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Numerical modeling and experimental validation of an adaptive pneumatic gripper for collaborative robotic palletizing

Karabegović, I.[a], Isić, S.[b], Vojić, S.[c], Husak, E.[c], Banjanović-Mehmedović, L.[d], Mahmić, M.[c], Bičo Ćar, M.[e], Radončić, A.[f]

[a]Academy of Sciences and Arts of Bosnia and Herzegovina, Sarajevo, Bosnia and Herzegovina
[b]University "Džemal Bijedić" of Mostar, Mechanical Faculty, Mostar, Bosnia and Herzegovina
[c]University of Bihać, Technical Faculty Bihać, Bihać, Bosnia and Herzegovina
[d]University of Tuzla, Faculty of Electrical Engineering, Tuzla, Bosnia and Herzegovina
[e]University of Sarajevo, School of Economic and Business, Sarajevo, Bosnia and Herzegovina
[f]International BURCH University of Sarajevo, Sarajevo, Bosnia and Herzegovina

ABSTRACT

This paper presents the development and experimental validation of an adaptive pneumatic gripper for collaborative robotic palletizing of packages with varying mass and surface characteristics. The main objective is to determine the optimal gripping-force and minimum operating pressure required to ensure stable and safe handling without slippage. A dynamic mathematical model was developed, incorporating the effects of package mass, friction coefficient, contact surface area, and inertial forces during manipulation. Numerical analysis was performed for different friction conditions (μ = 0.30-0.90) and contact configurations, enabling the determination of the minimum required gripping-forces and corresponding operating pressures. Experimental validation was conducted on a real industrial system with a collaborative robot. The results show a linear relationship between pressure and gripping-force, described by $F = 22.152\,p - 17.535$, with a high correlation coefficient ($R^2 \approx 0.998$). The maximum experimentally obtained gripping-force was approximately 70-75 N at a pressure of around 4 bar. Quantitative deviations between numerical and experimental results (65-75 %) were observed and corrected by introducing a calibration factor ($k_{corr} \approx 0.30$). The proposed model and experimental system enable reliable optimization of gripping-force and improve manipulation stability under real industrial conditions. The main contribution of this study lies in the integration of analytical modelling, numerical optimization, and industrial experimental validation for collaborative robotic palletizing systems

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**Corresponding author:*
isak1910@hotmail.com
(Karabegović, I.)

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1. Introduction

In recent years, the implementation of Industry 4.0 technologies has significantly transformed manufacturing systems, enabling higher efficiency, flexibility, and reliability of production processes. Material handling operations, including picking, sorting, and palletizing, have become key components of automation in modern production and logistics systems [1]. Alongside conventional industrial robots, the growing implementation of collaborative robots (cobots) has enabled safer human–robot interaction and more flexible integration into modern manufacturing environments. This technological advancement has accelerated the development of adaptive and soft robotic grippers capable of manipulating objects with diverse dimensions, masses, and surface properties [2-4]. Despite recent advances, reliable manipulation and palletizing of heterogeneous packages remain a major challenge. Conventional grippers are typically designed for uniform objects, which limits their applicability in dynamic production environments and may lead to unstable gripping, product deformation, and reduced operational efficiency. The need for adaptive and flexible gripping solutions has been confirmed in studies addressing multi-object grasping and modular or detachable gripper concepts [5, 6]. Motivated by these challenges, this paper focuses on the development and optimization of an adaptive pneumatic gripper for collaborative robotic palletizing of packages with masses up to 10 kg. A dynamic mathematical model of gripping-force is developed, considering the effects of friction, contact surface, and inertial forces during manipulation. In contrast to previous studies that are primarily based on simulations or laboratory experiments, the proposed model is experimentally validated under real industrial conditions [7-9]. The main contribution of this research lies in the integration of analytical modelling, numerical optimization, and experimental validation, providing a reliable framework for the design and application of adaptive grippers in collaborative robotic systems.

2. Critical review of contemporary research on adaptive robotic grippers

2.1 Adaptive grippers in collaborative robotics

During the handling and manipulation of materials, semi-finished products, and finished products of different dimensions and shapes in manufacturing processes, flexible and adaptive grippers represent one of the fundamental components in the automation of production systems. In recent years, research and development of soft adaptive grippers have intensified through the implementation of advanced elastic materials, combined actuation mechanisms, and contact control systems between the gripper fingers and manipulated objects, as widely reported in studies on soft robotic grippers and granular jamming-based gripping systems [10, 11].

Of particular importance is the concept of variable stiffness, which enables an increase in gripping-force while maintaining adaptation to the shape of the object. Systems such as the Variable Stiffness Particle Phalange demonstrate an efficient transition between flexible and rigid manipulation modes [12, 13]. Hybrid systems that combine flexible and rigid elements expand the functional range of manipulation, simultaneously enabling stable gripping and high adaptability to the object. With the implementation of collaborative robots in manufacturing automation, technical requirements are increasingly shaped by safety standards and the need for safe human–robot interaction. Iqbal *et al.* [6] in their research propose the concept of detachable grippers that increase system flexibility and operational safety. The implementation of reconfigurable finger joints and optimized cobot operating parameters enables controlled stiffness variation during real-time operation, thereby ensuring safe and efficient adaptation of the manipulation process in collaborative industrial environments [14, 15].

2.2 Contemporary grasping techniques and product manipulation in intelligent manufacturing processes

Grippers used in traditional and collaborative industrial robots employ mechanical, pneumatic, and hybrid approaches, while recent development trends are directed toward adaptive systems based on sensory feedback. Recent approaches also include the application of reinforcement learning methods for adaptive robotic manipulation in human–robot collaboration environments, enabling improved grasping performance under uncertain and dynamic conditions [16]. Recent developments also include adaptive force control strategies for soft robotic gripping systems [17]. Soft pneumatic grippers are constructed on the principle of interconnected pressurized chambers, structures based on the jamming effect, and combined actuators that enable high contact adaptability. Grippers with variable stiffness mechanisms, capable of transitioning from a soft, flexible state to a rigid state through the application of external pressure or vacuum, are particularly effective in manipulating sensitive or deformable objects without causing damage [18-20]. Biomechanically inspired designs with multiple curvatures and variable stiffness optimize contact pressure distribution and enhance gripping stability. Palletizing system configurations within Industry 4.0 manufacturing environments are evolving toward modular and intelligent architectures that integrate adaptive grippers and sensory feedback, thereby improving flexibility, reliability, and cycle efficiency in dynamic production cells [21, 22].

2.3 Limitations of existing solutions and development perspectives

Despite significant technological progress achieved in recent years, existing gripper solutions remain limited in terms of load capacity, long-term reliability, and performance validation in real, continuous industrial operations. Many grippers are optimized for specific tasks or uniform objects, whereas highly adaptable configurations remain insufficiently investigated under industrial operating conditions. From the perspective of operational safety, Patalas-Maliszewska [23] emphasizes that the requirements of ISO/TS 15066 are often not systematically integrated during the early design stages of gripper design, particularly in soft and hybrid systems. Although variable stiffness represents a promising concept, its real-time control in dynamic industrial cells remains a technical challenge [24]. These shortcomings indicate the need to develop adaptive grippers that are energy-efficient, safety-compliant, sensor-equipped, and capable of stable and reliable gripping-force control. The proposed methodology integrates an analytical model, numerical optimization, and industrial experimental validation in order to improve existing solutions.

3. Research methodology

The research focuses on the development of an adaptive gripper for automated manipulation and palletizing of products with different masses and dimensions. The proposed methodology combines engineering calculations, numerical modeling, simulation analysis, and experimental verification within a collaborative robotic system. The applied methodological framework enables the development of an adaptive gripper capable of reliably handling packages weighing up to 10 kg, with a focus on stable gripping, operational safety, and optimal distribution of contact forces. The research methodology is divided into two parts:

- development and investigation of the numerical model of gripping-force, and
- design and implementation of experimental research for the purpose of verifying the obtained results.

