EAI Endorsed Transactions
on Digital Transformation of Industrial Processes
Research Article EAI.EU

Design of a Multifunctional Pick & Place Gripper for Palletizing and Handling Cardboard Boxes and Europallets

Adriano A. Santos[1,2,*], António F. da Silva[1,2], Carlos Felgueiras[3], Paulo Jorge Silva[3] and Filipe Pereira[1,2]

[1]ISEP, Polytechnic of Porto, rua Dr. António Bernardino de Almeida, 4249-015 Porto, Portugal
[2]INEGI–Institute of Science and Innovation in Mechanical and Industrial Engineering, Porto, Portugal
[3]CIETI, ISEP, Polytechnic of Porto, rua Dr. António Bernardino de Almeida, 4249-015 Porto, Portugal

Abstract

European industry wants to respond in good time to the demands of the European market, and the world market in general. These responses must consider the changes taking place in the industry, considering possible updates to its production lines and methods. Increasing production capacity, renewing lines and adapting production methods often lead to the integration of robotic systems both in the production phase and in packaging, i.e. in the palletizing. Adopting this type of solution at the final stage of the process will significantly increase the quality with which products are handled and packaged. The aim of this work is to present a solution for handling cardboard boxes and palletizing them on a europallet. The gripper developed is designed to handle cardboard boxes and standard pallets in a multidisciplinary manner, regardless of their positioning. Its integration into a robotic system solves not only the problems of repeatability, but also the associated ergonomic problems, increasing productivity and consequently the success of the organization. The incorporation of different technologies has led to the development of functional and reliable equipment capable of performing multiple tasks.

Keywords: Cardboard boxes, End-Effector, Gripper, Palletizing, Pick & Place, Robotic systems

Received on 21 August 2026, accepted on 08 September 2026, published on 11 September 2026

Copyright © 2026 Adriano A. Santos *et al.*, licensed to EAI. This is an open access article distributed under the terms of the CC BY-NC-SA 4.0, which permits copying, redistributing, remixing, transformation, and building upon the material in any medium so long as the original work is properly cited.

doi: 10.4108/dtip.14671

1. Introduction

In a globalized scenario, industries organizations are looking for alternatives that will allow them to become more competitive, increasing productivity and guaranteeing the quality of production processes at low cost [1]. To guarantee the creation of value and ensure competitiveness and growth in the volume of production combined with quality, it is necessary to guarantee organizational, social and technical skills that make it possible, through new technologies, to make the most of the resources and make operations faster and simpler [2].

Then, the use of robots on production lines improves profitability and reorganizes production space, thus giving operators higher value-added and more ergonomic tasks. Today, many industries have opted to integrate robotic systems into their lines that can carry out welding [3], assembly and object handling [4], operating continuously, safely and with quality.

The Industrial Revolution (IR) is effective and is changing the way industries work, at a time when the need for personalized production demands more response and quality. In this sense, the introduction of robotics systems into

*Corresponding author. Email: ads@isep.ipp.pt

industrial processes has revolutionized our view of industry, which, despite requiring Human Resources (HR) to have digital skills [5], offers great advantages essentially associated with repetitive and monotonous tasks such as pelletizing. It is undeniable that industry is an ever-changing ‘process’ and that, to reach the industrial level we have today, major transformations had to take place in industry. However, it is up to higher education to support the Fourth and Five Industrial Revolution and face the challenges inherent in developing skills capable of dealing with digital innovations and the integration of advanced technologies, including artificial intelligence (AI), into the learning and technology transfer chain, such as virtual reality (VR), augmented reality (AR) and machine learning (ML) [6][7]. On the other hand, regardless of the phase of the industrial revolution (4IR) or (5IR), the focus of companies continues to be on obtaining intelligent products and services that contribute to more efficient productivity combined with social responsibility.

The 1IR began in England in the 17th century with the mechanization of the textile industry, while the 2IR, known as the technological revolution, came about with the electrification of assembly lines. The 3IR came about with the use of electronics combined with information systems, which allowed for the automation of production lines and the use of robotics systems, but it wasn't until the 4IR that a reduction in production costs was achieved with a considerable increase in quality through digitalization and automation [8]. The concept of 4IR, or Industry 4.0 (I4.0), is related to the idea of intelligent and fully automated factories, where the fusion of virtual and reality adds value by favoring development, production and recycling [9]. All this industrial evolution has not only been limited to the development of more efficient production lines but has also had a major impact on the evolution of robotics systems. So, just as industry has evolved with its well-defined phases, robotics systems and the concept behind it have undergone major transformations. At first, robots were treated as ‘prisoners’ behind isolation grids, but now they have ‘broken free’ and are at the heart of production lines, side by side with operators. On the other hand, the integration of vision systems [10] and artificial intelligence (AI) has allowed robots to perceive their surroundings and thus have cognitive capabilities, making them intelligent machines [11] capable of solving problems [12]. Today, robots are installed in operators' workplaces, sharing the same space in perfect human-robot collaboration (HCR) with safety, flexibility and versatility, even when used in the most inhospitable environments such as mining and construction [13].

In this scenario, the realization of a robotic pelletizing solution depends not only on the initial capital invested, but also on a whole study of implementation, equipment and spatial integration [4]. Thus, it is necessary to consider the working space, the speed and reach of the arm [14], its kinematics and dynamics, the payload and precision, as well as the degrees of freedom (DoF) of the arm [15]. No less important and not to be overlooked is the joint configuration of the roll-pitch-roll (ZYZ) or pitch-yaw-roll (XYZ) wrist, i.e. spherical wrist or human wrist. Although the choice of an industrial robot may be more considered, when opting for a cobot (collaborative robot), flexibility and load capacity must be considered, which is lower than in industrial options, since they will work integrated, without protective grids, in the production lines [16]. Cobots perform the less ergonomic and repetitive tasks in parallel with operators, freeing them up for more demanding, complex and higher-value tasks. This possibility takes the cobot to a level of immense applications in which the operator becomes the robot's working ‘partner’ [17].

Robotics systems are currently a determining factor in the industrial evolution of any sector. Consequently, investment in robotics systems can be expected to reduce production downtime, with a corresponding increase in production volume associated with high-quality standards. Downtimes are events that are unavoidable in some way, whether it's corrective or preventive maintenance or adapting to new products. In this case, the stoppage can be understood as necessary for reprogramming on the manufacturing line. In this case, known as online programming or teaching [18][19], it becomes unsuitable because it requires physical interaction which contributes to increased downtime [20]. System downtime is a factor that penalizes productivity, so an offline scheduling approach will minimize these downtimes and singularity problems. Offline programming, generated autonomously from the physical system, requires the use of dedicated simulation software that can minimize downtime [14][15] by predefining and simulating all the movements of the robot arm, but requires specialized personnel [21].

1.1. Palletization

Palletizing, as a process, focuses on an organizational method of storing products or materials efficiently and distributed on a pallet to facilitate agile handling and easy transport. Given the repetitiveness of these tasks, as well as the ergonomic constraints of the operation [22], their automation has always been one of the industry's priorities. Thus, with the introduction of robotics systems, in addition to increasing production capacity, action is eliminated at the end of the line which, if carried out by operators, is repetitive, monotonous and has no added value. This type of activity is not ergonomic, unappealing or challenging, which makes the operator's daily activity uninteresting. The robotization of operations such as palletizing is therefore perfectly feasible, since robots can carry them out completely and be integrated into a 24/7 system, without fatigue, without ergonomic hazards and with an effective increase in productivity.

