

# DESIGN OF THE UR5 ROBOT ARM GRIPPER

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**Abstract:** Developed an electric parallel-jaw gripper to replace pneumatic end-effectors for the UR5 robot at the Technical University of Liberec's Department of Manufacturing Systems and Automation. The project addresses the challenge of maintaining compressed air during field operations, especially when no supply is available. Three design options—a rack-and-pinion, a cam linkage, and a hybrid — were evaluated; the rack-and-pinion was selected. It handles objects from 10 to 50 mm and supports loads up to 5 kg. Force calculations showed a gripping force of 49.24 N and a motor torque of 0.27 Nm for 1 kg loads, with a safety factor of 2. Two prototypes were built. Prototype 1 had issues with rotational stability and power-failure locking, which were fixed in Prototype 2 through redesigns and a switch to a JGY-370 worm-gear motor. Structural analysis confirmed the design's strength with a maximum stress of 22.142 MPa, offering a safety factor of about 3.8. The estimated manufacturing cost is 60–80 EUR, cheaper than commercial options.

**Keywords:** Electric gripper, UR5, Collaborative robot, rack-and-pinion, Worm gear, FDM/FFF 3D printing, PLA, FEA

## 1 Introduction

The Universal Robots UR5 are common in labs and industries, working alongside humans without safety barriers [1]. The UR5, popular in university labs like the Technical University of Liberec, has a 5 kg payload and 850 mm reach, making it highly manoeuvrable and easy to program via PolyScope. Its standard pneumatic end effector is reliable indoors but impractical outdoors or at customer sites without a compressed-air supply. This project aims to develop a self-contained, electrical gripper for the UR5 to handle small prismatic objects 10-50 mm, with a practical load of 1 kg.

The design process included problem analysis, conceptual design, three variants, detailed calculations, and prototype testing, with validation via 3D printing and CNC machining from Departmental resources.

## 2 Design Variants and Requirements

During the preliminary design phase, my thesis supervisor and I developed three mechanical concepts that each transform rotary motor motion into linear finger motion for a parallel-jaw gripper. All have the same 50 mm finger stroke from 10 mm to 50 mm. A load of 1 kg is to be manipulated by the gripper. All custom parts should be manufacturable using departmental machines, such as an FDM/FFF 3D printer and a CNC milling machine. The total gripper weight should be as low as possible; the total payload capacity is 5 kg when a 1 kg object is manipulated, including the gripper and its accessories.

### 2.1 Variant 1 – Rack-and-Pinion (selected)

A single central spur gear (the pinion) is mounted on the motor output shaft and engages two opposing racks simultaneously. Each rack is attached to a separate gripper finger carriage. When the motor turns the pinion clockwise, one rack moves outward while the other moves inward by equal amounts, producing symmetric finger movement. Because both racks are driven by the same pinion, the object being gripped remains centred on the gripper axis,

regardless of its size. This feature is known as the centring grip. The link between the motor's rotation angle and the finger displacement is direct. Variant 1 is positioned as the top choice in the selection matrix.

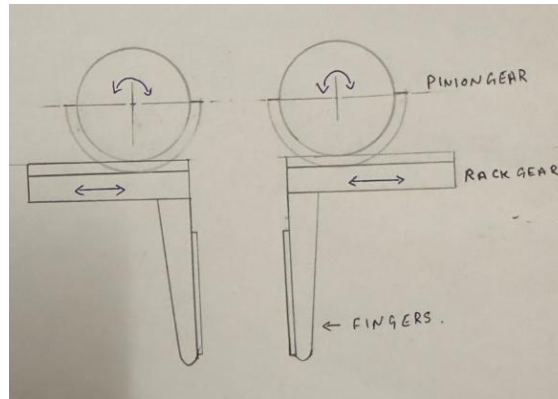


Figure 1: Variant 1  
Parallel rack-and-pinion concept (hand sketch) Source: own

## 2.2 Variant 2 – Cam and Linkage Mechanism

Variant 2 uses a rotating cam profile powered by the motor to generate the main displacement. As the motor turns, the cam moves a follower along a path defined by its outline. This follower's motion is then transmitted to the gripper fingers via a bar linkage. By designing the cam profile carefully. This non-linear motion can be advantageous in applications that need high force at a particular jaw-open position.