3.1 Development of the numerical model of gripping-force

The development of the gripping-force model for the adaptive gripper begins with defining the characteristics of the products handled and palletized by the system. The analysis included product geometry, mass, surface stiffness, as well as the coefficient of friction occurring between the gripper fingers and the product during gripping. The adaptive gripper is designed to handle products weighing up to 10 kg while ensuring reliable handling, uniform distribution of contact forces, and prevention of slipping during lifting and transportation. During lifting and transfer of the product, the interaction between contact forces, gripping stability, and variable stiffness characteristics must be carefully considered. These factors are essential for minimizing deformation and ensuring reliable force distribution during the manipulation of objects with different geometric and mechanical properties, as emphasized in [25]. The listed parameters directly influence the selection of the gripping mechanism and the required gripping-force, particularly for products of different masses and variable shapes.

Based on the functional requirements, the technical characteristics of the adaptive gripper were defined as follows:

- maximum allowable load up to 10 kg,
- minimum gripping depth for objects with irregular geometric shapes,
- optimal cycle time in a real industrial environment,
- structural limitations caused by stiffness and deformation in the contact zone,
- compliance with the safety requirements defined by ISO/TS 15066 for collaborative robots.

Based on recommendations from the literature, the gripper design included an assessment of safety risks under conditions of close human–collaborative robot interaction, defining safety force limits as well as control mechanisms to prevent overload during object gripping. After defining the requirements, the optimal gripping principle using the gripper was selected. The package-handling system employs an adaptive gripper with two rigid fingers, where gripping stability results from mechanical strength and proper dimensioning of the contact surfaces. In accordance with previous research, systems based on rigid mechanical construction provide high stability and reliability of manipulation. Adjustment of the gripping-force is achieved through the control system, enabling precise real-time control of the gripping-force, which is particularly important when handling different loads in palletizing processes.

Within the numerical analysis, the following steps were carried out:

- 3D modeling of the gripper,
- force analysis using the finite element method (FEA),
- optimization of contact geometry,
- simulation of lifting packages weighing up to 10 kg.

The simulations analyzed deformations, stress distribution, and the response of flexible elements under load. Dynamic simulations were also conducted to assess gripping stability during robot acceleration in palletizing cycles. This approach enabled design optimization prior to manufacturing the physical prototype.

3.2 Definition of experimental configuration parameters

The integration of the adaptive gripper with the collaborative robot was realized using a standard flange connection, in accordance with ISO 9409-1. The mechatronic gripper–collaborative robot system was equipped with sensors for measuring pressure, force, and displacement, enabling real-time data acquisition and verification of numerical values of the gripping-force.

The experiment defined the following parameters:

- verification of safety limits of the gripping-force,
- positioning accuracy during palletizing,
- repeatability of gripping and releasing cycles,
- manipulation stability under vertical and horizontal accelerations.

During experimental investigations, the listed system parameters were tested under real industrial conditions, with different product masses and varying contact conditions, including different coefficients of friction and contact surfaces between the adaptive gripper fingers and the product. Effective force control ensured stable manipulation of different loads, confirming the industrial applicability of the system. Final system verification was conducted through testing of the palletizing cycle with two different product masses. The obtained results confirmed the reliability, stability, and operational efficiency of the gripper under industrial operating conditions.

3.3 Research hypothesis

The integration of an analytical gripping-force model based on stability conditions, combined with numerical optimization of contact parameters and experimental validation, enables accurate prediction of the required gripping-force and ensures stable and safe handling of packages with variable mass (up to 10 kg) in collaborative robotic systems under real industrial conditions.

The key analytical relations used in the gripping-force model are given below. For clarity and consistency, the following notation is adopted throughout the analytical and numerical analysis:

- external load acting on the package,
- gravitational force acting on the package,
- inertial force generated during robot motion,
- friction force at the finger–package interface,
- minimum required normal gripping-force,
- operational gripping-force generated by the pneumatic actuator,
- contact area between the gripper fingers and the package,
- effective pneumatic-cylinder piston area.

The minimum required normal gripping-force is determined from the friction stability condition:

$$F_{N,min} = \frac{m \cdot g}{\mu} \tag{1}$$

where m is the package mass, g is the gravitational acceleration, and μ is the friction coefficient between the gripper fingers and the package surface.

The operational gripping-force generated by the pneumatic actuator is determined as:

$$F_{op} = p \cdot A_p \tag{2}$$

where p denotes the pneumatic operating pressure and A_p represents the effective pneumatic-cylinder piston area.

4. Development of an adaptive gripper

4.1 Conceptual analysis and design of the adaptive gripper

Conceptual approach and definition of geometry

In the design development process of an adaptive gripper, it is necessary to begin with its geometric solution, which should enable universal application in the manipulation of products (in this case boxes) of different dimensions and shapes. The structure of the adaptive gripper itself is based on a combination of elastic and rigid elements in order to achieve the capability of adapting to the contact surface of the product being manipulated. The application of variable stiffness in the gripper enables the adaptation of the structure to operational requirements, thereby increasing the stability and safety of manipulation. Such an approach in the development of the adaptive gripper design contributes to increased reliability when handling heavier loads, as confirmed in relevant research.

Structural elements and material selection

The selection of appropriate materials for the construction of the adaptive gripper plays a key role in achieving the durability of the gripper itself and in attaining functional adaptability. For the adaptive gripper we used an aluminum structure with two fingers, and in the aluminum two-finger gripper the change of stiffness is not achieved through elastic chambers or jamming mechanisms, but stability and gripping-force are regulated by pneumatic drive and the mechanical structure of the lever system. Such a gripper structure ensures high mechanical resistance and minimal deformations under load, while adaptation to different packages is achieved by adjusting the operating pressure in the cylinder. In this way, control and regulation of the gripping-force is enabled depending on the mass and dimensions of the product. The fingers that provide the contact surfaces are coated with industrial rubber with a high coefficient of friction, thereby compensating for the lack of elastic adaptive elements and ensuring stable contact without slipping. The aluminum frame structure of the adaptive gripper is modular, allowing easy replacement of fingers or pads, as well as adjustment of the gripping width without complex structural interventions. Consequently, a reliable and technically simple configuration suitable for industrial and logistics applications is achieved.

Adaptation to packages of different dimensions

With the adaptive aluminum two-finger gripper, adaptation to different package dimensions for lifting is achieved by mechanical adjustment of the finger stroke range and force regulation through the pneumatic system. Controlled opening and closing of the gripper is achieved by a double-acting cylinder, while the adjustable gripping width enables manipulation of packages with different dimensions without requiring complex adaptive mechanisms. Optimal contact with the object surface is achieved by parallel movement of the fingers and uniform distribution of force through rubber contact pads. Regulation of the working air pressure enables precise adjustment of the gripping-force in accordance with the mass and characteristics of the package, thereby preventing slipping or deformation of the packaging. The simple mechanical structure of the adaptive gripper achieved by a lever system ensures stability and synchronized finger movement without increasing control complexity. Consequently, reliable and efficient adaptation to standard logistics packages of different dimensions is achieved, while maintaining the robustness and industrial applicability of the system.