Robots are currently used to palletize a variety of products, such as boxes, bags and bottles, in industries such as the food, medical, building materials and agricultural sectors. This automation of pelletizing processes is currently one of the main needs of companies, given the competitiveness of industry in general, where the competitiveness of a global market means that any improvement in the process results in a significant return. On the other hand, in conceptual terms, the implementation of a robotic palletizing system is based on the analysis of the most suitable pelletizing method for the task to be automated - conventional: adapted to situations where high production speeds are required or robotic: where the main concern is versatility [23] - but also on the model and number of robots, the area of implementation and the assessment of economic viability [4].

1.2. Palletizer software

Industry has undergone a major technological evolution, essentially driven by the emergence of Industry 4.0. This brings intelligence to production systems on the factory floor through Virtual Reality (VR), where Cyber-Physical Systems (CPS) merge with reality. The Internet of Things (IoT) and Digital Twins (DT) are the link to Industry 5.0, where the integration of the precision of robots/cobots in the manufacturing industry with the creativity of human beings centered on CPS's [24] makes it possible to develop, in a virtual environment, the necessary programmer for the most diverse equipment, namely robots, without the need for them to be physically available or present [14][15].

This virtualization arose from the real need to reduce downtimes on production lines, i.e. to replace the physical robot with a virtual twin. Robot manufacturers have therefore developed their own programming languages, including their kinematic models, based on their hardware and software, which make them non-portable languages. Therefore, manufacturers such as ABB (Asea Brown Boveri) International, hardware used in this work, have developed their own palletizing application, Palletizing PowerPack, using the RAPID programming language, providing it as an integrated package in the RobotStudio® programming and simulation environment [25], [26]. The concept behind the development of this application is to make software available that quickly provides tools to implement pelletizing functions with ABB solutions in the most intuitive way possible, with the fewest steps and parameters, reducing the learning curve [27]. This application consists of several parameters to control and supervise the robot's movements and to calculate and create the layout of the pallets. These parameters include not only defining the size of the boxes to be handled, the dimensions of the pallets, the configuration and optimization of the stack and the number of layers [28], but also other parameters such as the maximum reach, the center of its tool and the positioning of the pick and place, among others. Figure 1 shows examples of palletization.

Figure 1. Examples of palletization

These applications are not exclusive to ABB, as all robot manufacturers offer specific pelletizing solutions in their standardized software, such as YASKAWA [29], KUKA [30], Universal Robots [31] and others. Figure 2 shows part of Yaskawa's pallet parameterization software and its possible configurations.

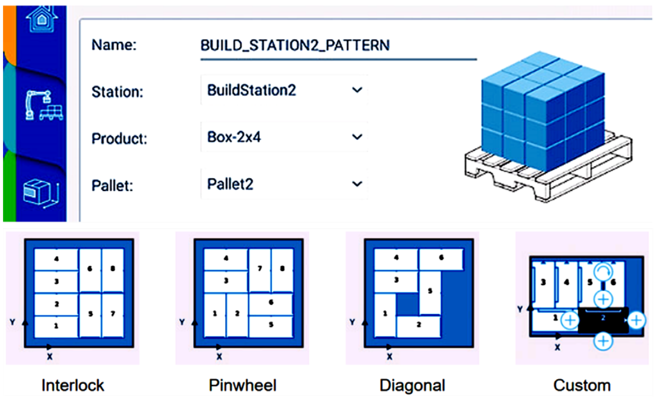

Figure 2. Example of pallet customization of Yaskawa software

On the other hand, in terms of software, there is a more comprehensive and generic offer for programming different makes and models of robots, maintaining the configuration of inputs, outputs and commands that the proprietary software provides [32]-[34], in a data support file or by additional software that guarantees the compatibility of the codes developed in the generalist software with the robot controllers. Thus, the aim of using any generic palletizing simulation system or proprietary software is to make it possible to define all the characteristics of how pelletizing will be carried out. In this sense, whether generic or proprietary software is used, the goal of programming is to define the shape and dimensions of the pallet, the pick and place points, the approach points, the tool center point (TCP) and the robot's working area. In addition to these points, the objects to be palletized and their layout must also be considered (see Figure 2), as well as the number of layers. From the point of view of centralizing the robot cell, the whole process can be controlled by a Programmable Logic Controller (PLC) which controls the entire information exchange interface between the robot controller and the several states of the cell.

This work is structured in five Sections: The first Section presents the problem and reviews the literature. The second Section presents the objectives to be achieved by developing the project, while the third Section presents the methods to analyze the problem and material used. Section four presents the results and their discussion while Section five concludes the document and discusses future work.

2. Objectives

The work carried out in this project aims to demonstrate the operational functionality of robotic systems in general, with an emphasis on their integration into pelletizing processes. These systems aim to solve the problems associated with manual processes with low added value and reduced downtime. To this end, we intend to show what has been achieved in the development of a multifunctional end-effector capable of replacing pallets, europallets, in the process of palletizing products, contained in standard cardboard boxes. To achieve these objectives, it was necessary to apply the following methodologies:

- Study of the applicability of robotic arms in industry in the field of robotics systems applied to palletizing.
- Evaluation of the restrictions that may be involved in the development of the pila, considering current regulations, safety measures, loads and, above all, its multifunctionality.
- Study of stress concentration, using the finite element method (FEM), in the various components of the end-effector developed.

In line with the above, we began by analyzing the solutions offered by various gripper manufacturers that could in some way meet the desired objective, i.e. the development of a multifunctional end-effector. From this initial assessment, it was possible to develop the final solution not only in terms of dimensions, but also in terms of total mass, according to the object to be palletized, at the lowest possible cost. On the other hand, and considering its dual functionality, handling pallets and cardboard boxes, the gripping capacity to be exercised by the gripper and its behavior when its elements are subjected to compressive and tensile forces, i.e. the stresses applied to the end-effector's fingers, were considered.

3. Methods and materials

This section presents the methodology used to develop the end-effector. The first step was to analyze the market and evaluate handling offers similarity to the objective under study, i.e. a multifunctional end-effector for handling pallets and standard cardboard boxes. The methodology was as follows:

- Study on the components to be incorporated.
- Studying the characteristics of cardboard boxes and Europallets.
- Dimensioning the handling structure.
- Behavior analysis with finite element methods.

3.1 Preamble

The system developed consists of two subsystems responsible for tightening the boxes to palletizing and another for manipulated pallets. The two systems are independent and were developed since one operation is carried out at a time, i.e. during the palletizing operation, it is not possible to transport a pallet and vice versa. This limitation is due to the payload of the robot used (ABB IRB 1600) and the challenge of management a second object while already the gripper carrying one. This restriction is only related to the load capacity of the robot used. The possibility of handling two objects at the same time will be feasible if another robot model is chosen, with a greater load capacity, and if some changes are made to the flange that connects the robot to the gripper frame.