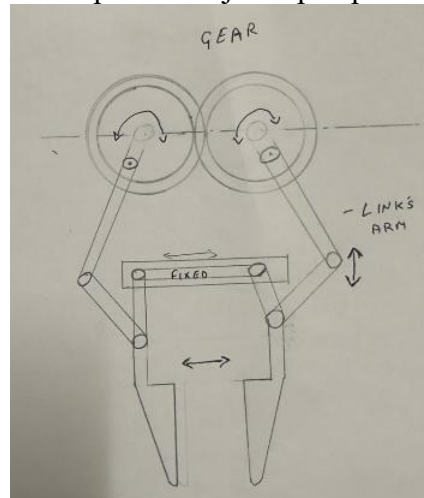


Figure 2: Variant 2  
Cam and linkage mechanism concept (hand sketch) Source: own

## 2.3 Variant 3 – Spur Gear and Linkage Hybrid

Variant 3 combines a key spur gear stage with a secondary linkage system. The motor drives a central pinion that engages two sector gears, or gear segments, mounted on either side. Each sector gear features an eccentric pin that moves a connecting rod, which, in turn, pushes the finger carriage along its guide rail. This arrangement operates like a slider-crank mechanism on each side, synchronised by a shared gear pair. The gear stage ensures symmetrical finger movement, while the slider-crank stage allows for stroke amplification.

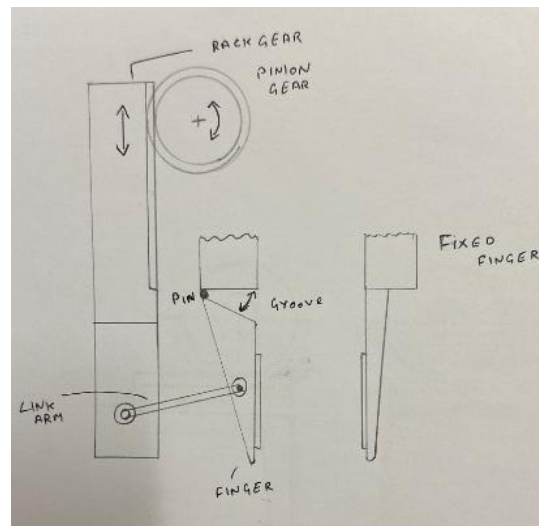


Figure 3: Variant 3

Spur gear and linkage hybrid concept (hand sketch) Source: own

### 3 Variant Selection – Ranking Method

The ordinal ranking method, also known as the scoring method, was used to systematically select variants following the approach of Pahl and Beitz [5]. It assigns an ordinal rank to each variant based on evaluation criteria: 1 for the best and 3 for the worst. The variant with the lowest total score is chosen. This method was preferred over more complex techniques such as AHP, TOPSIS, or weighted sum because, with only three variants and five equally important criteria, adding mathematical complexity does not enhance the reliability of the results. Moreover, the ordinal ranking method offers a fully transparent and auditable decision-making process.

#### 3.1 Evaluation Criteria and Ranking Matrix Results

Five evaluation criteria (K1–K5) were defined based on the design requirements established in Chapter 3:

