3D-printed metal material such as 17-4-ph-stainless-steel [30]. It is possible to incorporate a force sensor into the jacket in order to precisely measure and control the loads exerted on the gripped object; this method will not only protect the object, but also the gripper finger and its internal parts from permanent deformation; one possible sensor that may be suitable for this type of gripper is the single-zone Force Sensing Resistor [31, 32]. For more accurate and precise localization and recognition of the object, it's possible to integrate a vision system to the gripper platform.

Our gripper is designed for applications where force sensing is not required or is of no significance. A force sensor may be unnecessary for a robotic gripper in applications such as basic pick-and-place applications with homogenous objects, handling hard objects that are unlikely to be harmed, or employing grippers with fixed mechanical stops to avoid over-clamping. Similarly, magnetic or vacuum grippers, which do not require contact, may eliminate force sensors. In addition, soft grippers, such as those used to handle fruits, are designed to gently grasp for objects and may not require force feedback, because their materials naturally limit applied pressure. In such circumstances, eliminating a force sensor simplifies design, reduces costs, and maintains dependable performance.

The modeled gear train has taken up a considerable volume, which can be solved by building multistage planetary gears to minimize the pitch diameter of each planetary, resulting in an upward shift in the equipped area. The worm gear and brushed DC motor, which replaced the Brushless DC motor (BLDC) used in the patented 3FG15 gripper [33], provided the advantage of designing a simple controller and eliminating the need to design a braking system or relying on the stall effect used in BLDC motors, resulting in a lower cost but larger gripper. The used encoder and motor can be changed with a better and more precise ones; it is recommended to utilize servo motors such as MX-28AT servo motor [34].

Table VI compares grippers based on numerous criteria and indicates significant variances. In terms of external gripping stroke, the 3D printed gripper has a range of 40–134 mm, while the 3FG15 gripper has a slightly larger range of 4–152 mm. It is worth noting that the Robotiq gripper lacks precise data in this category. Internally, the 3D printed gripper has a range of 70–164 mm, which exceeds both the 3FG15 gripper (35–176 mm) and the Robotiq gripper (155 mm). When it comes to grip force, the 3D printed gripper outperforms the 3FG15 gripper with a force of 240N, while the Robotiq gripper has a variable range of 10–240 N (Flexible) and 30–70 N. Furthermore, the 3D printed gripper has a much lower mass of 0.62 kg, compared to 1.15 kg for the 3FG15 gripper and 2.3 kg for the Robotiq gripper. Despite its tiny dimensions of 156×158×180 mm, which match those of the 3FG15 gripper, the 3D printed gripper varies from the bigger Robotiq gripper, which measures 233×131×212 mm. The comparison between the three grippers reveals a spectrum of choices based on cost, features, compatibility, ease of use, reliability, and support. The 3FG15 Gripper, priced at $5,710 [35], is tailored for collaborative robots with precise gripping capabilities and integrated force sensing, ensuring consistent performance in collaborative settings and typically includes manufacturer support with an integrated controller. In contrast, the Robotiq Gripper, priced significantly higher at $21,900 [36], offers a robust construction, advanced gripping features, and compatibility with a wide range of industrial robot models, accompanied by comprehensive support services and a built-in controller for intuitive operation. Meanwhile, the 3D Printed Gripper, at $245 without a controller, presents an affordable yet customizable option with variable compatibility and reliance on user knowledge for assembly, maintenance, and controller integration.

The materials used in the study can be altered based on the end-user's needs for a more durable product. The only limitation that appeared was in the diameter of gripping, and as shown in the comparison Table VI, the range is lower than the 3FG15, due to the increase in the geometry of the 3D-printed finger, and this limitation cannot be avoided to protect the product from failures caused by imposed stresses.

TABLE VI. GRIPPERS COMPARISON

Gripper	3FG15 gripper	3D printed gripper	Robotiq gripper [19]
External gripping stroke (mm)	4–152	40–134	N/A
Internal gripping stroke (mm)	35–176	70–164	155
Grip force (N)	10–240 Grip 10–140 Flexible	10–240	30–70
Gripper mass (kg)	1.15	0.62	2.3
General dimensions	156×158×180	156×158×180	233×131×212
Price (USD)	5710	245	21,900

V. CONCLUSION

This study presents a 3D printed design for a 3-finger gripper assembly to assist researchers and end-users in the industrial area. The technology of 3D printing allowed us to build at the lowest feasible cost, and the use of ABS plastic decreased the weight by half when compared to the 3FG15 gripper. Despite this, ABS plastic has several problems such as low UV resistance, limited heat resistance, poor chemical resistance, non-biodegradability, the propensity for warping, the emission of aromas and fumes, bonding issues, and recycling concerns. These difficulties can have an influence on the product's longevity, environmental impact, and usability for different applications.

This study goes into detail about the design, analysis, and simulation of grippers. This design is designed to address the constraints and restrictions of commercial robotic end effectors, such as secret design elements and specifications, stiffness, and pricing. The model design and simulation were done using Autodesk Inventor Professional software, and the spare components were sourced from online websites or local marketplaces. Several methods for modifying and improving this gripper were briefly presented, including touch sensors, vision systems, gear train upgrades, and finger upgrades and modifications.

While 3D printing provides benefits such as quick prototyping and personalization, it also poses obstacles in terms of material characteristics, structural integrity, and manufacturing accuracy. One key drawback is the restricted selection of materials appropriate for 3D printing, which limits the gripper's effectiveness and endurance. Furthermore, the layer-by-layer additive manufacturing technique can cause structural flaws and surface imperfections, compromising gripping performance and dependability. Furthermore, the precision of 3D printing technology limits complicated shapes and small features, making the gripper less adaptable to a wide range of items. Addressing these limits will necessitate advances in material science, printing processes, and post-processing technologies to improve the performance and adaptability of 3D printed robotic grippers.

It is feasible to rebuild this gripper to have four fingers, however, this design must be extensively researched to determine its benefits and drawbacks. A forward-looking vision of the future for this notion is to have a stronger grasp on the cost of size and pricing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Mohammad Al Mashagbeh conducted the research, analyzed the data, and wrote the paper. Migdad Tamimi was responsible for the mechanical design, writing the paper, and conducting the simulations. Romil Al-Adwan handled the validation and reviewed the manuscript. All authors had approved the final version manuscript.

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