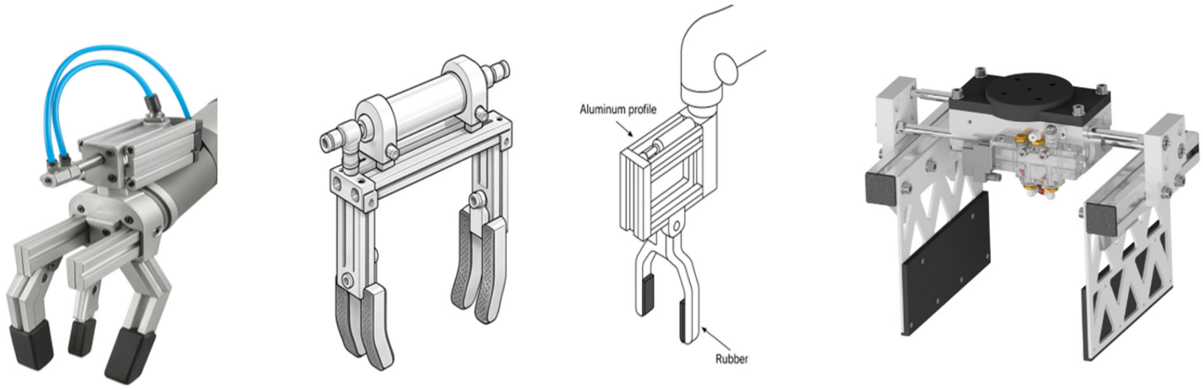
Integrated sensor system

The adaptive gripper is equipped with force and pressure sensors, as well as contact-detection modules. These components continuously monitor deformations and stresses within the structure. Positioning sensors additionally enable precise determination of the relative position of the fingers in relation to the object. In the adaptive aluminum two-finger gripper, the structure is optimized to achieve both low mass and sufficient mechanical strength. During the product-gripping phase, the system adapts to the contact surface through the geometric configuration of the fingers and controlled clamping pressure. During load transport, the structure ensures stable force transmission with minimal deformation due to the appropriate dimensioning of profiles and joints. The CAD model of the gripper was developed in a 3D environment, where all key elements were modeled: aluminum supports, finger actuation mechanism, contact surfaces, and mounting interface to the robotic arm. It must be emphasized that special attention was devoted to optimization of mass and stiffness of the structure through material selection (aluminum alloy) and appropriate cross-sections. The functionality and mechanical reliability of the structure were verified by numerical simulations, including FEA analyses of deformations, stress distribution, and safety factor under different loads. After the analytical-numerical analysis of the structure, experimental testing of the gripper was performed on objects of different masses and dimensions, thereby confirming gripping stability, uniform force distribution, and reliable operation under real industrial operating conditions.

4.2 A new concept of an adaptive gripper for manipulation of packages of different dimensions

For the development of the design of an adaptive gripper for manipulation of packages of different dimensions, we had four concepts with structures of three and two fingers, as shown in Fig. 1. During the realization of the structure, we decided on the design of the adaptive gripper shown in Fig. 1d. The gripper shown in Fig. 1d was designed as a compact, lightweight, and modular unit intended to be integrated with a collaborative robot for operation in an industrial environment. The structure of the presented adaptive gripper is optimized for the manipulation of packages of different masses and dimensions, while ensuring stability, safety, and high repeatability of grasping operations during palletizing of finished products in an industrial environment. Modern approaches to the development of adaptive grippers integrated with collaborative robots emphasize the need to balance mechanical strength and adaptability, particularly in applications where direct human–robot interaction is present [23]. The load-bearing structure of the adaptive gripper consists of an aluminum profile frame (as shown in Fig. 1d), which enables a favorable ratio between mass and mechanical resistance. The use of aluminum contributes to the reduction of system inertia, which is crucial for operation with collaborative robots where safety standards require limited kinetic energy. The modular concept allows easy integration of additional sensing and control components. According to contemporary research in the field of flexible grippers, modularity and reconfigurability represent key factors in adaptive manipulation systems [26]. In the gripper, the central working mechanism is a double-acting pneumatic cylinder located in the upper part of the structure. Motion transmission is realized through a lever system that synchronously actuates two symmetrical fingers. Pneumatic drive enables fast and repeatable working cycles, which is of particular importance in logistics applications with high package throughput. By regulating the input pressure of compressed air, precise control of the gripping-force is achieved, ensuring stable manipulation without damaging the packaging.

Research in the field of variable stiffness and adaptive grippers confirms that controlled force regulation directly influences contact stability and significantly reduces the risk of slipping during manipulation [27]. The gripper fingers are made of aluminum alloy with protruding triangular elements for mass reduction (as shown in Fig. 1d), while their contact surfaces are coated with industrial rubber with a high coefficient of friction (EPDM or NBR). Consequently, a solution is obtained that increases grasping stability and reduces the required normal contact force. The coefficient of friction represents one of the key parameters in calculating the minimum gripping-force, as emphasized in research on adaptive and soft-grip systems [28]. The implemented structure of the adaptive gripper is suitable for manipulation of cardboard boxes, plastic containers, and other objects with flat contact surfaces typical for e-commerce and logistics systems. The developed adaptive gripper structure demonstrates high efficiency in production processes involving products of different masses and dimensions. However, certain limitations occur when handling packages heavier than 10 kg, deformable products, or irregularly shaped items. When manipulation of such products is required, it is necessary to use more advanced solutions such as vacuum or soft robotic grippers. Despite the mentioned limitations, the simplicity of the structure, operational reliability, and optimized mass make this adaptive gripper a practical solution for collaborative robotic applications in modern industrial environments.



a) b) c) d)

Fig. 1 Different design solutions of the adaptive gripper for package grasping

Technical characteristics and performance analysis of the adaptive gripper

The adaptive aluminum two-finger gripper is designed for production processes in which finished products are transferred from a conveyor belt onto a Euro pallet. In addition to this application, the gripper is intended for use in warehouses, e-commerce distribution systems, logistics centers, and assembly lines, where it can be integrated with collaborative robots from various manufacturers, including KUKA iiwa, FANUC CRX, UR, Hanwha, Doosan, and JAKA.

Structure and materials

- The load-bearing frame is made of aluminum profiles with dimensions 30×30 mm,
- The fingers are designed and manufactured from aluminum alloy sheet metal with a thickness of 5 mm (where certain areas are removed in triangular shapes to reduce weight) with joint mechanisms,
- Contact coating: industrial rubber (EPDM, NBR),
- Drive element: double-acting pneumatic cylinder,
- Transmission mechanism: system of levers and sliding joints.

Pneumatic performance

- Operating pressure: 4-7 bar,
- Cycle time: approximately 0.1-0.3 s,
- Gripping-force regulation is ensured by adjusting the input pressure.

Mass and payload

- Gripper mass: 0.5-1.2 kg (depending on configuration),
- Payload capacity: 2-10 kg, depending on finger width and coefficient of friction.

Integration

- Standardized flange according to ISO 9409-1,
- Possibility of integrating additional sensor and soft-grip modules.

The adaptive pneumatic aluminum gripper offers several advantages, including modularity, low mass, adjustable gripping-force, and simple integration into existing industrial processes. However, limitations occur when handling non-standard or sensitive packages. At the same time, the identified disadvantages and limitations indicate areas that require further technological improvement, particularly when handling non-standard or sensitive packages. These technical characteristics provide a reliable basis for further numerical and experimental evaluation of the gripper's performance under real industrial conditions. A quantitative analysis of key technical parameters was performed with the aim of objectively assessing the functional and operational properties of the adaptive pneumatic aluminum gripper. Relevant indicators of cycle efficiency, safety factor, coefficient of friction, maximum gripping-force, and deformation behavior of the system under load were analyzed and evaluated. Objective quantitative verification of robotic end-effectors and safe physical human–robot interaction represents a dominant research approach in collaborative robotic systems operating alongside humans [29, 30]. Certain parameters, such as minimum gripping-force, safety coefficient, contact stability, and adaptive force regulation, are directly related to manipulation reliability and prevention of object slipping during handling operations. In the analysis of the adaptive pneumatic gripper, analytical and performance-evaluation approaches based on the relationship between load mass, gravitational acceleration, coefficient of friction, and adaptive force regulation are increasingly used to optimize gripping-force without unnecessarily increasing contact pressure. Similar optimization principles have also been discussed in studies on bio-inspired soft robotic concepts [31, 32]. The obtained results provide a reliable basis for validation of the structural solution and further optimization of operational performance.

The analysis of the data presented in Table 1 confirms that the adaptive pneumatic gripper achieves high operational reliability and stability when manipulating standard logistics packages. A safety factor greater than 1.5 ensures stable handling even under variations in mass, while the coefficient of friction has a decisive influence on the optimization of gripping-force and the prevention of slipping. Such an approach to quantitative evaluation is aligned with contemporary methodologies for the validation of industrial robotic systems, particularly in the case of collaborative robots.