1. K1 — Grip Type and Symmetry produce a parallel, centred grip for prismatic objects without extra syncing. Variant 1 has an inherent centring grip (rank 1). Variant 2 offers parallel motion with careful linkage, needs validation (rank 2). Variant 3 has angular jaw motion needing conversion to parallel (rank 3).
2. K2 — Component Count and Complexity: fewer parts mean simpler assembly, fewer failure points, and lower manufacturing costs. Variant 1 has 3 moving parts (rank 1). Variants 2 and 3 have 8+ parts with multiple pivot joints (rank 3)
3. K3 — Manufacturability: Variant 1 uses standard gear STL files, no custom gear needed (rank 1). Variants 2 and 3 need a custom cam or slider-crank and tighter tolerances (rank 2)
4. K4 — Motor Efficiency: Variant 1 has the shortest, most efficient transmission (rank 1). Variant 2 needs more torque for linkage friction (rank 2). Variant 3 needs more torque due to meshing and linkage friction (rank 3).
5. K5 — Future Development: Variant 1 can be modified (module, tooth count, stroke) without redesign (rank 1). Variants 2 and 3 need a full redesign if stroke or force change (ranks 2 and 3).
- 6.

Table:1 Ordinal ranking matrix for variant selection (lower total score = better overall)

Variant	K1 Grip	K2 Parts	K3 Manuf.	K4 Motor	K5 Adapt.	Sum	Rank
Variant -1	1	1	1	1	1	5	1 <sup>st</sup>
Variant -2	2	3	2	2	2	11	2 <sup>nd</sup>
Variant -3	3	3	2	3	3	14	3 <sup>rd</sup>

Variant 1 has the lowest total score (5) and is evidently the best option. Its parallel rack-and-pinion system fulfils all assessment criteria: it offers an inherent centring grip (K1), involves only three moving parts (K2), uses standard Igus STL gear files [6] (K3), delivers the most efficient motor-to-finger force transfer (K4), and is straightforward to modify for future requirements (K5). Consequently, variant 1 will be developed further in the following chapters.

## 4 Gripping Force Drive Calculations and Motor Selection

The following calculations determine the minimum gripping force and motor torque required to hold a 1 kg prismatic object during manipulation of the UR5 robot, with a safety factor of 2 throughout, using the methodology from Shigley [3].

Mass of gripping object (m): 1 kg, Gravitational acceleration (g): 9.81 m/s<sup>2</sup>, Maximum Robot acceleration (a): 2.5 m/s<sup>2</sup>, Friction coefficient (μ): 0.5 (PLA finger surface to metal objects), Safety factor (S): 2, Number of gripper fingers(n): 2.

### 4.1 Gripping Force Calculations

Effective inertial load – The gripper must resist the object's weight and the additional inertial force generated during robot acceleration:

$$F_{\text{eff}} = m \times (g + a) = 1 \times (9.81 + 2.5) = 12.31 \text{ N} \quad (1)$$

Adjusted force with the Factor of safety:

$$F_{\text{adj}} = F_{\text{eff}} \times S = 12.31 \times 2.0 = 24.62 \text{ N} \quad (2)$$

Required normal force per finger. The friction force at each finger contact must prevent slipping:

$$F_{\text{finger}} = F_{\text{adj}} / (n \times \mu) = 24.62 / (2 \times 0.5) = 24.62 \text{ N per finger} \quad (3)$$

Total clamping force. Following the parallel jaw grippers, the total gripping force is the sum of the two finger normal forces:

$$F_{\text{total}} = F_{\text{finger}} \times n = 24.62 \times 2 = 49.24 \text{ N} \quad (4)$$

### 4.2 Rack and Pinion Geometry

Gear module (m): 0.5, Number of Pinion teeth (Z): 22, Total jaw opening range: 50 mm, 25 mm per side.

Pitch diameter and pitch radius:

$$d = m \times z = 0.5 \times 22 = 11 \text{ mm} \quad (5)$$

$$r = d / 2 = 5.5 \text{ mm} = 0.0055 \text{ m} \quad (6)$$

Require motor torque:

$$T_{\text{required}} = F_{\text{finger}} \times r = 24.62 \times 0.0055 = 0.1354 \text{ Nm per rack} \quad (7)$$

$$T_{\text{total}} = 0.1354 \times 2 = 0.2708 \text{ Nm} \quad (8)$$

A minimum motor torque of 0.30–0.40 Nm is specified as the design requirement, applying a working margin above the 0.27 Nm analytical result to account for mechanical friction in the gear train and guide-rod sliding resistance.

