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Development, testing and comparative analysis of a vacuum and soft gripper for robotic grasping tasks

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1. Introduction

As robotics advances, grasping technologies play an increasingly important role [12]. The value of a robotic arm largely depends on the type of end effector installed on it: even a precise arm is of limited use if the gripper cannot adapt to the shape, weight or material of the handled object. Traditional rigid parallel-jaw grippers are simple and strong, but in many cases they cannot properly handle irregularly shaped or fragile objects.

One of the main directions in industrial automation today is that robots are becoming more flexible and adaptive systems instead of moving only along rigid, predefined paths. In a modern plant it is rare for the same robot to perform exactly the same task every day on identical objects; instead, products of various sizes, shapes and materials move along production lines. Handling this variety depends partly on the robot-control software, but also partly on the mechanics: the gripping system.

In this paper we developed and compared two robotic grippers based on different operating principles: a mechanically actuated soft gripper made of flexible material and a vacuum gripper. During development, besides the mechanical design, special attention was paid to optimizing the transmission geometry, specifically the bell-crank arrangement and maximizing the mechanical advantage in the closed position. During testing, we examined grasping success for objects of different sizes, shapes and materials, as well as gripping force and behaviour during sustained operation.

The two technologies operate according to different principles, are optimal for different object types, and involve different engineering challenges. The soft gripper relies on elastic deformation, while the vacuum gripper relies on pressure difference. Accordingly, the optimization questions are also different: for the soft gripper, geometry and force transmission are critical; for the vacuum gripper, pneumatic sealing and the load-bearing capacity of the mechanical frame are critical. Based on the results, we make concrete recommendations for which task types each gripper is more suitable and how they can be integrated into a unified CAN-bus robotic system.

The experience gained during the project goes beyond the operation of the individual grippers. It gives an instructive picture of how mechanical design, the anisotropic behaviour of 3D-printed parts, pneumatic force transmission and microcontroller-based control are combined in a real robotic device. One particularly interesting lesson was that an apparently small change in mechanical geometry, the length ratio of the levers, can improve system performance by an order of magnitude. This shows that robotics is not simply a matter of using larger motors.

The paper follows the logical sequence of the development. Chapter 2 presents the concepts and theoretical foundations of the two grippers. Chapters 3 and 4 describe the mechanical and electronic structure. Chapter 5 presents the control software. Chapter 6 discusses the failures encountered during prototyping and their engineering lessons. Chapter 7 contains the measurement results. Chapter 8 summarizes the experience and presents future directions, including integration into a CAN-bus robotic system.

2. The concepts and theoretical foundations of the two grippers

2.1 Operating principle of the soft gripper

The operation of the soft gripper is based on elastic deformation [1]. Its fingers are not rigid; they can deform, so they contact the grasped object over a larger surface. This provides several advantages at the same time: better adhesion, lower risk of damaging the object, and greater adaptability to irregular shapes.

Compared with classical rigid parallel-jaw grippers, the flexible finger behaves like a soft cushion. When it grasps an object, the finger first touches the object surface, and further closing motion deforms the finger rather than the object. This is important because, in a rigid gripper, the closing force acts directly on the object and may easily damage a fragile item if the force is high. The flexible finger, by contrast, absorbs the extra force while maintaining stable adhesion.

The same principle can also be found in nature: neither a monkey hand nor a human hand is rigid; the fingers flexibly conform to the object being held. Robotic soft grippers follow this biological inspiration [2]. Other interesting solutions also exist in soft robotics, such as jamming grippers, where granular material, for example coffee inside an elastic bag, is stiffened around the object by vacuum [3]. These, however, represent a separate research direction and are not discussed in this paper.

In our design (Figure 1), the system closes mechanically using a linear motor that moves the fingers through a transmission. The fingertips are made of flexible TPU material and follow the shape of the object during grasping [16]. This concept works particularly well with irregular, rounded or slightly deformable objects, roughly in cases where a rigid parallel-jaw gripper would fail.