The cardboard boxes tightening system consists of three main elements: the servomotor as the drive base, the belt and the power screw. The combination of these three components makes it possible to tighten the cardboard boxes in any of their dimensions, if these are within the possible values for which the system was designed. The use of a servomotor makes it possible to precisely tighten each of the boxes, thus enabling the handling of heavier and more robust goods, but also more fragile goods, without risk of damage. The toothed belt transmits the movement to the power screw, which converts the rotary movement into linear movement, allowing the gripper to be closed or opened. This approach allows you to operate on any type of box with dimensions that fall within the range defined. On the other hand, the pallet handling system was developed using two pneumatic cylinders responsible for gripping the pallet. This system allows the pallet to be gripped and handled according to its orientation, i.e. according to width (XY orientation) or length (XX orientation), Figure 3. To increase its functionality, the pallet handler was designed with a 45º inclination, which improved the ability to grip the stored pallets and thus gave it the ability to handle them in any position, horizontal or vertical, without compromising the rest of the structure.

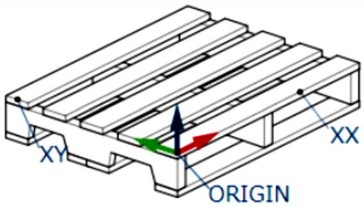

Figure 3. Pallet orientation and coordinates

3.1.1. Cardboard boxes

The transport and distribution market are usually based on packaging products in standardized cardboard boxes with different dimensions and loads. This approach to palletizing aims to demonstrate the handling capacity of the *gripper* developed and how it handles DIN (Deutsches Institut für Normung) double corrugated cardboard boxes with dimensions between 200 mm and 600 mm, minimum width and maximum length respectively, and a height of 400 mm (see Figure 1). The choice of these dimensions not only allows for different combinations of palletizing boxes (see Figure 2), but also conditions the width of the *gripper*, which has a maximum gripping capacity of 600 mm, although it is always possible to handle boxes in an X or Y orientation that have a dimension of 600 mm, as is the case with boxes measuring 810x610x420 mm, for example, as long as the maximum defined load is not exceeded.

On the other hand, regarding the force exerted by the clamp during tightening, it is necessary to ensure that the force exerted does not exceed the compressive strength of the cardboard box. This resistance factor, provided it is not exceeded, guarantees the integrity of its handling. In this case, it is essential to know the compressive strength of the cartons, as this is a determining factor when choosing the servomotor. Consequently, given that the packaging is standardized, the resistance to compression without deformation is also a standardized value defined by the Box Compression Test (BCT), application of a vertical force to the box, and the Edge Crush Test (ECT), edge compression strength, according to the American Society for Testing and Materials, ASTM D642, and the ISO 12048 standard [35].

3.1.2. Europallets characterization

Pallets, and europallets in particular, are used all over the world in the logistics sector, but especially in Europe. This type of equipment plays an important role in the global economy, not only in terms of sustainability along the supply chain (returnable transport objects - RTI), but also in general use, which translates into the ability to transport, display and distribute goods in a solid and compact form [36], but above all in its use on production lines. It is therefore on this last objective, the use of EUR 1 pallets (800x1200x114 mm), that the work carried out focuses on palletizing in a production line.

Euro pallets have standardized dimensions in accordance with EN-ISSO 8611-1:2022. These elements, usually made of wood, have the dimensions mentioned above and a mass of around 25 kg, considering that the wood is dry, i.e. with a moisture content of 22%. Figure 4 shows the structure of a solid wood pallet made of EN 13382 pine, as well as a possible palletization model of cardboard boxes.

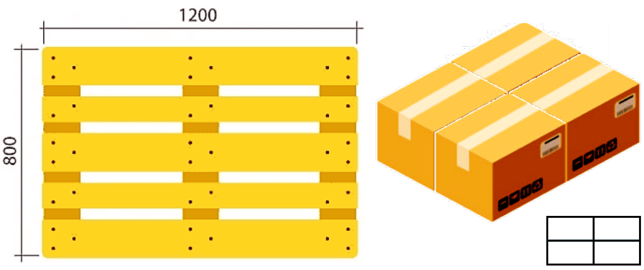

Figure 4. Characteristics of europallets and palletizing customization

4. End-effector

The following sections aim to outline the basis for the entire development of the end-effector, considering the external dimensions of the boxes to be palletized, their maximum weight and strength, as well as the characteristics of europallets.

4.1. Structural Design

The equipment developed offers dual handling functionality. This duality centers on the handling of europallets, feeding the palletizing lines, and the handling of the cardboard boxes to be palletized. Although the systems are completely independent, the ability to perform both operations simultaneously depends on the order in which the europallets and boxes are picked up. These constraints are imposed by the physical characteristics of the robot, namely its load capacity, as well as by the working area required to perform the movements. Furthermore, dual loading is limited by the sequence of movements, which dictates that the pallet must be picked up first, followed only then by the collection of the boxes. However, from an operational perspective, this would not be the ideal solution, as it would require the pallet to be placed first, with the additional weight associated with the transported box.

Consequently, the structural design of the end-effector is also constrained by the dimensions of the pallets, their weight and all the effects associated with a large object suspended at the end of the end-effector. Furthermore, the varying dimensions of the cardboard boxes to be transported must also be considered, so this necessitates, from a design perspective, to develop a mechanism capable of operating with the different dimensions – both in length and width – of the various DIN boxes. Figure 5 shows the final configuration of the end-effector developed.

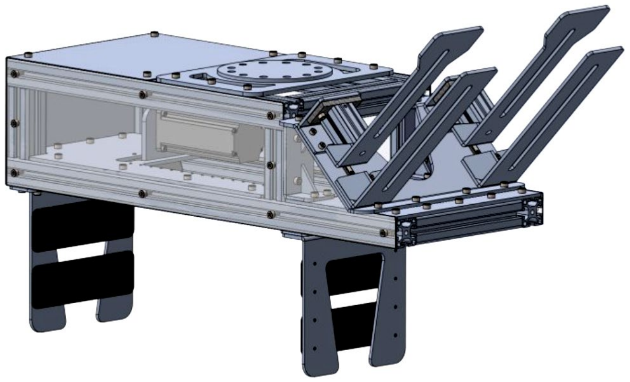

Figure 5. End-effector

It can be seen from the analysis of the previous figure that the box handling system consists of a movable *gripper* that will adapt to the different dimensions of the cardboard boxes. This handling and securing of the DIN cardboard boxes, adjusted to the dimensions of the boxes, is carried out by a servomotor that drives a trapezoidal power screw [37], which, through the self-locking system, ensures that the boxes remain secure during handling. Meanwhile, the handling of pallets, which is carried out according to their width or length, is achieved by mechanical clamping with the aid of two pneumatic cylinders set at a 45° angle. This arrangement allows pallets to be picked up in any position and prevents collisions with other equipment, provided there is sufficient working space.

4.2. Dynamic analysis of the system

In any project, studies of its dimensional parameters are essential. In this case, in addition to ensuring the proper operation of the palletizing system (end-effector), these parameters are directly related to the masses to be handled, as well as the forces to be applied and the speeds required for securing the load. This section presents the study analyzing the forces required to perform the palletizing operation.

4.2.1. Gripper clamping system

Currently, there are cardboard boxes on the market in a variety of sizes and with different load capacities. Handling standardized boxes requires that the *gripper* be sized to fit the standard box dimensions (200 to 600 mm). These dimensions therefore define the limits to which the *gripper* is constrained; that is, a width of 600 mm or less for larger boxes, and for smaller boxes, it is necessary to ensure that one of the sides is at least 200 mm wide.