Rack Stroke and Minimum Length:

$$\text{Linear travel per revolution} = \pi \times d = \pi \times 11 = 34.56 \text{ mm} \quad (9)$$

$$\text{Required rotation for 20 mm finger travel: } \theta = (20/34.56) \times 360 = 208^\circ \quad (10)$$

$$\text{Engagement margin (~6 teeth): } 6 \times (\pi \times m) = 9.42 \text{ mm} \quad (11)$$

$$\text{Minimum rack length per side} = 20 + 9.42 = 29.42 \text{ mm} \rightarrow \text{use 35 mm} \quad (12)$$

The spur gear (pinion) and rack gears were generated as print-ready STL files using the IguS online 3D-printing configuration tool [6]. The tool validates gear geometry for the selected module, tooth count, and bore diameter, generates an optimised involute tooth profile for FDM printing, and designs the geometry for the igus. This eliminates the need for custom CAD work on the gear and ensures the tooth profile is correctly sized for the printer's resolution.

#### 4.3 Motor Selection – Initial (NEMA 17 Stepper)

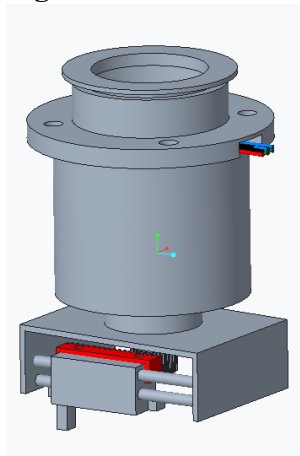
Based on the torque requirement, a NEMA 17 hybrid stepper motor (Microcon SX17-1705 [8]) was selected for the initial design. It provides a holding torque of 0.60 Nm and a dynamic torque of approximately 0.48 Nm, both exceeding the 0.27 Nm requirement. The 1.8° full-step resolution (200 steps/revolution) provides sub-millimetre finger positioning through the rack-and-pinion geometry [3].

As described in the upcoming chapter, this motor was later replaced due to a critical safety issue discovered during prototype-1 testing. The stepper motor provides no mechanical self-locking when de-energised, causing the gripper to release its payload during power interruptions.

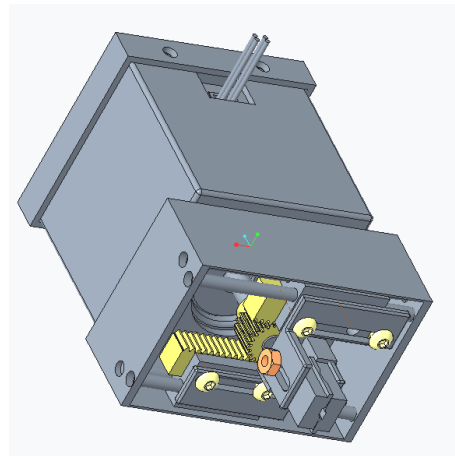
## 5 Initial Design Iterations and Prototype Iterations

After selecting the motor and gear, the gripper body was developed. Two versions were assessed for manufacturability, compatibility with the UR5 flange, and assembly. Based on supervisor feedback, the design shifted from intricate curved profiles to flat-faced shapes, which can be produced on the department's FDM printer without support and machined on CNC for aluminium parts.

### 5.1 Body Design Iterations



(a)



(b)

Figure 4: Design Iterations

- (a) Design iteration -1 concept (CAD Software) Source: own  
 (b) Design iteration -2 Concept (CAD Software) Source: own

Using both design concepts, I have combined them to produce the third and final design of the gripper.