2.2 Operating principle of the vacuum gripper

The vacuum gripper, by contrast, operates on a completely different principle: the object is held by the pressure difference between ambient air pressure and the partial vacuum created under the suction cup [4]. In the sealed air space between the suction cup and the object surface, the pump extracts air, while the outside atmosphere applies pressure in the opposite direction. The balance of these two effects holds the cup and the object together. The theoretical holding force is given by F = n x A x DeltaP x mu, where n is the number of suction cups, A is the effective area of one cup, DeltaP is the pressure difference, and mu is a safety and friction coefficient. In vertical lifting, the role of mu is critical: it expresses how much of the theoretical maximum the system can actually hold because of leakage, surface unevenness and dynamic effects. In industrial practice, mu is about 0.5 for vertical lifting, while in a horizontal arrangement, where the weight does not work directly against the vacuum force, 0.25 may be sufficient.

Our system uses four silicone suction cups with a diameter of 50 mm. The effective area of one cup is A approximately 19.63 cm2 (r2 x pi). If the pumps can generate a pressure difference of -0.5 bar (50 kPa), the theoretical maximum lifting force is F = 4 x 0.001963 m2 x 50,000 Pa approximately 392.6 N, which would theoretically allow about 40 kg to be lifted. In practice, however, because of dynamic effects and leakage, the load capacity was limited to 20 kg using a safety factor of 2.

It is also worth mentioning that the pressure difference changes with altitude. At sea level, atmospheric pressure is 101.3 kPa, so the theoretically achievable maximum DeltaP is about 101 kPa if the pump could create a full vacuum. Our pumps achieve about half of this value (50 kPa), which is typical for commercial vacuum pumps. Industrial-grade pumps, such as Schmalz or Festo products, can reach 80-90 kPa, but their price is far beyond the budget of a student project.

This technology (Figure 2) provides a major advantage for flat-surfaced, fragile or porous objects: lifting a cardboard or glass box with vacuum is faster and gentler than with any mechanical gripper.

The silicone suction cup can also seal on uneven surfaces because the flexible material fills microscopic gaps [18]. Its disadvantages are that it practically does not work on porous materials such as textiles or foam, because the pump cannot maintain the pressure difference, and the pneumatic system is considerably more complex than that of a mechanical gripper.

2.3 Comparison and selected application areas

The material selection shown in Table 1 follows the principle of functional separation: each component is made from a material that has optimal properties for its particular role instead of using a single compromise material for the entire structure. The contrast between the rigid PLA/PETG frame and the flexible TPU fingertip is the most important. The frame must retain its shape to transmit gripping forces, while the fingertip must deform to match the surface of the object. Steel shafts and miniature ball bearings at the joints ensure durability and low-friction motion, which could not be maintained in the long term using polymer parts alone [9][11].

Aspect	Soft gripper	Vacuum gripper
Optimal object type	Irregular, rounded	Flat, smooth surface
Max. gripping force (practical)	~38,5 N	~200 N (20 kg limit)
Speed (release)	Slow (motor-driven)	Very fast (valve)
Mechanical complexity	Medium	High (pneumatics)
Risk of object damage	Very low	Low (on smooth surfaces)

Table 1. Comparison of the two gripper concepts.

3. Mechanical design and structure

3.1 Structural design of the soft gripper

The soft gripper (Figure 3) has a two-finger design, which enables stable, multi-point grasping. The main components are the rigid frame, two moving fingers with joints, and the drive mechanism that transmits the linear motor motion to the fingers. The fingers have a slightly curved shape, which helps them wrap around the object.

The material selection was optimized for the different functions: PLA or PETG for the frame, both 3D-printable and sufficiently rigid; TPU for the fingertips, which is flexible and provides good grip; steel for the shafts; and miniature ball bearings for the joints [20]. TPU is essential because it provides flexibility and the adhesive contact surface.

Component	Material	Role
Frame	PLA / PETG	Rigid structure
Fingertips	TPU	Flexible gripping surface
Shafts	Steel	Joint fixation
Bearings	Miniature ball bearing	Low-friction motion

Table 2. Material selection for the soft gripper.

3.2 Structural design of the vacuum gripper

The vacuum gripping system is based on a kit designed for a nominal load capacity of 20 kg [5]. Its main components are four silicone suction cups with a diameter of 50 mm, a spring-loaded telescopic suspension that compensates for positioning inaccuracy of the robot arm along the Z axis and protects the workpiece from

collision, two high-performance vacuum pumps, and a three-way electronic valve for rapid release.