Table 1 Quantitative performance analysis of the adaptive pneumatic gripper

Evaluation parameter	Description of functional aspect	Typical values (Experimental range)	Engineering interpretation
Cycle efficiency (%)	Ratio of successful grasps to total number of operations	96-99 %	High repeatability and manipulation reliability
Cycle time (s)	Time required for opening and closing of the fingers	0.10-0.30 s	Suitable for high-frequency logistics processes
Safety factor (k_s)	Ratio of maximum load capacity to nominal load	1.5-2.2	Ensures stability under variations in package mass
Coefficient of friction (μ)	Rubber–cardboard / rubber–plastic contact	0.60-0.85	Directly influences the required gripping-force
Maximum gripping-force (N)	Generated force at an operating pressure of 6 bar	120-250 N	Adjustable by regulating input pressure
Maximum elastic deformation (mm)	Finger deformation under full load	0.5-1.8 mm	Within allowable elastic limits
Energy consumption per cycle (J)	Compressed air consumption per operation	8-18 J	Depends on cylinder volume and operating pressure
Maximum payload (kg)	Maximum allowable package mass	2-10 kg	Depending on finger width and friction

5. Numerical analysis of gripping-force

The numerical analysis of the gripping-force of the object (package) was carried out by performing an analysis of the optimal gripping-force. The optimal gripping-force is determined based on the mass of the product, the coefficient of friction of the finger material, and the geometry of the contact surface. Excessive force may cause deformation of the package, while insufficient force increases the risk of slipping. The numerical analysis of the gripping-forces was modeled by applying a sliding friction model and contact pressure occurring on the fingers of the analyzed gripper. The optimal gripping-force for object manipulation (packages) is defined by relating it to the weight of the package lifted by the gripper and the coefficient of friction:

$$F_\mu = \mu \cdot F_N$$
$$F_\mu \geq m \cdot g \quad (3)$$
$$F_N \geq \frac{m \cdot g}{\mu}$$

Here, F_N denotes the total normal gripping-force applied by the gripper fingers, while F_μ represents the friction force generated at the contact interface.

The optimization model for determining the gripping-force is based on the package mass and the contact area between the gripper fingers and the package. After determining the minimum required normal gripping-force, the force distribution over the contact surface is analyzed in order to avoid local damage and deformation of the package during manipulation. The contact pressure between the gripper fingers and the package is defined by Eq. 4 and is determined based on the operational gripping-force and the total contact area.

The contact pressure between the gripper fingers and the package is defined as:

$$p_k = \frac{F_{op}}{A_k} \quad (4)$$

where p_k denotes the contact pressure between the gripper fingers and the package, is the operational gripping-force generated by the pneumatic actuator, and A_k represents the total contact area between the gripper fingers and the package.

The pneumatic actuators integrated into the gripper structure enable precise regulation of the gripping-force through adjustment of the input pressure, thereby facilitating reliable manipulation of packages with different masses and geometric characteristics. Their fast response and simple mechanical configuration make them well suited for industrial robotic grippers, where stable and adaptive force control is required. By integrating force sensors, adaptive control algorithms, and advanced robotic end-effector frameworks into the gripper system, higher operational accuracy and continuous monitoring of the contact force at the object interface are achieved, enabling improved force regulation, adaptive gripping performance, and manipulation stability under real operating conditions [33, 34]. Based on this feedback, the system can adaptively adjust the gripping-force in real time, reducing the risk of deformation of sensitive products or dropping of the object (load slipping). Consequently, a more stable and safer manipulation process is achieved, especially in applications where objects differ in mass, material, or friction characteristics. Adaptive adjustment of the gripping-force requires the integration of a sensor-feedback-based control system, as illustrated in Fig. 2. Autonomous control enables feedback based on measured values, rather than predefined pressure settings. The control algorithm of the pneumatic (or vacuum) robotic gripper used for object handling is shown in the block diagram in Fig. 2, where the signal flow from the sensor, through the controller, to the actuator is clearly illustrated.

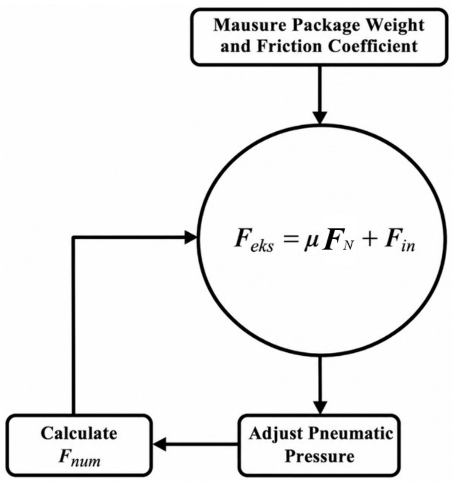


Fig. 2 Optimization control diagram of the adaptive pneumatic gripper

The control scheme of the pneumatic gripper begins with the determination of the package mass and the coefficient of friction between the gripper fingers and the object surface, as grasp stability, adaptive force regulation, and contact interaction are critical factors in the robotic manipulation of objects with varying stiffness and surface characteristics [35]. The pressure regulator controls the pneumatic actuator in order to achieve the desired gripping-force, while feedback obtained from the integrated force sensors enables adaptive real-time adjustment and prevents the application of excessive contact force. Consequently, the implemented control structure improves manipulation stability and enables wider grasping capability through adaptive stiffness regulation of the gripper fingers under varying operating conditions [36].

5.1 Numerical estimation of the gripping-force as a function of the variable coefficient of friction and effective contact area in the palletizing production process

This section presents a numerical example of calculating the optimal gripping-force for lifting a package based on real input parameters. The numerical analysis was performed on a finished product in the production process, a package with dimensions 280 × 190 × 100 mm and a mass of 6 kg, shown in Fig. 3. The package consists of six jars of jam wrapped in smooth plastic film. The packages arrive at the production line, where they are picked up by a collaborative robot equipped with a gripper and placed onto a pallet. The numerical analysis included different coefficients of friction ($\mu = 0.30$-0.90), corresponding to typical contact conditions between the gripper fingers and the package surface. In this part of the analysis, the safety factor k_s, applied by some authors, was not included. The safety factor will be considered at a later stage of the analysis. The intention was to perform a numerical evaluation that reflects real industrial operating conditions.

Fig. 3 Product for palletizing – package of jam jars with a mass of m = 6 kg

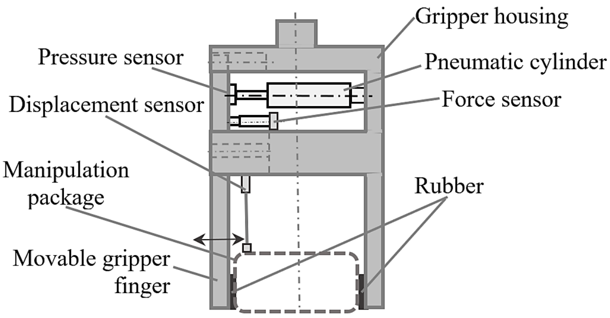


Fig. 4 Schematic representation of the adaptive gripper for package palletizing

The design of the adaptive gripper, shown in Fig. 4, consists of two fingers — one fixed and the other movable — which are actuated by a pneumatic cylinder connected to an industrial compressed air supply.

The presented gripper is used for palletizing packages with the dimensions and mass shown in Fig. 3. The input data for the numerical analysis are as follows [35]: package mass m = 6.00 kg, gravitational acceleration $g = 9.81\ \mathrm{m/s^2}$, and coefficient of friction μ = 0.40. The minimum required normal gripping-force was determined for a two-finger adaptive gripper. The required normal gripping-force calculated from the friction condition amounts to 147.15 N and represents the minimum normal gripping-force required to prevent package slipping during manipulation. This value is important for proper gripper dimensioning, pneumatic-cylinder selection, and determination of the required operating pressure. Two contact configurations were considered:

- Variant I: each finger has three contact points, resulting in a total of six contact points and a contact area of A_k = 24 cm^2.
- Variant II: each finger has one contact point, resulting in a total of two contact points and a contact area of A_k = 40 cm^2.

To ensure reliable lifting of the package without slipping, the friction force generated at the contact surfaces between the gripper fingers and the package must be greater than the total external load acting on the package. In addition to the gravitational force, inertial forces generated during lifting and transfer must also be taken into account. The corresponding analytical relations are given in Eq. 5.

$$\begin{gathered} F_\mu = \mu \cdot F_{N,min} \ \geq \ F_{req} \\ G = m \cdot g \\ F_{inv} = m \cdot a_v; \ \ F_{inh} = m \cdot a_h \\ F_{req} = G + F_{in} \\ F_{N,min} = \frac{F_{req}}{\mu} \end{gathered} \tag{5}$$

where F_μ denotes the friction force at the contact interface, is the minimum required normal gripping-force, G represents the gravitational force acting on the package, while F_{inv} and F_{inh} represent the vertical and horizontal components of the inertial force generated during lifting and transfer of the package.