When the *gripper* grasps the boxes, care must be taken to ensure that the force applied is not excessive, to prevent the boxes from being crushed. Assessing the compressive strength of cardboard boxes using the Box Compression Test (BCT), in accordance with ASTM D642 and ISO 12048 [35], is essential to ensure their integrity during transport and handling. On the other hand, given the versatility of the *gripper* that was developed, it is important to note that, during palletizing, the dimensions of the *gripper's* mounting system must be considered, as one might expect, these dimensions make it impossible to place the boxes right up against one another. However, the space between each box will be minimal and will disappear as soon as the boxes are secured to the pallet using straps or another method that ensures safety during transport. Given the limitations imposed by the palletizing system, it was determined that the maximum mass to be handled would be 30 kg when moved vertically relative to the robot arm. On the other hand, although this is not excessive mass, it is necessary to consider that the friction between the metal parts and the cardboard boxes is low, therefore, it is essential to coat the parts with a rubber film (rubber/cardboard friction ranging from 0.5 to 0.8).

Power screw

As mentioned earlier, the cardboard boxes are handled by a servomotor which, in conjunction with a trapezoidal-threaded lead screw, moves the end-effector's *grippers* horizontally, causing them to move in a linear fashion during closing or opening. Therefore, to achieve the linear motion required for the *gripper* to open and close, it is necessary to use a linear guide system consisting of profiled rails and guide carriages.

Thus, in addition to the smooth operation ensured by the trapezoidal spindle, the spindle must also be self-locking. This feature ensures that, during the movements performed by the robotic system, the hub cannot move backward, that is, the box cannot come loose and consequently fall off. To achieve this, it is necessary to ensure that the coefficient of friction resulting from the interaction between the spindle and the hub is sufficient to ensure that the spindle locks in place on its own. Table 1 presents the data regarding the spindle.

Table 1. Spindle Characteristics

Description	Symbol	Value	Units
External diameter	d (D)	14	mm
Inner diameter	d_r $(D2)$	10	mm
Average diameter	d_m $(D1)$	12	mm
Step	p (P)	4	mm
Coefficient of friction [2]	μ	0.19	-
Advance	l	4	mm
Fillet angle	2α	30	°
Propeller pitch angle	λ	6	°

The necessary condition for a trapezoidal-threaded power screw to exhibit self-locking is given in Eq. (1). As can be seen from the values presented in Table 1, the self-locking condition for the power screw with the specified characteristics and dimensions is thus satisfied, where $\tan\lambda \cos\alpha = 0.11$ is equals to 0.11.

[2] Value obtained from reference [37]

$$\mu > \tan \lambda \cos \alpha \quad (1)$$

Figure 6 shows a close-up of the spindle, the hub, the servomotor, claws and the maximum opening of the grippers.

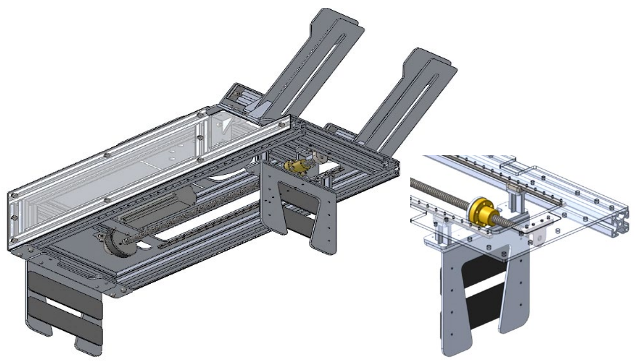

Figure 6. End-effector, bottom view

On the other hand, in addition to the force the clamps must be exerted during securing, the drag to which the boxes may be subjected was also considered, since they may be dragged along the conveyor. To supplement the above, it should be noted that the system was designed with one fixed part and one moving part (Figure 6), coordinated with the translational motion provided by the lead screw. Under these conditions, the coefficient of friction should be based on the most unfavorable case, which is when the friction between the box and the conveyor belt is highest. Figure 7 shows a schematic representation of the cardboard box being picked up by the conveyor belt, as well as the Free-Body Diagram (FBD) of the piking processes.

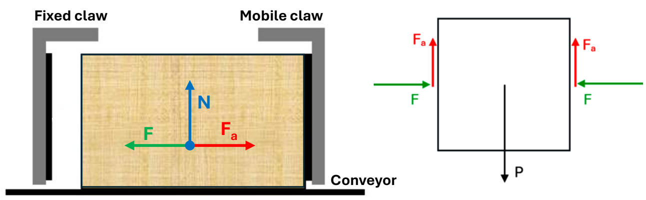

Figure 7. Pick cardboard box on conveyor and FBD

Considering the DCL in Figure 7 (right-hand figure), the force that the gripper's moving part would need to exert on the box was calculated using Eq. (2) to bring it into contact with the fixed part and, consequently, to clamp it and move it.

$$F = F_a \Leftrightarrow F = \mu N \quad (2)$$

The calculation of the clamping force to be applied to the spindle to overcome the friction in the spindle threads and the external force F, which has a value of 235.44 N is obtained using Eq. (3). This equation allows the maximum clamping force to be calculated so that the friction is overcome and the box can be held against the fixed clamp.

$$F_s = \frac{l + \pi \mu d_m \sec \alpha}{\pi d_m - \mu l \sec \alpha} F \quad (3)$$

For its part, the torque applied to the spindle (M_S) to overcome the external load and the friction in the threads is calculated using Eq. (4).

$$M_s = \frac{l + \pi \mu d_m \sec \alpha}{\pi d_m - \mu l \sec \alpha} \times \frac{F d_m}{2} \quad (4)$$

It should be noted that, in calculating these two values, equations (2) and (3), which were used to calculate the force and torque applied to the spindle, were adapted for horizontal motion, since the original equations pertain to load-lifting motions using trapezoidal-threaded power screws [38], in other words, the parallelism between the tightening of the cardboard boxes and the upward movement was ensured.

To validate these choices, the von Mises criterion was used, which made it possible to calculate the stress state at a generic point by using the stress tensor to transform the triaxial stress state at a critical point on the spindle into an equivalent uniaxial stress state. Thus, we can conclude that the shear stress occurs in the outer radii of the spindle cylinder, which correspond to the roots of the threads, acting in a direction normal to the plane perpendicular to the "y" axis and in the direction of the "z" axis [37], Eq. (5).

$$\tau_{yz} = \frac{16 M_s}{\pi d_r^2} \quad (5)$$

The torsional moment also induces a shear stress at the root of the threads caused by a tangential force. This tangential force gives rise to pure shear in the thread section of the spindle, which is calculated using Eq. (6). This shear stress acts in the direction normal to the plane perpendicular to the "x" axis and is exerted in the direction of the "z" axis [37].

$$\tau_{yz} = \frac{4 M_s}{\pi d_r^2 \, n_{fil} \, p} \quad (6)$$

where n_{fil} is the number of spindle fillets. The equivalent von Mises stress (σ_{vM}) can be calculated based on the stresses applied to the spindle. In this regard, the calculation of the spindle speed is related to the time required for the hub to travel along the spindle, which is directly associated with the dimensions of the boxes to be handled. For this purpose, a stroke length of 520 mm, determined during the project's development, and a maximum stroke time of 3 s were assumed. The maximum spindle rotation speed was calculated at 2 600 rpm, which was a critical value for selecting the linear guides. Figure 8 shows the power spindle used and its corresponding hub.