The value of the telescopic suspension should not be underestimated. During grasping with a robotic arm, positioning error along the Z axis can typically be 1-3 mm, depending on the precision of the arm. If the gripper head is mounted rigidly to the arm, arriving with excessive force will either break the suction cup or damage the workpiece. The telescopic spring element absorbs this extra movement: when the cup contacts the object, the spring compresses, and the robot arm can continue moving without applying additional load to the grasp.

The frame structure was designed in Shapr3D [17] for FDM (Fused Deposition Modeling) 3D printing. The main design aspects were integrated tube routing, including arranging and shortening the 300 mm silicone tubes so that they do not catch during robot-arm movement; weight optimization, using a hollow frame with reinforcing ribs to preserve the robot-arm dynamics, because the lower the gripper self-weight, the greater the effective payload; and ease of assembly, including mounting points for the Arduino Nano and the control modules.

The pneumatic system (Figure 4) is dual-circuit: it consists of a suction branch and a blow-off branch. The suction branch contains the pumps and the one-way valve, which prevents air from flowing back when the pump stops and prevents loss of vacuum. The blow-off branch connects to the outside atmosphere through the three-way electronic valve; this branch is activated during release.

Figure 4. Vacuum gripper in operation

3.3 Force transmission: the bell-crank arrangement and mechanical advantage

In the first version of the soft gripper, the gripping force was insufficient. Troubleshooting showed that the problem was the geometry: the output lever, which closes the fingers, was too long compared with the input lever driven by the linear motor, so the motor torque was not transformed into sufficiently strong gripping force.

To solve this, we selected a classical mechanical arrangement: the bell crank, an L-shaped two-arm lever. A bell crank is a hinged lever in which the input and output arms form an angle and rotate around a common pivot. Its advantage is that the mechanical advantage, or force-transmission ratio, can be controlled simply through the ratio of lever lengths [8]. If the input arm is made longer and the output arm shorter, the relatively smaller pulling force of the motor is transformed into a high gripping force at the finger.

We also considered an important fine-tuning aspect: mechanical advantage is not constant during motion but depends on the lever angle. In our arrangement, the kinematics were dimensioned so that the maximum mechanical advantage occurs exactly in the final phase of grasping, near the closed position. This provides extra force exactly where it is most needed, when the finger already contacts the object and the gripping force increases. The finger closes quickly at the beginning of the closing phase, with low mechanical advantage but high speed, and then slows down at the end while biting onto the object with strong force.

As a result of the modifications, increasing the input lever length, shortening the output lever, and optimizing the kinematics for the closed position, the gripping force increased significantly; exact data are provided in Section 7.1. This lesson has a broader meaning: in a robotic gripper, raw motor power alone is not enough. The geometry and kinematics of the mechanism determine whether that force actually reaches the gripping point and in which phase of the motion.

4. Electronic system

4.1 Electronics of the soft gripper

A simple but reliable system was built to control the soft gripper. The main components are an Arduino Nano microcontroller [14], a Cytron motor driver for the linear motor [6], two push buttons for opening and closing, and a 12 V power supply. The system supply-voltage range is between 7.4 V and 12 V.

The wiring is minimal: pin D4 is direction (DIR), D5 is PWM control, D2 is the opening button, and D3 is the closing button. All components share a common ground. During the first prototype we learned an important lesson: the grounds (GND) of the Arduino and the motor driver must be connected, otherwise the system operates unreliably or stops completely. This is a classic grounding error that many beginners encounter.

4.2 Electronics of the vacuum gripper

The vacuum system is also controlled by an Arduino Nano microcontroller [7]. Because the pumps and valves draw high current, they cannot be driven directly from Arduino pins. Therefore, we installed two PWM digital electronic switches that galvanically isolate the logic circuit from the power circuit. This is important for two reasons: it protects the microcontroller from voltage spikes caused by switching inductive loads, and it allows the pumps to operate from a separate supply voltage.