Inertial forces generated during gripping and lifting must be considered in the gripping-force analysis. In order to ensure stable palletizing operation without accumulation of packages on the conveyor belt, the following operating accelerations of the gripper were assumed: vertical acceleration 0.5 m/s^2, and horizontal acceleration 0.5 m/s^2.

The F_{inh} vertical inertial-force component and the F_{inh} horizontal inertial-force component were determined according to Eq. 5. The total inertial force generated during gripper operation amounts to F_{in} = 4.242 N, while the total external load acting on the package equals F_{req} = 63.10 N.

In Variant I, each finger has three contact surfaces of 4 cm^2, resulting in a total contact area of 24 cm^2. In Variant II, each finger has one contact surface of 20 cm^2, resulting in a total contact area of 40 cm^2.

Table 2 summarizes the calculated operational gripping-force values for the two contact configurations under the considered friction and pneumatic-pressure conditions. The values presented in Table 2 represent operational gripping-force values generated under predefined pneumatic-pressure conditions and are therefore not directly equivalent to the theoretical minimum normal gripping-force defined by Eq. 5.

The values presented in Table 2 represent operational gripping-force values generated under predefined pneumatic-pressure conditions and are therefore distinct from the theoretical minimum normal gripping-force obtained from the friction stability condition.

At first glance, the results presented in Table 2 may appear to contradict the classical friction-based relation, according to which the required minimum gripping-force decreases with an increase in the coefficient of friction. However, it is important to emphasize that the values presented in Table 2 are not derived solely from the analytical minimum normal gripping-force relation $F_{N,min} = \frac{mg}{\mu}$, but from an extended model that includes the influence of pneumatic pressure, contact configuration, contact area, and inertial forces during manipulation. In the presented numerical analysis, the operational gripping-force is calculated based on the pressure–force relationship $F_{op} = p \cdot A_p$ where the pneumatic operating pressure is treated as a controlled variable. For each friction coefficient, the operating pressure is adjusted to ensure stable and reliable manipulation under dynamic operating conditions, including vertical and horizontal accelerations during palletizing.

Table 2 Calculated operational gripping force values for different contact configurations and pneumatic-pressure conditions during manipulation of a 6 kg package

Friction Coefficient μ	Pneumatic pressure p (bar)	Variant I. contact area A_k (cm²)	Variant II. contact area A_k (cm²)	Variant I. operational gripping-force F_{op} (N)	Variant I. gripping-force including inertial effects $F_{op}+F_{in}$ (N)	Variant II. operational gripping-force F_{op} (N)	Variant II. gripping-force including inertial effects $F_{op}+F_{in}$ (N)
0.30	0.30	24	40	21.60	25.84	36.00	40.24
0.35	0.35	24	40	29.40	33.64	49.00	53.24
0.40	0.40	24	40	38.40	42.64	64.00	68.24
0.45	0.45	24	40	48.60	52.84	81.00	85.24
0.50	0.50	24	40	60.00	64.24	100.00	104.24
0.55	0.55	24	40	72.60	76.84	121.00	125.24
0.60	0.60	24	40	86.40	90.64	144.00	148.24
0.65	0.65	24	40	101.40	105.64	169.00	173.24
0.70	0.70	24	40	117.60	121.84	196.00	200.24
0.75	0.75	24	40	126.00	130.24	225.00	229.24
0.80	0.80	24	40	153.69	157.93	256.00	260.24
0.85	0.85	24	40	173.40	177.64	289.00	294.24
0.90	0.90	24	40	194.40	198.64	324.00	328.24

As a result, an increase in the friction coefficient is accompanied by an increase in the applied pressure, which leads to a corresponding increase in the calculated gripping-force. Therefore, the observed trend does not represent the theoretical minimum gripping-force, but rather the required operational gripping-force under predefined operating conditions. This approach reflects real industrial practice, where the gripping-force is often intentionally increased to ensure stability, compensate for dynamic effects, and maintain safety margins. Such numerical analysis enables the assessment of the minimum forces and pneumatic requirements necessary for reliable manipulation of a package with a mass of 6 kg. The diagram shown in Fig. 5 presents the results of the numerical analysis from Table 2, carried out for the verification of the calculated gripping-forces and the behavior of the pneumatic gripper under real operating conditions. The diagram illustrates the relationship between the operating pressure and the achieved gripping-force for Variant I and Variant II contact configurations between both gripper fingers and the package during palletizing, thereby enabling the determination of the minimum pressure required for safe lifting of the package. The diagram shows that the gripping-force F_v increases linearly with the increase of the operating pressure in the pneumatic actuator, for both Variant I and Variant II. Higher pressure proportionally increases the normal force exerted by the gripper fingers on the package.

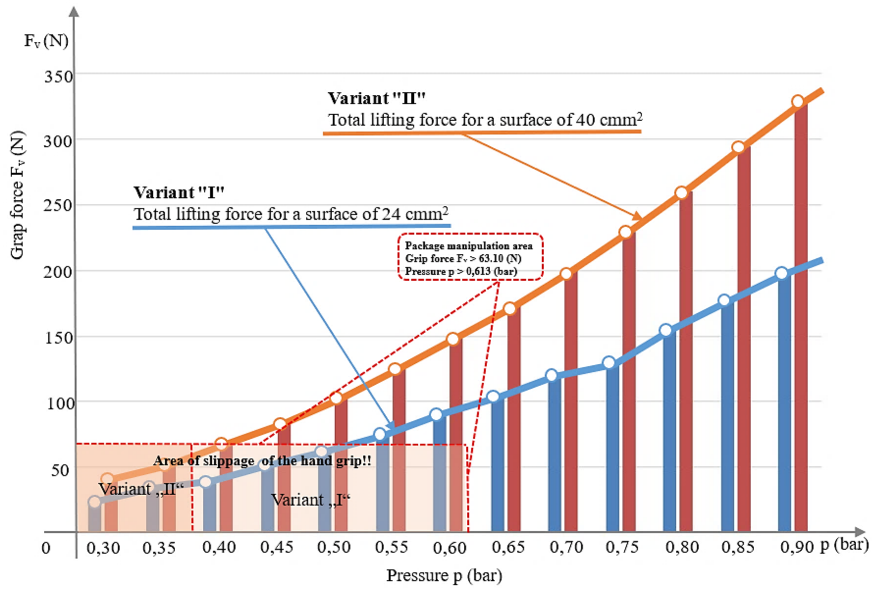


Fig. 5 Numerical values of the operational gripping-force F_{num} as a function of the operating pressure p

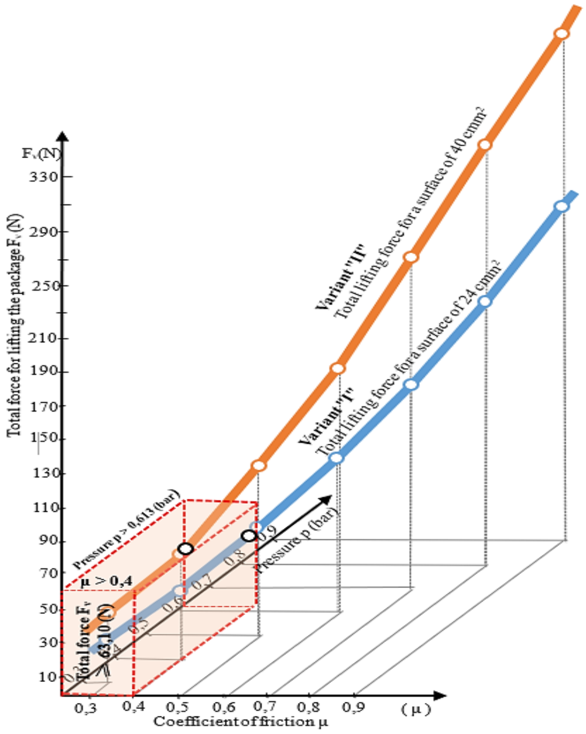


Fig. 6 Numerical values of the operational gripping-force F_{num} as a function of the coefficient of friction μ and the operating pressure p

The curve enables determination of the optimal pressure required to ensure reliable gripping without slipping or excessive loading of the package. Fig. 6 illustrates the variation in the operational gripping-force of the adaptive gripper in Variants I and II as a function of the coefficient of friction and the operating pressure. It also shows the dependence of the total lifting force required to prevent slipping on the coefficient of friction μ and the operating pressure required for normal palletizing of the package. The variation of the force required for proper gripper operation during palletizing confirms the influence of different contact materials on the gripper performance. Furthermore, the lifting force is also a function of the operating pressure and the contact area between the gripper fingers and the package. These diagrams are useful for the engineering design of pneumatic grippers and for determining the safety margins required for their normal operation.