Figure 8. Power screw, with spindle and hub [39]

Servomotor

Servomotor is responsible for providing the torque needed to move the clamp while securing the boxes. Then, the torque provided must be calculated based on the specifications defined for the power screw. Furthermore, considering that the servomotor will have to operate in an intermittent mode, with constant stops and rapid starts, the rated torque and peak torque should be 1.27 Nm and 3.81 Nm, respectively, since they are the most relevant characteristics for its design. Furthermore, it should be noted that the peak torque must exceed the required value to ensure that the servomotor does not constantly operate at its limit, thereby increasing its durability while maintaining its efficiency. Similarly, the rated torque, a characteristic related to the torque value that the servomotor continuously produces at rated speed and power, must also exceed the value calculated for the system's operation.

V-belt

Belts are used to connect two or more pulleys that together form a flexible mechanical drive system capable of transmitting motion from the drive shaft. For this reason, and to select the appropriate belt profile, it is necessary to calculate the design power and the total load factor ($C2$). On the other hand, given that the robotic palletizing system operates throughout the day and is driven by a servo motor, the basic load coefficient ($C0$) will be set to 1.7 [40] Consequently, the choice of timing belt profile fell on a "3M" profile "OMEGA HP" timing belt from Optibel [40]. Notwithstanding all of this, the concept and function of the 1:2 speed ratio for the belt dimensions were determined according to the formula presented in [38], that is, with 100 teeth, a center-to-center distance of 69.37 mm, and a standard width of 15 mm.

Linear rails

To achieve linear translational motion of the end-effector's grippers during the closing or opening of the gripper, it was necessary to use a guidance system consisting of a linear guide system, comprising a profiled rail and guide carriages. The movable gripper is attached to a flange that has two sets of connecting parts: one set is secured to the drive screw hub, and the other two are secured to the carriages mounted on the profiled rails, ensuring that the translational movement is guided throughout its entire stroke (Figure 9). Therefore, considering the minimum clamping dimension of 200 mm and a maximum clamping dimension of 600 mm, as well as a maximum translational speed of the spindle of 0.173 m/s and the need to optimize the work area, the choice fell on the Norelem 21425-0907X0495 model, which ensures a maximum travel speed of 3 m/s [41].

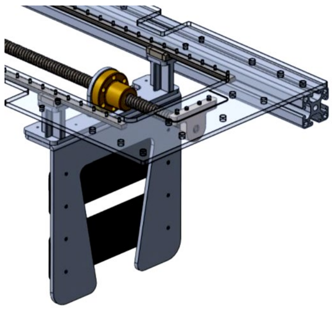

Figure 9. Linear guides and movable clamp

Pallet handling

Euro pallets are pallets with standardized dimensions, so there was no need to develop a mechanism that had to adapt to different sizes. Although different, the pallet clamping system and the box clamping system share some common components, such as the profiled rails and guide carriages, which perform the same function of guiding the translational movement of the components during clamping and release. Building on these similarities, the system was also designed to include a fixed part on the clamping plate and another part that is clamped to the guide carriage and the pneumatic cylinder rod, the assembly of these components is shown in Figure 10. From the previous figure, it is clear that the fixed part and the moving part that will clamp the pallet have different configurations. These configuration differences, specifically, the wider tip, were designed to increase the contact area with the pallet's surface.

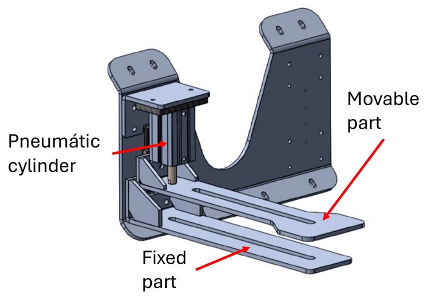

Figure 10. Pallet clamping system

The system was developed to enable the clamping and movement of pallets in two different positions, as shown in Figure 11. The system was developed to allow pallets to be clamped and moved into two different positions: the pallet can be clamped along its length (Figure 11a), or it can be clamped across its width (Figure 11b). This feature allows pallets to be picked up regardless of their position. In addition, the pallet clamping mechanism is mounted on the outer structure of the end-effector (see Figure 5), which allows the robotic cell to handle the pallets without requiring them to be in a horizontal position.

Figure 11. Pallet clamping: (a) by length; (b) by width [42]

An analysis of Figure 11b clearly shows the need to use a "spoon-shaped" claw tip. This configuration allows the europallet to be secured without the risk of the claws getting caught between the boards. However, for the purposes of sizing the components, a mass of 25 kg was assumed for each pallet. It was also assumed that there are no variations in the thickness of the wooden boards of the europallet, and therefore their masses remain constant.

5. Structural analysis of the end-effector

The purpose of structural analysis using the Finite Element Method (FEM) is to study the behavior of materials, specifically to determine the stress and strain states of a solid subjected to external forces. The use of FEM makes it possible to analyze and modify a structure or mechanism based on the results obtained, that is, to optimize the components and achieve a balance between materials and manufacturing costs [43]. Thus, based on a static analysis of the structure, the behavior of the various components of the end-effector under constant forces was determined.

However, although a finer mesh allows for results that are closer to reality, even if at the cost of increased computational capacity and processing time, it was necessary to conduct a mesh convergence study, starting with a coarser mesh using larger elements. This approach allows us to find the balance that leads to mesh convergence to obtain the applied von Mises stress and displacement, Figure 12.

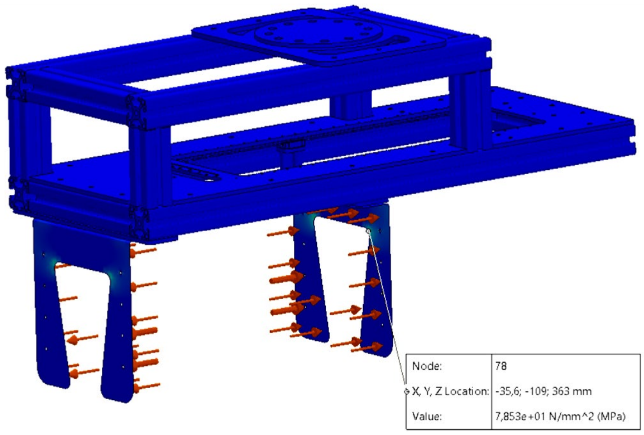

Figure 12. Mesh convergence study point

Based on the various analyses performed on the mesh, it was determined that a percentage deviation of less than 3% between successive iterations would result in the selected mesh. Equation (7) was used to calculate the percentage deviation

$$Deviation\ (\%) = \frac{|Iteration_n - Iteration_{m-1}|}{Iteration_{m-1}} \quad (7)$$

Some of the values obtained from the iterations are shown in Table 2.

Table 2. Values from mesh convergence study.