The pneumatic system consists of two circuits: a suction branch and a blow-off branch. The three-way electronic valve is the key component for rapid release. When the Release button is pressed, the valve connects the closed vacuum circuit to the outside atmosphere, so the negative pressure equalizes immediately. This enables release that is orders of magnitude faster than simply stopping the pump and waiting for leakage to equalize the pressure.

5. Control software

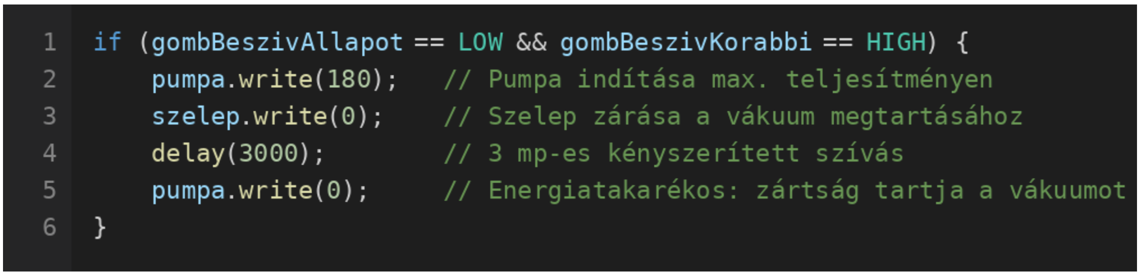
5.1 Control logic of the soft gripper

The soft gripper operates with manual control using two push buttons: one opens and the other closes it. If neither is pressed, the motor stops. The software (Figure 5) must satisfy several safety requirements: it must not drive two directions at the same time, which would damage the motor driver; the motor must stop safely; and unnecessary loading must be avoided. The code was written in the Arduino IDE [15] with minimal dependencies.

5.2 Control logic of the vacuum gripper

Interestingly, the vacuum system software uses the Servo.h library, not because servos are controlled, but because the digital electronic switches used in the system interpret a standard servo signal (50 Hz, 1-2 ms pulse width) as a control signal. This is a surprising but effective solution: the switch interprets a 1 ms servo pulse, or 0 degrees, as off, and a 2 ms pulse, or 180 degrees, as on. Thus the binary control of pumps and valves can be conveniently integrated into Arduino using a well-established and stable library.

The control cycle (Figure 6) can be divided into three phases. In the suction phase, when the button is pressed, the pump starts at maximum duty cycle, the valve remains closed, and the system applies forced suction for 2 seconds to create a stable vacuum. In the holding phase, the pump can be stopped: the code relies on the sealed pneumatic system, and the default position of the three-way valve maintains the vacuum. This is energy-efficient because the pump consumes no power when it only has to hold an already formed vacuum. In the release phase, the second button activates the valve, which removes the vacuum and equalizes the internal pressure with the environment, so the object is released immediately.



```
if (gombBeszivAllapot == LOW && gombBeszivKorabbi == HIGH) {
    pumpa.write(180);   // Pumpa indítása max. teljesítményen
    szelep.write(0);    // Szelep zárása a vákuum megtartásához
    delay(3000);        // 3 mp-es kényszerített szívás
    pumpa.write(0);     // Energiatakarékos: zártság tartja a vákuumot
}
```

Figure 6. Detail of the control algorithm

The debouncing implemented in the software ensures that mechanical vibration of the push buttons does not generate false commands. Debouncing works by waiting, after a button press is detected, until the signal remains stable in the same state for a minimum period, typically 20-50 ms, and only then treating it as a valid event. Without this, a cheaper button could report 5-10 presses from a single real press, which would cause serious problems in a robot.

The forced 2-second suction cycle is also an important engineering decision. It ensures that the pump has enough time to evacuate the air from the tubes and from under the cups before the system enters a static state. The approximately 300 mm silicone tubes and the volume under the four cups cannot be evacuated in a few tenths of a second. If the system moved on too early, it would not be able to hold the load. This time was tuned experimentally and can be reduced if the tube is shorter or the pump is more powerful.

6. Failure analysis and engineering lessons

During the development of both prototypes we encountered several failures that provided important engineering lessons. These failures are not setbacks but part of how real development progresses.