6. Conducting the experiment and analysis of the obtained results

6.1 Experimental setup

The experiment for testing the adaptive pneumatic gripper was conducted in a work cell designed as an integrated system for automated package picking and placement onto a Euro pallet (automated palletizing) in a real industrial environment. The work cell consists of a belt conveyor on which jam packages arriving from production, each containing six jars, are transported; a collaborative robot equipped with an adaptive pneumatic gripper of proprietary design; a Euro pallet on which the packages are stacked; and an accompanying sensor and control system.

In the production process, the belt conveyor is used for the continuous delivery of packages to the location where automated palletizing onto a Euro pallet is performed. The packages arriving from the production process consist of six glass jars of jam, grouped in a cardboard holder and additionally wrapped in plastic (stretch) film for stability during handling, as shown in Fig. 3. The dimensions and mass of the package (given in Section 5.1) correspond to typical food products intended for retail, which enables a realistic simulation of the industrial process. The collaborative robot is positioned beside the belt conveyor so that its workspace covers both the package pick-up zone on the conveyor and the Euro pallet onto which the packages are stacked. An adaptive pneumatic gripper is mounted on the end-effector of the collaborative robot. The gripper, which integrates all sensors required for gripping-force optimization, is designed for the safe handling of packages of different dimensions and masses on the belt conveyor and for their palletizing onto a Euro pallet through adjustment of the contact surface, operating pressure, and clamping force.

Package placement on the conveyor

Packages with six jars of jam arrive from the packaging cell, grouped in a cardboard holder and additionally wrapped in plastic (stretch) film, and are transported on the belt conveyor. They are placed with a correct orientation, with the longer side parallel to the direction of conveyor movement. The conveyor belt speed is constant (but can be adjusted) and enables the delivery of packages with jars to a predefined pick position where the packages are taken by the adaptive pneumatic gripper, as shown in Fig. 7. In the package pickup zone, a reference point (pick point) is defined using a presence sensor (as shown in Fig. 7). In this way, precise positioning of the package relative to the robot coordinate system is ensured. This approach minimizes the need for additional trajectory corrections and increases the repeatability of package picking and placement onto the Euro pallet.

Fig. 7 Work cell for package palletizing

Integration with the Euro pallet

The jam packages are picked up by the adaptive pneumatic gripper integrated on the collaborative robot, and the robot transfers and stacks them onto a Euro pallet of standard dimensions (1200 × 800 mm), which is placed within the robot workspace with a clearly defined base coordinate in the control system. The palletizing system is implemented using a layer-by-layer programming pattern, where the arrangement between rows and layers is predefined in order to achieve a stable load structure on the pallet for further transport. After picking the package from the conveyor, the robot generates an optimal trajectory to the target position on the pallet, with controlled lowering and gradual unloading of the gripper. After releasing the package, the robot returns to the initial position and the cycle repeats. Particular attention was paid to aligning the stacking height with the maximum allowable pallet load height, as well as maintaining the stability of packages wrapped in stretch film.

Sensor system

The package-palletizing work cell was equipped with a sensor system for monitoring and analyzing key process parameters during the experiments, including operating pressure in the pneumatic cylinder, gripping-force, package displacement, and package arrival at the conveyor pick-up zone, as shown in Fig. 7 [26, 29]. The sensor system in the work cell includes the following sensors:

- Package presence sensor on the conveyor belt (detection of arrival in the pick zone),
- Pressure sensor in the pneumatic system (measurement of operating pressure in the gripper cylinder),
- Force sensor on the gripper contact surface (measurement of package clamping force),
- Displacement/slip sensor (detection of possible relative package movement during lifting),
- Internal feedback of the collaborative robot (position, speed, and joint torques).

Table 3 Overview of sensors integrated into the experimental robotic palletizing cell

No.	Sensor type	Sensor model	Measuring range / Technical characteristics	Output signal type	Sensor accuracy	Position in robotic cell	Function in the system
1	Non-contact displacement sensor	BALLUFF BAW M12 (alternative: HC-SR04 Ultrasonic Arduino sensor)	Detection range up to 2 mm (alternative: 3-400 cm); sampling rate: 50-100 Hz	Analog (0-10 V) (alternative: digital)	± 0.3 % FS (alternative: ± 10 cm)	Above the conveyor belt in the pick zone	Detection of package arrival and activation of the robot pick-and-place sequence; input signal for cycle synchronization
2	Strain-gauge pressure sensor	P8AP	Measuring range: 0 kPa to 2 MPa; calibrated according to manufacturer specifications	Analog (0-2 mV/V)	± 0.3 % FS	Pneumatic line of the gripper	Monitoring of operating pressure and stability of the pneumatic gripper system; validation of pressure–force relationship
3	Force sensor (Load cell)	U2B	Single-axis force measurement; nominal capacity adapted to gripping range; sampling rate: 100 Hz	Analog (0-2 mV/V)	± 0.3 % FS	Integrated between the side plates of the gripper	Measurement of package clamping force and optimization of gripping-force; experimental validation of analytical model
4	Acceleration sensor	ASC 5631	Measurement of acceleration in three orthogonal directions; frequency range up to 1 kHz	Analog (0.5-4.5 V)	± 1 % FS	Integrated on the gripper	Measurement of dynamic load during robot motion; detection of transient disturbances affecting gripping stability
5	Linear displacement sensor (LVDT)	WA20	Precise linear displacement measurement up to 20 mm; high repeatability (< 0.1 % FS)	Analog (0-10 V)	± 0.3 % FS	On the gripper mechanism	Detection of possible slipping or displacement of the package during manipulation; validation of gripping stability condition

The specified sensor models, along with their technical characteristics and functions in the palletizing work cell, are presented in Table 3. The sensor-system enables comprehensive monitoring of both static and dynamic parameters of the gripping and package-manipulation process under real industrial conditions. The integration of force, pressure, and displacement sensors provides direct experimental validation of the analytical gripping-force model, while the accelerometer provides insight into dynamic disturbances that may affect manipulation stability. In particular, measurements of gripping-force and pressure in the pneumatic system were used to verify the force–pressure relationship, while displacement data and possible package slippage were used to confirm the stability condition defined in the research hypothesis. Such an approach ensures high reliability of the results, reproducibility of the experiment, and direct applicability of the developed model in industrial applications of collaborative robotics. All sensors were calibrated prior to the experiment to ensure measurement accuracy and repeatability of the obtained results.

6.2 Measurement of the minimum gripping-force

The measurement of the minimum gripping-force was conducted with the aim of experimentally determining the lowest force required for stable and safe manipulation of packages without slipping during lifting and transportation in the palletizing process. The obtained experimental results were compared with the numerical values defined in Chapter 5, where the minimum gripping-force was determined as a function of package mass, friction coefficient, and contact conditions between the gripper fingers and the package. During the experimental investigation, the minimum gripping-force was determined by gradually increasing the operating pressure in the pneumatic actuator until stable gripping without slipping was achieved. The values of gripping-force and pressure were continuously monitored using the integrated sensor system described in Chapter 6.1, which enabled precise determination of the boundary conditions for stable manipulation under real industrial operating conditions. For the experiment, the minimum and maximum coefficients of friction at the contact interface between the gripper and the package, both covered with protective film, were determined, and the results are shown in Fig. 8.