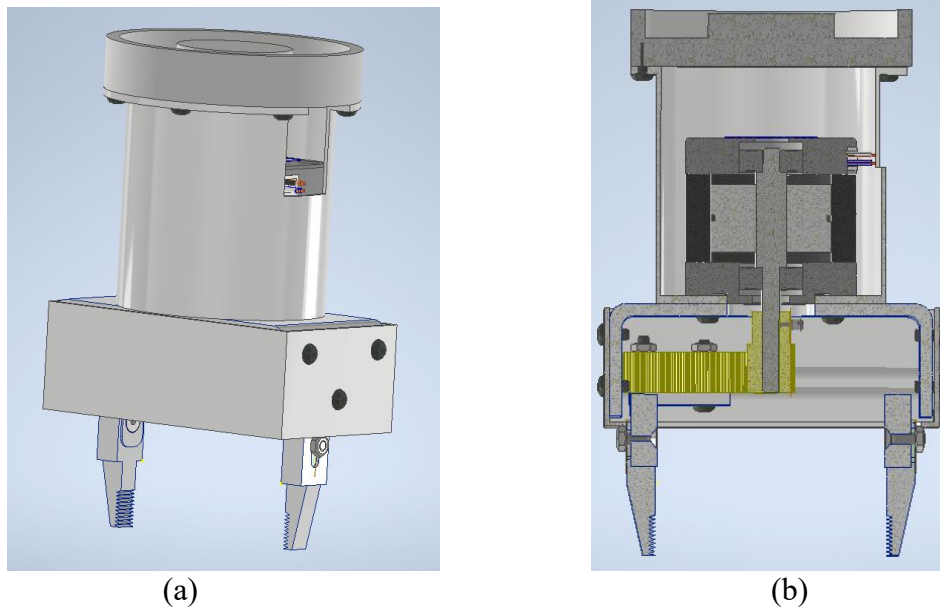


Figure 5: CAD assembly of the developed design for Prototyping  
 (a) Iso Metric view of the design (CAD Software) Source: own  
 (b) Section view of the design (CAD Software) Source: own

## 5.2 Assembled Prototype -1

All custom parts from the initial CAD model were exported as STL files and printed on the department's FDM printer using PLA filament at a layer height of 0.2 mm and 50% rectilinear infill. Aluminium guide rods and M3 fasteners were sourced from stock. The NEMA 17 stepper motor was mounted and wired for a test. The complete assembly underwent repeated manual functional tests: the motor was driven, and the fingers cycled through their full 50 mm stroke, with each component's behaviour observed.

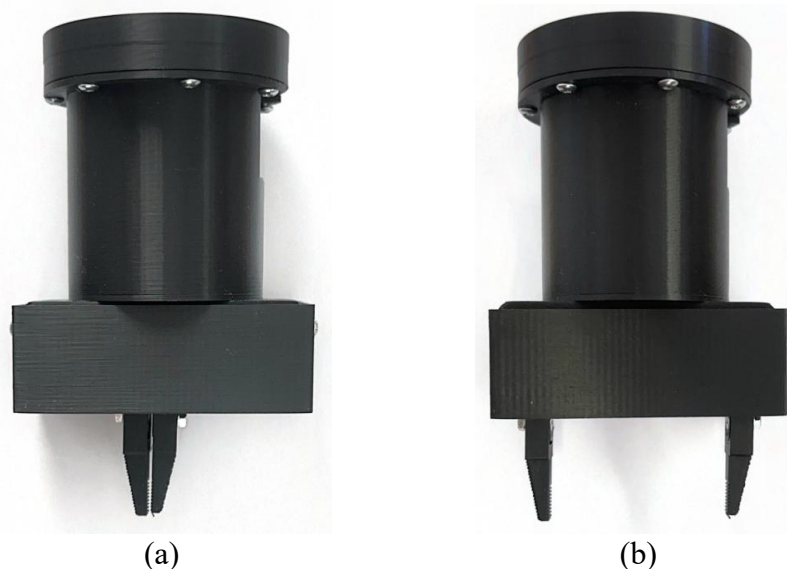


Figure 6: Prototype -1

- (a) Fully assembled Prototype - 1 jaw in closed position. Source: own  
 (b) Fully assembled prototype -1 in jaw fully open position. Source: own

The assembled prototype confirmed the basic viability of the design: the motor drove the pinion, both racks moved symmetrically, and the fingers opened and closed across the full 0–50 mm range. The rotatable motor mount performed well in practice, confirming the design intent.