6.1 Force-transmission problem of the soft gripper

The first version did not produce the expected gripping force. Troubleshooting showed that the problem was geometry: the output lever was too long compared with the input lever, so the motor torque was not transformed into sufficiently strong gripping force. Increasing the input lever and shortening the output lever significantly increased the force. The lesson is that calculating a drive mechanism does not end with selecting the motor; the mechanical advantage must also be considered.

6.2 Structural failure of the vacuum gripper frame

The vacuum prototype suffered a critical failure during testing: the approximately 400 N force generated by the four 50 mm cups exceeded the load-bearing capacity of the 3D-printed frame structure. The frame failed at two points. One was material fatigue around the screw holes, where concentrated stress caused the PLA/PETG material to crack along the screw heads. The other was layer separation, or delamination: the tensile force generated by the vacuum was perpendicular to the printed layers, which is the weakest direction of an FDM-printed part.

The root cause of the failure was the anisotropy of the PETG-HF material [9, 11]. This filament has excellent printability and good impact resistance, but because of FDM technology the part is direction-dependent: adhesion between layers in the Z direction is much weaker than the strength along the filament direction. Typical values indicate that PETG tensile strength along the filament is 45-50 MPa, while interlayer strength is only 25-35 MPa. Thus the weaker direction withstands about 40-50% less load. When the load direction is perpendicular to the layers, meaning that it tends to pull the layers apart, this weaker value governs the behaviour.

The continuous 400 N tensile load also caused the material to respond through creep. Creep is a phenomenon in which plastic gradually deforms under sustained load even below its tensile strength and eventually fails. In PETG this can be observed even at room temperature if the constant stress reaches 50-60% of the tensile strength [10]. In our case, the process started at the screw holes and then cracks initiated at the stress peaks.

Another important cause of the failure was stress concentration. When a screw pulls on a hole in a plastic part, the stress is not distributed uniformly; it concentrates on the small area around the screw head. In theory this is described by the stress concentration factor Kt [8], which can be as high as 3-4 around screw holes. This means that if the nominal stress is 15 MPa, calculated by dividing the screw force over the full cross-section, the peak stress may reach 45-60 MPa, which is already at the failure level of PETG.

The most important lesson is that in vacuum grippers it is not only the payload, the weight of the lifted object, that matters, but also the reaction force that loads the frame. Because the theoretical holding force of the four cups reaches 400 N, the frame connection points should be designed with at least a 2.5 safety factor while taking into account the anisotropic properties of FDM technology.

6.3 Improvement directions for version 2.0

For the vacuum system we planned three concrete engineering modifications for the next iteration.

First: a hybrid frame structure. In the load-bearing elements, aluminum reinforcing plates will be placed at the critical points instead of 3D-printed plastic. The tensile strength of aluminum, typically 250-310 MPa for 6000-series alloys, is an order of magnitude higher than that of PETG, 45-50 MPa along the filament direction, so it requires a much smaller cross-section under the same load. Plastic remains in non-load-bearing cover and mounting roles, where weight and ease of manufacturing are more important than strength.

Second: modification of the printing orientation. The parts must be redesigned so that the main load direction is parallel to the layers rather than perpendicular to them, thereby using the tensile strength along the filament direction. In practice this means that the original models must be repositioned in the printer for almost every part, and in many cases post-print manual support removal will also look different. In the slicer software, typically Cura or PrusaSlicer, the orientation is selected based on force-flow analysis.

Third: large-area metal washers will be used at bolted joints. These distribute point loads over a larger surface and reduce the Kt stress-concentration factor. The practical recommendation is that the washer should be at least twice the diameter of the screw head being used. This can reduce the stress peak around the screw head by about half.

The frame geometry should also be reconsidered according to force-flow optimization principles. Ideally, the structure should be arranged so that the vacuum force does not pull the bolted joints apart in tension, but instead creates compressive loading between frame elements, because plastic is much more resistant to compression than to tension. A classical example is a bridge: if a pillar is loaded in tension, cables are used; if it is loaded in compression, stone columns are used. The same principle applies to the design of plastic parts.

During the complete redesign, the safety factor (SF) should be dimensioned to 2.5. The anisotropic nature of FDM 3D printing and the many manufacturing variables that cannot all be tested, such as printing temperature, extrusion speed and cooling rate, justify this conservative approach [19]. For a precision-manufactured metal part, a safety factor of 1.5 would be sufficient.