Iteration	Number of elements	Stress (MPa)	Displacement	Deviation
1	454432	79,73	0,44	-
2	581132	76,66	0,38	3,85
3	589957	80,81	0,39	5,41
4	694369	78,61	0,35	2,72
5	796769	78,53	0,40	0,10

The graph shown in Figure 13 illustrates how stress and displacement values at the selected point converge as the mesh is refined. The final appearance of the resulting mesh is shown in Figure 13, depicting the clamping of the box with the highest mass, which was defined at the beginning of this project, as well as the simulation of the mechanism responsible for clamping the pallet.

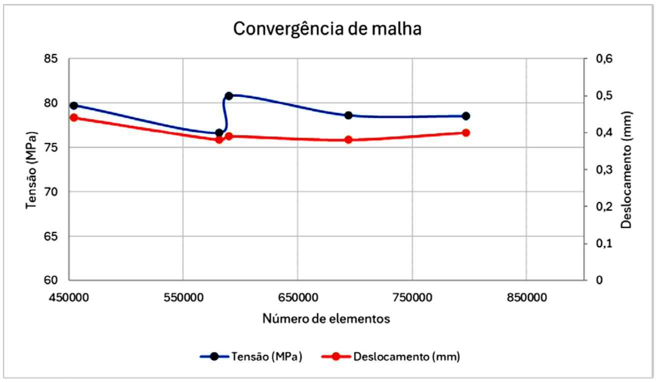

Figure 13. Mesh convergence

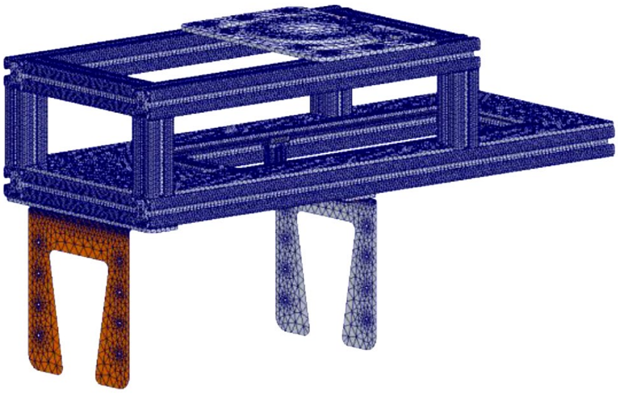

Figure 14. Mesh after convergence

When performing the simulation of the cardboard box compression, we choose to exclude structural elements that do not have a direct influence on the study. This approach ensures that the results are reliable without increasing computational requirements; in other words, only the components that account for most of the structure's resistance are included—such as the outer structure, the flange connecting to the robotic arm, and the parts associated with the clamping mechanism, ranging from the profiled rails to the gripper's "fingers." (see Figure 14).

The previously defined clamping forces, F=294.30 N, acting over a clamping width of 400 mm and applied internally to the end-effector fingers, were considered as boundary conditions. Note that all forces are transmitted to the connecting flange between the end-effector and the robot arm; it is also evident that there is a high stress concentration in the profiled rails and at the connection of the guide carriages. As can be seen in Figure 15, when the housing is tightened, the area of the profiled rails where the guided carriages are located exhibits higher stress values. On the other hand, regarding the area of greatest stress in the "fingers" of the gripper, the stress values are also considered to be high; however, as with the profiled rails, the stress value was found to be below the material's reference yield strength.

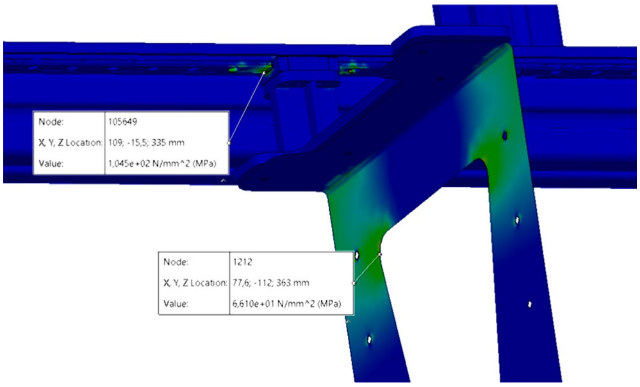

Figure 15. Stress points, gripper rail and fingers

About pallet handling, the procedure was the same. The less relevant components were excluded without compromising the accuracy of the results. Thus, the highest stress values were found in the area to the left of the parts that will secure the pallet. The highest stresses were found in the area where the moving part is connected to the pneumatic cylinder rod, see Figure 16. This stress concentration was to be expected, since this is the most critical area for the cylinder's forward movement, that is, the immobilized area of the pallet.

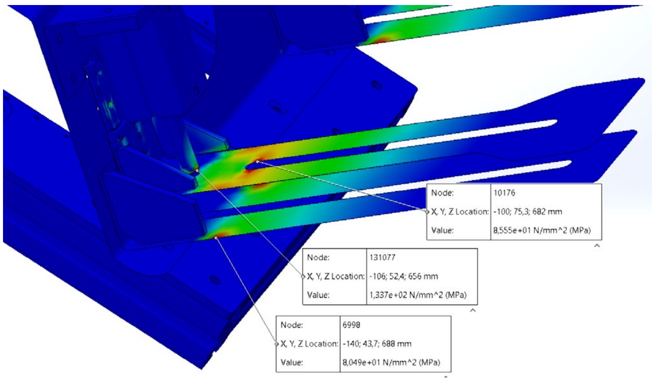

Figure 16. Stress points, pallet clamping

However, the application of vertical external forces to the gripper's fingers in a downward direction becomes largely irrelevant, since the points of greatest stress are in the inner areas of the mounting plate (Figure 17), indicated by the green color.

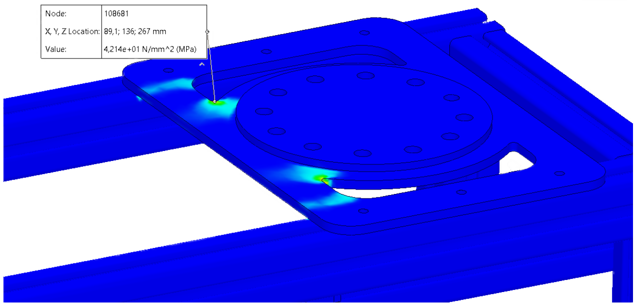

Figure 17. Stress points on the flange

5.1. End-effector assembly

The final assembly consists of a structure made of aluminum profiles that serves as the base for mounting all components and protective elements. The housing is secured by two parts, one fixed and one movable, both attached to the shaft. A pulley system, combined with a toothed belt, converts the rotary motion of the servomotor into linear motion, allowing the movable clamp to advance. This stroke is limited to a range between 200 mm and 600 mm, compatible with a standard DIN cardboard box.

Securing the pallets did not require any adjustments for different dimensions, since europallets follow standardized specifications thus, both the width and length remain constant. Based on this principle, it was necessary to design the moving part with a wider end, thereby increasing the contact area with the pallet surface. This geometry allows the system to adapt to movement depending on the pallet's width or length (see Figure 11). This solution allows pallets to be fed even when they are not completely horizontal.

The end effector is attached to the robot via a flange, ensuring precise integration between the developed mechanism and the selected robot, the ABB IRB 5710-90/2.7 [44]. The choice of this model considered the total mass of the components associated with the end effector, as well as the maximum expected load for the boxes, Figure 18.