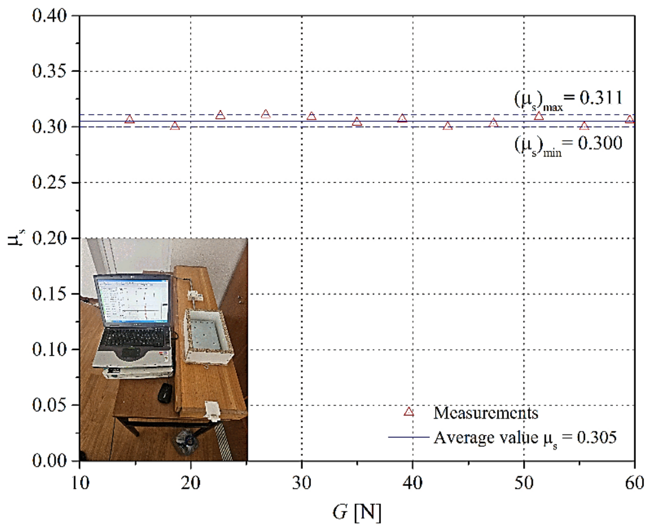


Fig. 8 Experimental results of determining the coefficient of friction at the contact point between the gripper and the package

Experimental determination of the coefficient of friction was carried out at the contact point between the gripper and the package, where both contact surfaces were covered with protective film. During testing, the minimum and maximum values of the coefficient of friction were determined, amounting to $\mu_{s,min} = 0.300$ and $\mu_{s,max} = 0.311$, while the mean value is $\mu_{s,avg} = 0.305$. The obtained results show low dispersion of values, which indicates high repeatability of measurements and stable contact conditions between the gripper and the package. The low variability of the coefficient of friction confirms the reliability of the experimental method and enables its use as a relevant input parameter in the numerical model. The experimental results are shown in Fig. 9, where the experimental determination of compressor pressure and pressure in the pneumatic cylinder was performed with the aim of analyzing their relationship with the achieved gripping-force required for lifting the package. During testing, the operating pressure of the compressor and the force exerted by the gripper on the package were continuously measured under real operating conditions. Based on the obtained data, it was possible to estimate the minimum pressure required for stable gripping without slipping. The experimental results are presented in the diagram. From the diagram, it can be observed that the compressor pressure (blue line) increases almost linearly over time up to approximately 4.1 bar, after which system stabilization occurs. At the same time, the gripping-force (red line) increases progressively and reaches a value of approximately 72-74 N, which represents the maximum achieved force in the experiment. In the initial phase of operation (up to $\sim$ 20 s), the force is very low due to insufficient pressure to achieve effective contact between the gripper and the package. After that, a rapid increase in force occurs, indicating a direct dependence of force on the pressure in the cylinder.

In the final stage of the experiment, force saturation is observed, although the pressure slightly increases, which indicates the presence of losses in the system and limitations of the mechanical structure. Such behavior confirms real operating conditions of the pneumatic system, where an increase in pressure does not always lead to a proportional increase in force due to the influence of friction, deformations, and internal losses. The relationship between compressor pressure and gripping-force was experimentally determined in order to define the actual relationship between the input pneumatic pressure and the force achieved by the gripper. During testing, the compressed air pressure and the corresponding force exerted by the gripper on the package were continuously measured. The experimentally obtained relationship between pneumatic pressure and the gripping-force exerted by the gripper on the package is presented in Fig. 10.

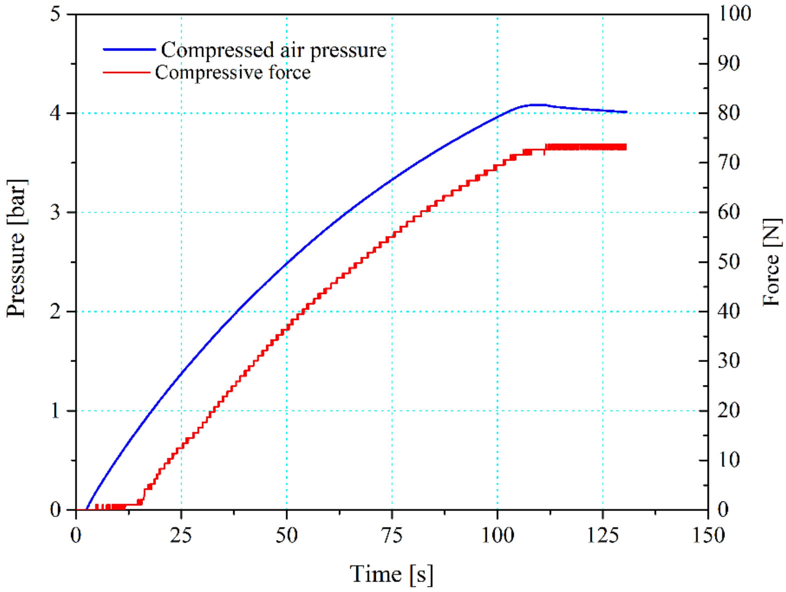


Fig. 9 Experimental variation of compressor pressure and gripping-force during package lifting

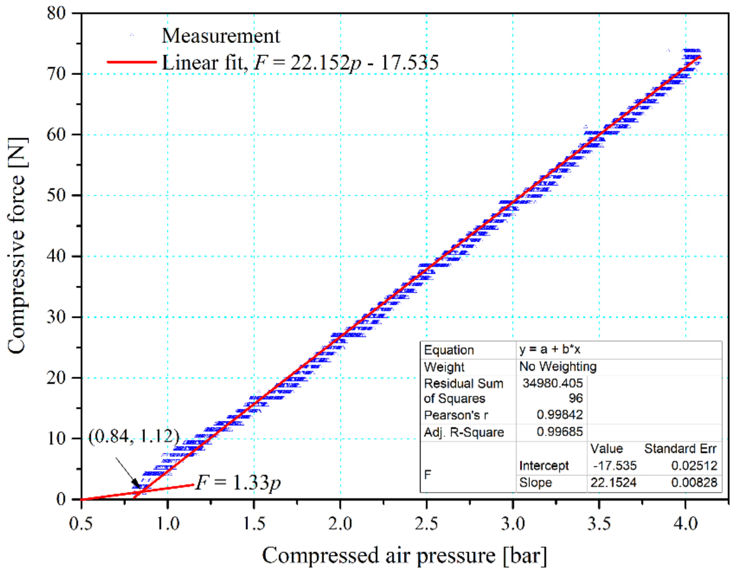


Fig. 10 Gripping-force as a function of pneumatic-cylinder pressure

During testing, the compressed air pressure and the corresponding force exerted by the gripper on the package were continuously measured. Based on the experimental data, it was possible to determine the functional dependence of force on pressure, as well as to evaluate the efficiency of the pneumatic system. The obtained results are presented in the diagram. From the diagram, a nearly linear relationship between compressed air pressure and gripping-force can be clearly observed, which is confirmed by the linear regression defined by the expression $F = 22.152\,p - 17.535$. The experimental points show high agreement with the regression line, which confirms a high correlation coefficient ($R^2 \approx 0.998$), indicating high measurement accuracy. In the initial region (below approximately 1 bar), the force is very small or negligible, indicating the existence of a system activation threshold due to mechanical and pneumatic losses. After this threshold, a stable and linear increase in force occurs with increasing pressure, where the force reaches values of approximately 70-75 N at a pressure of around 4 bar. Minor deviations of the experimental points from the regression line are caused by real effects such as friction in the cylinder, elastic deformations, and non-ideal contact conditions. Overall, the diagram confirms a reliable and predictable characteristic of the pneumatic system, which is crucial for precise control of gripping-force in industrial conditions.

Each experimental condition (defined by a specific pressure level and contact configuration) was repeated a minimum of five times in order to ensure the reliability and repeatability of the obtained results. The reported gripping-force values represent the averages of the repeated measurements, while the variation between trials remained within ± 3-5 %, indicating a high level of measurement consistency.

The relatively low dispersion of the results confirms the stability of the experimental setup, as well as the reliability of the sensor system used for force and pressure measurements. This ensures that the obtained results are statistically representative and suitable for comparison with the numerical model. This level of repeatability is consistent with standard industrial measurement practices.