7. Measurement results

7.1 Maximum gripping force of the soft gripper

To measure gripping force, we placed a digital kitchen scale between the jaws and closed the gripper at maximum duty cycle (PWM 255). The measured mass fluctuated between 3.5 and 4 kg during the tests. Using the relation F = m x g, the system is capable of applying approximately 38.5 N of gripping force. This value reflects the state after mechanical optimization; in the first prototype it was significantly lower.

7.2 Lifting tests of the soft gripper with different geometries

We lifted three differently shaped objects to a height of 10 cm and held them for 5 seconds. Five trials were performed with each object.

Object type	Typical size	Successful lift	Success rate
Cube	5 cm	5/5	100%
Sphere	4 cm diameter	5/5	100%
Cylinder	3 cm diameter	3/5	60%

Table 3. Results of the lifting tests of the soft gripper

For the cube and the sphere, the two-finger design and the TPU fingertips (Figure 7) wrapped around the object perfectly. In the case of the cylinder, the smaller diameter and vertical orientation produced a smaller contact surface, which caused the object to slip in two cases. This shows that for smaller-diameter cylindrical bodies, positioning is as critical as gripping force.

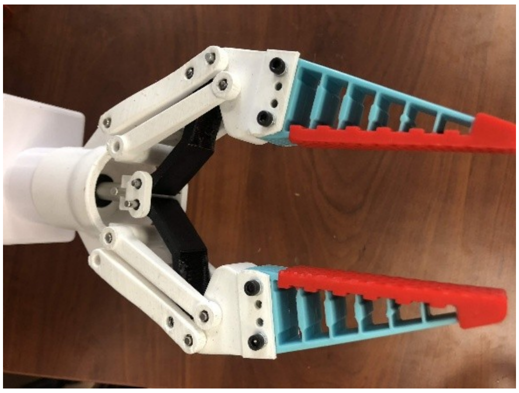


Figure 7. Image of the fingers

7.3 Load-capacity stress test of the soft gripper

In the ten-second holding plus shaking test series, we searched for the limits of the gripper (Table 4).

Object	Mass	Result
Phone	201 g	100% success, stable hold
Fire extinguisher	700 g	100% success
Soft drink bottle	1 558 g	Successful lifting and holding even under shaking
Water bottle	1 671 g	Successful lifting and holding
Iron bar	2 000 g	Partly successful — slipped out after 10 s

Table 4. Results of the soft gripper stress test.

In the case of the iron bar, lifting was successful, but by the end of the 10-second shaking phase the object slipped out because of the combination of smooth metal surface and high mass. This test clearly separates successful applications from borderline ones: the gripper confidently works with industrial or household objects of about 1.5 kg, while above 2 kg the result also depends on the nature of the surface, such as roughness and friction.

7.4 Theoretical and measured performance of the vacuum gripper

Under ideal conditions, air-tight adhesion, -0.5 bar pump performance and a hard, smooth surface, the theoretical maximum holding force of the four 50 mm cups is about 392.6 N. The practical maximum load capacity was designed as 20 kg (196 N) using a safety factor of 2.

All measurements were carried out on a balanced flat surface with 3 seconds of continuous vacuum.

Due to safety and object-related constraints, the system was able to hold 10.4 kg, but this was not the limit.

Based on the partial measurements, the developed system produces enough suction force to damage its own frame, so the pneumatic part functioned well; the bottleneck became the mechanical frame.

Other measurements show that it could hold a 1 kg metal plate in place for 47 seconds.

However, it held 5 kg for 15 seconds, showing that there is no direct linear proportionality between weight and holding time.

When adhering to a hard, smooth surface, the system reached a stable vacuum in 3-4 seconds, depending on pump performance and tube length. This forced suction time was also built into the software (see Section 5.2), ensuring that the system does not attempt to lift the object before the vacuum is formed.

7.5 Cycle-time comparison

In an industrial application, the gripping and release cycle time is a critical parameter; the speed of a packing machine beside a conveyor largely depends on it. This detail can also be compared quantitatively between the two technologies.