### 5.3 Critical Problem

The most critical problem identified during testing was the rotation of the finger-to-rack connector about the bolt axis under gripping load.

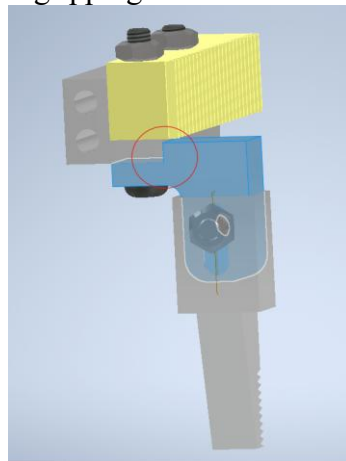


Figure 7: Prototype – 1 finger sub assembly

Close-up of the connector-rack joint; red circle indicates the rotation failure zone. (CAD Software) Source: own

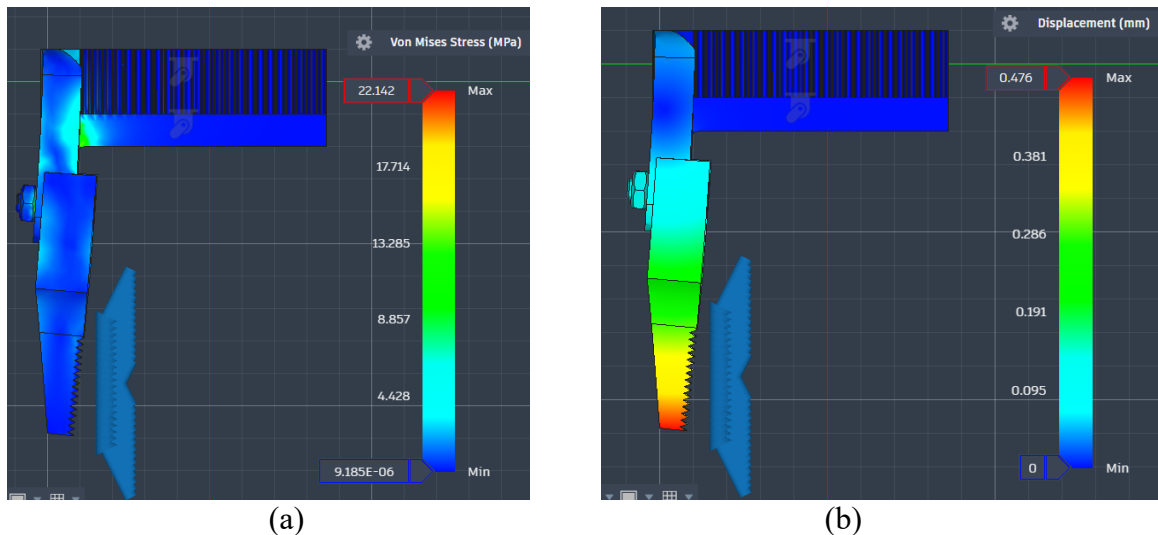
Rotation-induced finger misalignment can lead to unreliable grasping and accidental dropping. PLA near the bolt hole cracked after re-tightening, showing inadequate wall thickness against preload and bending. Variability in FDM tolerances compromised the anti-rotation, with a single bolt resisting preload and bending, indicating poor design.

### 5.4 Motor Replacement Worm Gear DC Motor

The NEMA 17 stepper was replaced with a JGY-370 24 V brushed DC motor with a 150:1 worm gearbox [4], offering 0.58 Nm torque, surpassing the 0.27 Nm requirement. A worm gear is self-locking if the lead angle is less than the friction angle [3], which is true here; the gear can't back-drive, ensuring the gripper stays in place without power and meeting safety needs in Section 8.3. The motor's back-drive resistance of about 30 kg exceeds the 1 kg load. The housing was redesigned for the larger motor, using a friction fit and a single locking screw instead of four bolts, simplifying assembly and reducing the risk of thread stripping.