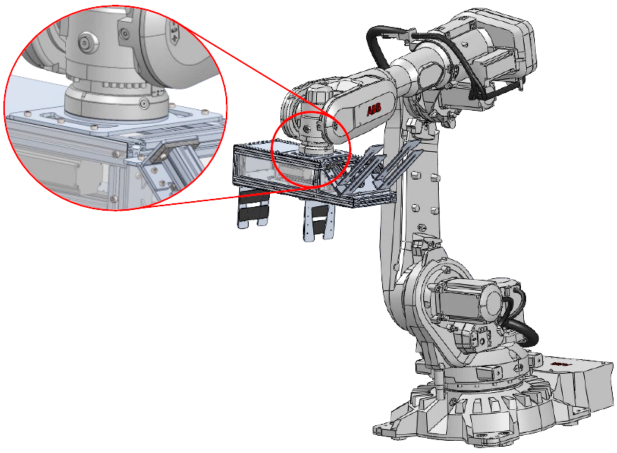

Figure 18. End-effector on the robot

Figure 19 shows a possible implementation of the end-effector in an operational environment. The robotic cell is supplied with europallets from a warehouse—stacked vertically or horizontally—and with cardboard boxes via a conveyor belt. The robot performs the task of picking up and placing the europallets and cardboard boxes, positioning each box on the europallet next to it. After completing the palletizing process, the robot removes the full europallet and places a new one in the work area, ensuring the continuity of the process.

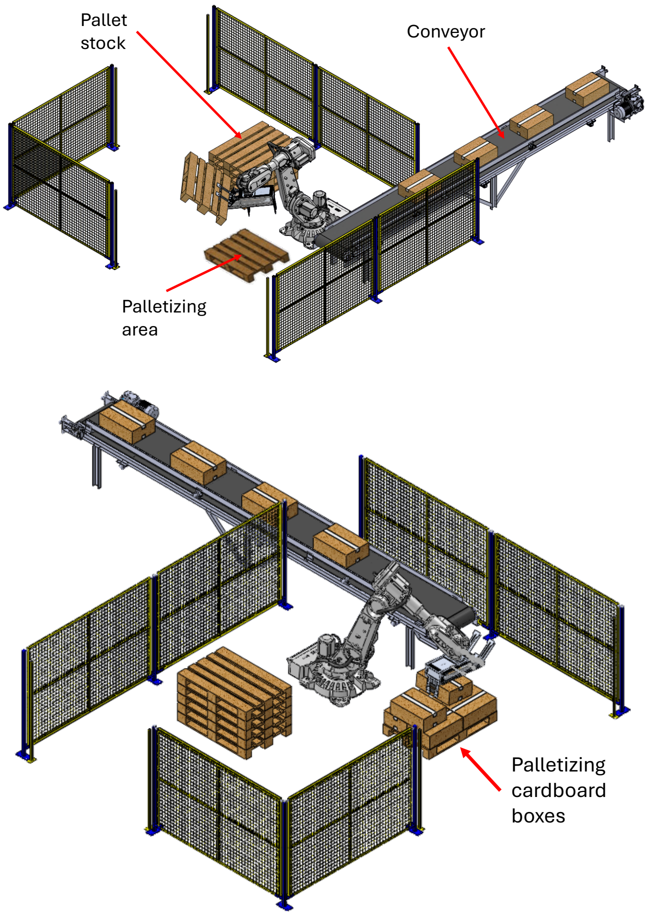

Figure 19. Use of the end-effector in the robotic cell

6. Conclusion

Robotic systems, especially those used for palletizing, have significantly increased productivity and improved the work environment from a social perspective. The introduction of these systems for low-value-added tasks has freed operators to perform more important duties. Today, they are widely used across a wide range of industrial sectors, contributing significantly to improvements in the quality and volume of work performed.

This study highlights the versatility of robotic systems and, above all, the operational capabilities of end-effectors and the wide range of functions they can perform. We present an end-effector capable of combining the handling of DIN cardboard boxes and europallets in a single robotic tool, capable of handling boxes ranging in size from 200 mm to 600 mm. The system requires only a stock of pallets in the work area and a continuous supply of boxes to operate. Thus, the integration of these two gripping mechanisms into a single component represents yet another significant advancement compared to the solutions currently available on the market.

The developed structure can transport large boxes, up to 600 mm in size, allowing them to be handled both longitudinally and transversely. However, the system is limited to handling parallelepiped objects, which partially restricts its scope of application.

As a future line of research, a range of easily interchangeable “finger” geometries could be designed, adaptable to the palletizing of other types of products. At the same time, integrating machine vision into the end-effector would constitute a significant advance, enabling the detection of the box’s orientation during palletizing [10] and eliminating the need to ensure a consistent orientation at the input, since the robot could automatically adjust its grip according to the identified orientation. Furthermore, a vision system would enable real-time recognition [45] of the dimensions of the objects to be palletized [46], allowing for the analysis of the best stacking strategy and the optimization of space utilization on the pallet.

Acknowledgements

The authors acknowledge Fundação para a Ciencia e a Tecnologia (FCT) for its financial support to LAETA via the project UID/50022/2025 (DOI: https://doi.org/10.54499/UID/50022/2025).

References

[1] C.B. Senthilkumar, S. Nallusamy. Enrichment of quality rate and output level in a medium scale manufacturing industry by implementation of appropriate quality tools. Mater. Today Proc. 2021; 37(2):817-822. https://doi.org/10.1016/j.matpr.2020.05.832.

[2] Elisabeth Lervåg Synnes, Torgeir Welo. Bridging the Gap between High and Low-volume Production through Enhancement of Integrative Capabilities. Procid. Manuf. 2016; 5:26-40. https://doi.org/10.1016/j.promfg.2016.08.006.

[3] Pop E, Campean E, Braga IC, Ispas D. New Product Development of a Robotic Soldering Cell Using Lean Manufacturing Methodology. Sust. 2022; 14(21):14057. https://doi.org/10.3390/su142114057.

[4] Alves F, Santos A, da Silva A, Pereira F, Felgueiras C, Silva P, Machado J. The adoption of industry 4.0 in the automotive industry: integration of collaborative robot systems in the injection moulding of deformable linear objects. J. Mach. Des. Aut. Intell. 2025; 3(1):20240004. https://doi.org/10.1515/jmdai-2024-0004.

[5] Dermawan, A., Wening, N., Vemberi, Y., & Fitriastuti, L. I. A Systematic Literature Review of Digital Skills and Human Resource Readiness for the Industrial Revolution Era 4.0 and 5.0. J. Mana. Kepem. Dan Super. Pend. (JMKSP). 2025; 10(1):245–259. https://doi.org/10.31851/jmksp.v10i1.17965.

[6] Almutairi, Y. M. N., Al-Saad, A. F., Elmelegy, R. I., Bakr, A. A. H., Abdallah, M. A. E., & Almotairi, K. M. N. Systematic literature review of fourth industrial revolution on higher education: Implications for higher education sustainability. Int. J. of Instruct. 2025; 18(2): 285-308. https://doi.org/10.29333/iji.2025.18216a.

[7] Shenkoya T, Kim E. Sustainability in Higher Education: Digital Transformation of the Fourth Industrial Revolution and Its Impact on Open Knowledge. Sust. 2023; 15(3):2473. https://doi.org/10.3390/su15032473.

[8] J. N. Pires. Robótica Industrial-Indústria 4.0. Lisboa, Lidel: 2018.