The cycle of the soft gripper depends on motor speed (Table 5). In the current system, at maximum PWM (255), the total closing time is about 1.8-2.2 seconds, and release, or opening, is of a similar order of magnitude. The disadvantage of the motor-driven solution is that the opening speed cannot be increased arbitrarily: the combined inertia of the motor and mechanics sets a limit.

The cycle of the vacuum gripper can be divided into two phases. The suction time, from pressing the button until stable vacuum is created, is about 2 seconds with the current pump size. The release time, however, is valve-controlled and therefore orders of magnitude faster: when the valve opens, the vacuum disappears in 0.2-0.3 seconds, depending on tube length and valve diameter. Thus, although suction is of the same order of magnitude as closing the soft gripper, release is 5-10 times faster.

Phase	Soft gripper	Vacuum gripper
Gripping (closing / suction)	~2,0 s	~2,0 s
Release (opening / blow-off)	~2,0 s	~0,3 s
Full cycle	~4,0 s	~2,3 s

Table 5. Cycle-time comparison of the two grippers (estimate based on partial data).

8. Evaluation and future directions

8.1 Comparison of the two technologies

Based on the experience, both gripper types have found their own application areas. The soft gripper has a simple structure, low cost and good adaptability; it is the winning concept for irregular, rounded or slightly deformable objects, fragile items and changing environments. The vacuum gripper, by contrast, is unbeatable on flat, smooth surfaces: it can apply much higher force, and its release speed is orders of magnitude better because it is valve-controlled rather than motor-driven.

In an industrial application the two approaches are not mutually exclusive but complementary. In a mixed gripping task, for example handling different boxes and irregular products, a dual gripper that contains both technologies is significantly more flexible than a monolithic solution [13].

The following decision matrix (Table 6) shows which gripper is the better choice for specific task types. The table was compiled from our own tests and literature recommendations.

Task	Recommended gripper	Reason
Cardboard box palletizing	Vacuum	Flat surface, fast release required
Handling fruit	Soft gripper	Fragile, irregular shape
Handling glass sheets	Vacuum	Smooth, rigid, fragile
Cables, wires	Soft gripper	Flexible, elongated shape
Assembly of metal parts	Soft gripper	Precise positioning, variable size
Packaged food (bag)	Vacuum	Flat package, fast transfer
Tools, instruments	Soft gripper	Varied shape, secure grip
Glass bottles (smooth body)	Mixed	Both technologies work

Table 6. Decision matrix: which gripper for which task.

8.2 Limitations and development directions of the soft gripper

The limitations of the current system are that the gripping force cannot be increased further because of the mechanical limits of the motor, there is no force or position feedback, so the software closes the fingers blindly, and the operation is purely manual. Accordingly, development directions proceed along several paths.

On the hardware side: a stronger motor and force and position sensors should be added so that the gripper can feel the object. On the software side: an automatic grasping algorithm should determine the appropriate gripping force from sensor signals, with force control to avoid object damage caused by excessive force. From a system-integration perspective: connection to a robot arm and CAN-bus communication with higher-level control.

8.3 Limitations and development directions of the vacuum gripper

The greatest limitation of the vacuum system in its current state is the weakness of the mechanical frame (see Section 6.2). The first task of version 2.0 is to create the hybrid frame structure, after which the actual load capacity and cycle time can be measured in a planned way.

Further development directions include installing a pressure sensor in the vacuum circuit, so the system can report if it has lost adhesion; an automatic gripping sequence, triggered by a robot-arm command instead of a button; and energy optimization. The current two-pump setup consumes a lot of energy, and a one-pump version with a larger valve or a reservoir solution could reduce consumption.

8.4 Integration into a CAN-bus robotic system

In a real robotic application, the gripper does not operate independently but as part of a larger system coordinated by higher-level control. Our current prototypes use manual push-button control, which is suitable for prototype development but insufficient for industrial integration. The next development step is therefore CAN-bus integration, which places both grippers into the same communication infrastructure.

The Controller Area Network (CAN) [21] is a robust, differential-signal, message-based bus widely used in automotive and industrial automation environments. Its characteristic feature is that adding new nodes to the system is minimal: the node only has to connect to the bus, select a unique ID and start communicating. Our two grippers can be integrated into this architecture by adding an MCP2515 SPI CAN controller and an SN65HVD230 transceiver beside the Arduino Nano; together these provide the CAN protocol logic and the physical layer.