## 6 Final Version of Prototype - 2

For the final version, several design changes have been implemented. The first is the redesign of the gripper finger. In prototype-1, it consists of 4 separate parts assembled using 3 x M3 fasteners. The redesign consists of two parts and requires only one M3 fastener. The rack and the finger interface extension are converted into a single part, plus a replaceable finger. The same redesigned finger is analysed using the static stress simulation module in Autodesk Fusion 360 software.



(a)

(b)

Figure 8: Finger of Prototype -2

(a) Von Mises stress distribution in Fusion 360 software. Source: own

(b) Total deformation distribution in Fusion 360 software. Source: own

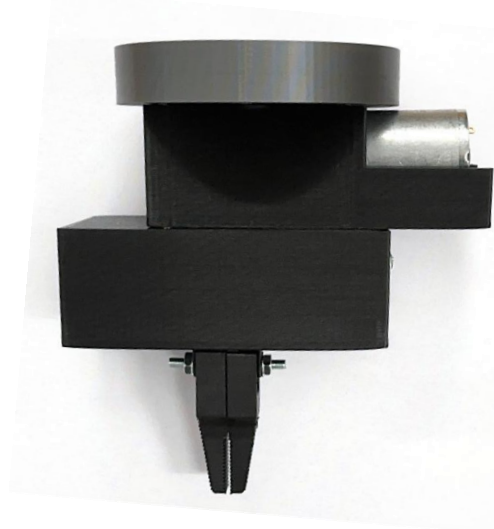
The maximum von Mises stress is 22.142 MPa at the guide-rod bore's root, where bending from fingertip load peaks. This is 40% of the 55 MPa yield strength of PLA [9], with a safety factor of about 3.808. However, Fusion 360's simulation assumes a solid, homogeneous, isotropic material, whereas an FDM-printed part with 50% infill is weaker and anisotropic, with perpendicular strength 50–70% of the in-plane strength. Thus, 22.142 MPa is an upper bound, not an exact prediction. The design is adequate for the prototype, with a safety factor of nearly 2 after 50% infill correction. For production, higher infill (80–100%) or PETG material is recommended for more margin.

### 6.1 Final version Prototype – 2

After assembly, the gripper was manually tested across its full range before electrical tests. The jaw stroke was cycled from 0 to 50 mm fifty times by hand, confirming smooth travel without binding. No guide-rod stiction or rack interference was detected. The anti-rotation feature was verified by applying lateral loads to each fingertip, observing no angular movement.



(a)



(b)

Figure 9: Prototype -2 Assembled view

- (a) Fully assembled Prototype - 3 jaw in fully open position. Source: own  
 (b) Fully assembled prototype -2 in the jaw fully closed position. Source: own