7. Discussion of numerical and experimental results

The comparison between numerical and experimental results shows a high level of agreement in terms of the functional dependence between gripping-force and pneumatic pressure. Both approaches confirm a linear relationship, which validates the analytical model for engineering applications. The experimental results exhibit a high correlation coefficient ($R^2 \approx 0.998$), confirming the reliability and repeatability of the measurements. However, quantitative differences between the numerical and experimental results were observed, with the numerical model predicting higher force values. A systematic deviation of approximately 65-75 % was observed between the numerical and experimental models, depending on the operating pressure. For example, at a pressure of $p \approx 4$ bar, the experimental force reaches approximately 70-75 N, while the numerical model predicts significantly higher values. These deviations are primarily caused by real system effects such as internal friction in the pneumatic actuator, mechanical losses in the transmission system, elastic deformations, and non-ideal contact conditions. The experimental results confirm that the actual gripping-force is lower than the theoretical value, which highlights the importance of model calibration for industrial applications. The introduction of a correction factor ($k_{corr} \approx 0.30$) improves the agreement between the numerical and experimental models. Despite these differences, the consistency of trends confirms the reliability and applicability of the developed model for engineering design and optimization of gripping systems.

7.1 Model calibration and correction factor for industrial application

In order to improve the agreement between the numerical model and experimental results, a calibration procedure was performed based on the experimentally obtained relationship between gripping-force and pneumatic pressure.

The experimental results show that the actual gripping-force can be described by a linear relationship:

$$F_{exp} = 22.152\,p - 17.535 \tag{6}$$

while the numerical model predicts a proportional relationship of the form:

$$F_{num} = k \cdot p \tag{7}$$

Here, k is the theoretical proportionality coefficient derived from the analytical gripping model. A comparison of the slopes of these functions reveals a significant discrepancy between the numerical and experimental results. This discrepancy is primarily caused by real system effects, including:

- internal friction in the pneumatic cylinder,
- mechanical losses in the lever transmission mechanism,
- elastic deformation of the gripper structure,
- non-ideal contact conditions between the gripper and the package.

To account for these effects, a correction (calibration) factor is introduced:

$$k_{corr} = \frac{F_{exp}}{F_{num}} \tag{8}$$

Based on the experimental data, the average value of the correction factor is:

$$k_{corr} \approx 0.30 \tag{9}$$

The introduction of this correction factor enables more accurate prediction of gripping-force under real industrial operating conditions and significantly improves the applicability of the developed model in engineering design and optimization of pneumatic gripping systems.

7.2 Analysis of the deviation between numerical and experimental results

To quantitatively evaluate the deviation between numerical and experimental results, a relative error analysis was performed. The relative error is defined as:

$$\varepsilon = \frac{|\, F_{num} - F_{exp} \,|}{F_{num}} \cdot 100\ \% \tag{10}$$

Based on the experimental data, the average deviation between the numerical and experimental results ranges between 65 % and 75 %, depending on the operating pressure. The error decreases slightly at higher pressures due to improved mechanical stability and reduced relative influence of friction losses. The main sources of error include:

- nonlinear friction effects in the pneumatic actuator,
- mechanical inefficiencies in the transmission system,
- structural compliance of the gripper,
- simplified assumptions in the analytical model.

Despite these deviations, the consistent linear trend observed in both numerical and experimental results confirms the validity of the model for engineering applications. From an engineering perspective, the results indicate that direct use of the analytical model without calibration may lead to overestimation of the required gripping-force. The introduction of a correction factor enables more realistic system design, reduces energy consumption, and minimizes the risk of product damage. This is particularly important in collaborative robotic applications, where excessive force may compromise safety and efficiency.

Furthermore, by introducing the correction factor defined in Subsection 7.1, the numerical model can be reformulated in a calibrated form:

$$F_{cal} = k_{corr} \cdot F_{num} \tag{11}$$

where $k_{corr} \approx 0.30$ represents the experimentally determined correction coefficient.

The application of the calibrated model significantly reduces the deviation between the numerical and experimental results, bringing the relative error to a level acceptable for engineering applications. This confirms that the initially high deviation (65-75 %) is not a consequence of model inadequacy, but rather of simplified assumptions and unmodeled real system losses. Therefore, the calibrated model provides a reliable basis for the design and optimization of pneumatic gripping systems in real industrial environments. To further generalize the applicability of the proposed system, the following considerations can be made:

- Although the experimental validation was conducted on a specific type of packaged product, the proposed adaptive pneumatic gripper is designed to handle a wider range of package geometries, materials, and surface conditions. The gripper utilizes a mechanical two-finger configuration with adjustable stroke and pressure-controlled gripping-force, enabling adaptation to packages of different dimensions and masses.
- The use of high-friction rubber contact surfaces (EPDM/NBR) allows stable gripping of various materials such as cardboard, plastic, and composite packaging commonly found in industrial and logistics environments. Variations in surface conditions, including smooth, coated, or slightly irregular surfaces, are compensated through adjustment of the pneumatic pressure, which directly controls the applied gripping-force.
- For regular-shaped packages (e.g., boxes and containers), the gripper ensures uniform force distribution and stable contact. However, for highly irregular, deformable, or very low-friction objects, the gripping performance may be limited, and alternative solutions such as vacuum or soft robotic grippers may be more suitable.

- These considerations indicate that the proposed system is applicable to a broad range of industrial packaging types while also clarifying its operational limitations, which will be further investigated in future research.

8. Conclusion

This paper presents the development, numerical modeling, and experimental validation of an adaptive pneumatic gripper for collaborative robotic palletizing applications. The proposed analytical model enables the determination of the optimal gripping-force as a function of package mass, friction coefficient, and contact conditions. Experimental results confirm a strong linear relationship between pneumatic pressure and gripping-force, described by the relation $F = 22.152\,p - 17.535$, with a high correlation coefficient ($R^2 \approx 0.998$), indicating excellent measurement accuracy and system repeatability. The maximum experimentally obtained gripping-force was approximately 70-75 N at an operating pressure of approximately 4 bar. Although quantitative deviations between numerical and experimental results were observed (approximately 65-75 %), these differences are attributed to real system effects, including pneumatic losses, mechanical friction, structural compliance, and non-ideal contact conditions. The introduction of a correction factor ($k_{corr} \approx\ 0.30$) significantly improves the agreement between the model and experimental data, enabling more accurate prediction of gripping-force under real industrial conditions. The developed system demonstrates reliable and stable performance in handling packages up to 10 kg, with optimized force control and reduced risk of slippage or product damage. The proposed methodology integrates analytical modelling, numerical optimization, and experimental validation. This approach provides a robust framework for the design and implementation of adaptive grippers in collaborative robotic systems. Future research will focus on the integration of real-time adaptive control strategies, sensor-based force regulation, and extension of the model to variable surface conditions and heterogeneous objects in dynamic industrial environments.

The proposed approach provides a practical framework for the design and optimization of adaptive pneumatic grippers in real industrial environments and helps bridge the gap between theoretical modelling and industrial implementation.

Although the experimental validation presented in this study focuses on short-term operation under controlled industrial conditions, the proposed adaptive pneumatic gripper is designed in accordance with standard industrial requirements for durability, repeatability, and continuous operation. The mechanical structure of the gripper, based on an aluminum frame and a pneumatic actuation system, ensures high robustness and low susceptibility to wear under cyclic loading conditions.

The use of industrial-grade components, including pneumatic cylinders and rubber contact surfaces, enables reliable operation in repetitive palletizing tasks typical for industrial environments. Furthermore, the observed high repeatability of experimental results and stable force–pressure characteristics indicate that the system is capable of maintaining consistent performance over extended operational cycles.

However, long-term performance aspects such as component wear, fatigue, and maintenance requirements were not the primary focus of this study and will be addressed in future research through extended lifecycle testing under continuous industrial operation.

These findings indicate that real-system effects, including pneumatic losses, mechanical friction, and structural compliance, significantly contribute to the deviation between numerical and experimental results, leading to an overestimation of the gripping-force in the analytical model. Therefore, for practical industrial application, the use of the calibrated model with the correction factor ($k\_corr \approx 0.30$) is essential to ensure accurate force prediction, avoid excessive gripping-force, and enhance system efficiency and operational safety.

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