The planned message format adapts to the different nature of the two grippers. For the soft gripper, the message would contain the desired gripping force on a 0-255 scale and the direction (open/close/stop). For the vacuum gripper, simpler binary commands are needed (start suction, release), possibly with pressure-level feedback in the status message. The two grippers would receive separate CAN IDs, for example 0x210 for the soft gripper and 0x220 for the vacuum gripper, so they could be controlled simultaneously.

This integration makes it possible for a higher-level decision maker, such as a Jetson main computer in a humanoid robot, to automatically select the appropriate gripper based on the task: flat, rigid object -> vacuum branch; irregular or fragile object -> soft gripper.

8.5 Budget

Based on the material costs (Table 7), both systems can be implemented for a fraction, approximately 5-10%, of the price of professional industrial grippers. The specific cost breakdown of the vacuum system is shown in the table below.

Description	Quantity	Unit price	Total
Vacuum kit (pumps, valves, 4 x 50 mm cups, tubes)	1 package	17 000 Ft	17 000 Ft
PETG-HF filament (frame structure)	~520 g	8 000 Ft/kg	4 160 Ft
Arduino Nano microcontroller	1 pc	2 000 Ft	2 000 Ft
MRS-101-C3 rocker switch (main switch)	1 pc	270 Ft	270 Ft
Vandal-resistant push buttons	2 pcs	1 000 Ft	2 000 Ft
TOTAL			25 430 Ft

Table 7. Material cost of the vacuum gripper.

This cost level makes the system suitable for educational purposes or for prototype-level automation in small and medium-sized enterprises, exactly the segment where the 300,000-500,000 HUF entry price of a professional industrial gripper is already a serious obstacle.

9. Abstract

In this thesis we presented and compared two robotic grippers built on different concepts: a soft gripper and a vacuum gripper. The mechanical soft gripper operates with flexible TPU fingertips, a two-finger design and a linear motor; the vacuum gripper uses four 50 mm silicone suction cups, a telescopic suspension and a three-way electronic valve. Both systems are controlled by an Arduino Nano microcontroller.

After optimization, the soft gripper achieves 38.5 N of gripping force, and during tests it lifted and held 1.5 kg objects with a 100% success rate even under shaking. Cylindrical objects with small diameter are more difficult to handle, with a 60% success rate. The theoretical maximum holding force of the vacuum system is 392.6 N, and its practical load capacity was designed for 20 kg; however, during testing the 3D-printed frame failed under the effect of the vacuum force, highlighting the importance of the anisotropic behaviour of FDM materials in design.

The result of the project is twofold: on the one hand, two working prototypes; on the other hand, concrete engineering lessons about how such a system should be dimensioned and developed. The future 2.0 versions will be built with hybrid plastic plus aluminum frame structures, sensor feedback and robot-arm integration.

10. Summary

In this thesis we present two robotic grippers built on different operating principles — a soft gripper and a vacuum gripper — and compare their performance. The mechanical soft gripper uses flexible TPU fingertips in a two-finger configuration, driven by a linear motor. The vacuum gripper uses four 50 mm silicone suction cups, a telescopic spring suspension, and a three-way electronic valve. Both systems are controlled by an Arduino Nano microcontroller.

After optimization, the soft gripper achieves 38.5 N of gripping force and successfully lifted and held 1.5 kg objects under dynamic stress with a 100% success rate. Smaller cylindrical objects proved harder to handle (60% success rate). The theoretical maximum holding force of the vacuum system is 392.6 N, with a practical load capacity designed for 20 kg; however, during testing the 3D-printed frame structure failed under the vacuum-induced reaction forces, which highlighted the importance of considering the anisotropic behavior of FDM-printed materials in the design process.

The outcome of the project is twofold: on the one hand two functional prototypes, and on the other hand concrete engineering lessons about how such a system should be sized and developed. The planned 2.0 versions will feature hybrid frame structures (plastic + aluminum reinforcement), sensor feedback, and robot arm integration.

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