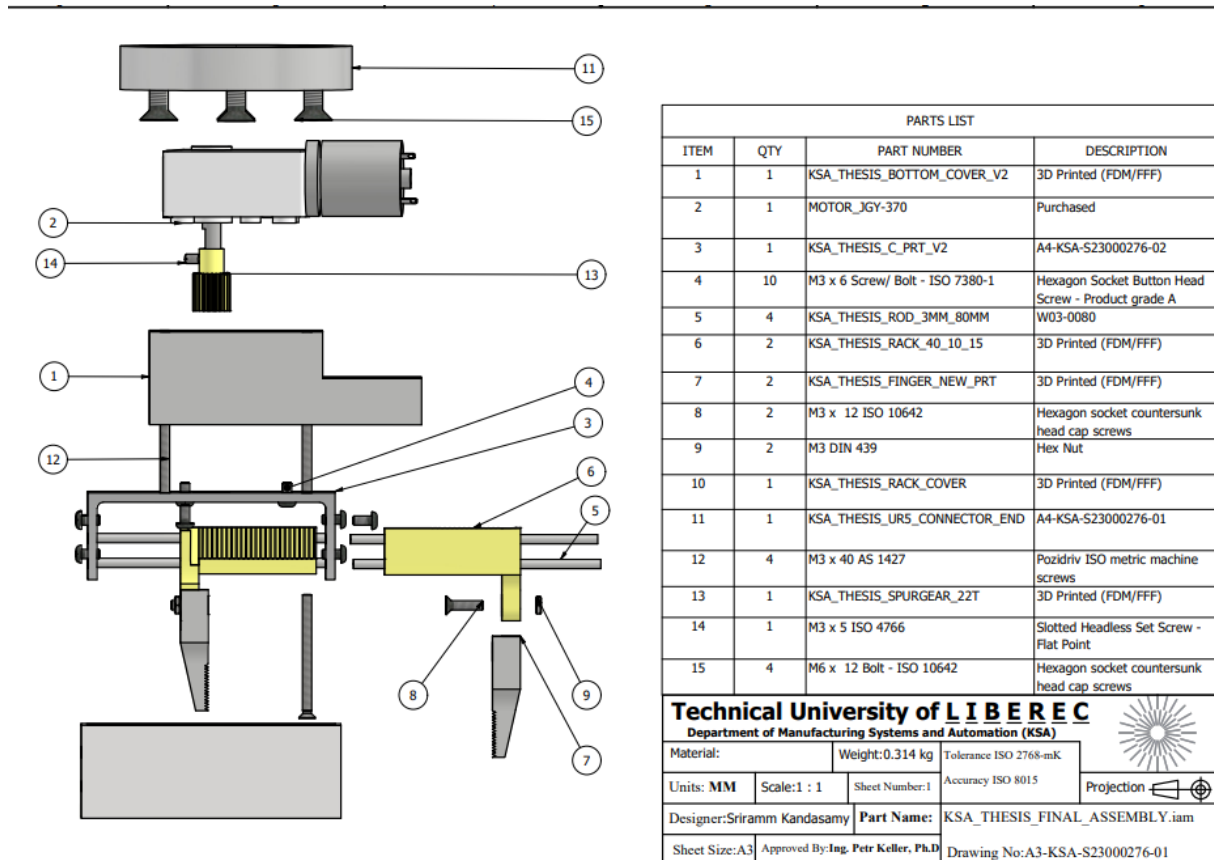


Figure 10: Prototype -2 Exploded view  
 Exploded view with Bill of Materials. Source: own

## 7 Conclusion

This was designed, built, and optimised as a parallel-jaw gripper for the UR5 robot.

The rack-and-pinion mechanism (Variant 1) was rated best based on five criteria. Force and torque calculations, assuming a 1 kg load, guided motor and gear selection following Shigley [3].

Two prototypes solved key design issues: a redesigned finger connector with an anti-rotation feature and a JGY-370 DC motor replacing the NEMA 17 stepper to prevent payload release.

Static FEA showed a maximum von Mises stress of 22.142 MPa, with a safety factor of 3.81, which reduces to 1.36 considering FDM effects [9] - acceptable for static gripping, but higher infill or material changes are needed for continuous use.

The gripper operates and grips objects from 0 to 50 mm, maintains grip without power, and can be made with departmental resources at a cost of 40–50 EUR- significantly cheaper than commercial options [11, 12, 13]. The design allows for future sensor integration.

## 8 Future work

Force measurement and control: the current open-loop control uses a fixed PWM duty cycle on the JGY-370 motor. Adding a current sensor or load cell would enable adjustable gripping force, preventing damage and meeting sensor needs. A magnetic encoder provides position

feedback. A linear potentiometer or shaft encoder allows finger-position detection, crucial for closed-loop robot use.

To ensure continuous duty, replace the PLA finger body with PETG for higher toughness or increase infill to 80–100%, raising the FEA safety factor to 2.5 for long-term cyclic loading. Upgrading the gear rack to 0.5 mm aluminium (80–150 CZK per 100 mm) prevents printed-tooth bending without extra design changes.

## 9 Acknowledgements

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