[9] M. A. Kamarul Bahrin, M. F. Othman, N. H. Nor Azli, e M. F. Talib. Industry 4.0: A Review on Industrial Automation and Robotic. Jurnal Teknologi. (Sc. & Eng.) 2016; 78(6-13): 285-308. https://doi.org/10.11113/jt.v78.9285.

[10] Santos, A.A., Schreurs, C., da Silva, A.F. *et al.* Integration of Artificial Vision and Image Processing into a Pick and Place Collaborative Robotic System. J Intell Robot Syst. 2024; 110(159). https://doi.org/10.1007/s10846-024-02195-z.

[11] S. Kuhlenschmidt, S. Weaver, e S. Morgan. 2: A Conceptual Framework for the Center. To Improve the Academy. 2010; 28(25-36). https://doi.org/10.1002/j.2334-4822.2010.tb00594.x.

[12] Maja J. Matarić. Introdução à Robótica. São Paulo, Brasil Blucher: 2014.

[13] Chukwuka Christian Ohueri, Md. Asrul Nasid Masrom, Masa Noguchi. Human-robot collaboration for building deconstruction in the context of construction 5.0. Aut. in Const. 2024; 167:105723. https://doi.org/10.1016/j.autcon.2024.105723.

[14] A. A. Santos, F. Pereira, e C. Felgueiras: Optimization and improving of the production capacity of a flexible tyre painting cell. Int J Adv Manuf Technol. 2025; 136(9):39573969. https://doi.org/10.1007/s00170-024-13208-4.

[15] A. A. Santos, F. Pereira, A. Monteiro, e J. Machado. Modelling and Simulation of a Pick&Place System using Modelica Modelling Language and an Inverse Kinematics Approach. Int. J. of Mech. and App Mech. 2024; 16:7-17. dx.doi.org/10.17683/ijomam/issue16.1.

[16] Universal Robotics. Tipos de Robôs Industriais, https://www.universal-robots.com, accessed 2025/02/18.

[17] A3Robotics. Collaborative Robots, https://www.automate.org/a3-content/what-are-collaborative-robots, accessed 2025/02/18.

[18] Müller F, Koch M, Hasse A. User Study to Validate the Performance of an Offline Robot Programming Method That Enables Robot-Independent Kinesthetic Instruction through the Use of Augmented Reality and Motion Capturing. Robotics. 2024; 13(3):35. https://doi.org/10.3390/robotics13030035.

[19] Bilancia P, Schmidt J, Raffaeli R, Peruzzini M, Pellicciari M. An Overview of Industrial Robots Control and Programming Approaches. App. Sci. 2023; 13(4):2582. https://doi.org/10.3390/app13042582.

[20] Santos, A.A., Haladus, J., Pereira, F., Felgueiras, C., Fazenda, R. Simulation Case Study for Improving Painting Tires Process Using the Fanuc Roboguide Software. In: Silva, F.J.G., Pereira, A.B., Campilho,

R.D.S.G. (eds) Flexible Automation and Intelligent Manufacturing: Establishing Bridges for More Sustainable Manufacturing Systems. FAIM 2023. Lecture Notes in Mechanical Engineering, Springer, Cham. 2024; pp. 517–524. https://doi.org/10.1007/978-3-031-38241-3_58.

[21] Lambrecht, J.; Chemnitz, M.; Kruger, J. Control Layer for Multi-Vendor Industrial Robot Interaction Providing Integration of Supervisory Process Control and Multifunctional Control Units. In Proceedings of the 2011 IEEE Conference on Technologies for Practical Robot Applications (TePRA), Woburn, MA, USA, 2011; pp. 115–120. https://doi.org/10.1109/TEPRA.2011.5753492.

[22] Rodrigues, M., Loureiro, I., Leão, C.P., Costa, N. How Ergonomics Is Contributing to Overall Equipment Effectiveness: A Case Study. In: Arezes, P. (eds) Advances in Safety Management and Human Factors. AHFE 2019. Advances in Intelligent Systems and Computing. Washington D.C., USA, 969:24-32. Springer, Cham, 2020. https://doi.org/10.1007/978-3-030-20497-6_3.

[23] PT Systems and Automation, Paletização Robótica e Convencional, https://www.ptchronos.com/pt/blog/paletizadorarobotica-versus-uma-paletizadora-convencional, last accessed 2025/02/23.

[24] Colombathanthri, A., Jomaa, W. & Chinniah, Y.A. Human-centered cyber-physical systems in manufacturing industry: a systematic search and review. Int J Adv Manuf Technol. 2025 136:2107–2141. https://doi.org/10.1007/s00170-024-14959-w.

[25] ABB Robotics Product specification Palletizing PowerPac, https://library.e.abb.com/public/7f2cedf1c65f8f16c125795f004435e5/3HAC041431-001_en_rev-.pdf, last accessed 2025/02/23.

[26] Monteiro A, Pereira F, Santos A, Machado J, Oliveira M (2024) Modelling and simulation of a pick & place system using Modelica modelling language and an inverse kinematics. Int J. Mech Appl Mech 16:7–17. https://doi.org/10.17683/ijomam/issue16.1.

[27] F. M. Moura and M. F. Silva. Application for automatic programming of palletizing robots, IEEE, 2018 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC). Torres Vedras, Portugal: 2018, p. 48-53. https://doi.org/10.1109/ICARSC.2018.8374159.

[28] Lee J-D, Chang C-H, Cheng E-S, Kuo C-C, Hsieh C-Y. Intelligent Robotic Palletizer System. Appl. Sc. 2021; 11(24):12159. https://doi.org/10.3390/app112412159.

[29] YASKAWA, Pallet Builder, https://www.motoman.com/en-us/products/programming/smart-pendant/pallet-builder, last accessed 2025/02/23.

[30] KUKA, KUKA.FlexPal, https://www.kuka.com/en-ch/products/robotics-systems/software/application-software/kuka_flexpal-palletizing-software, last accessed 2025/02/23.

[31] Universal Robots, Larning Path Palletizing, https://academy.universal-robots.com/learning-paths/palletizing/, last accessed 2025/02/23.

[32] Packer3D, Packer3D, http://www.packer3d.com/, last accessed 2025/02/04.

[33] Koona, Quick Pallet Maker, http://www.koona.com/qpm/, last accessed 2025/02/04.

[34] RoboDK, Palletizing, https://robodk.com/doc/en/Palletizing.html, last accessed 2025/02/04.

[35] Metropack, ECT (Edge Crush Test) and BCT (Box Compression Test) of a corrugated box, https://www.metropack.eu/definition/materials/corrugated-cardboard/ect-edgecrush-test-and-bct-box-compression-test-corrugated-box, last accessed 2025/03/05.

[36] Wieruszewski, M., Wdowiak-Postulak, A., Brol, J., Krzosek, S., Trocinski, A., Gocál, J. Nowak, T.: Qualitative and Strength Analysis of Pine (Pinus Sylvestris L.) Wood Materials - Study of Pallet Elements. Drewno. Prace Naukowe, Doniesienia, Komunikaty = Wood. Research Papers, Reports, Announcements. https://doi.org/10.53502/wood-196536.

[37] P. Flores. Projeto e Seleção de Componentes Mecânicos, 1ª edn. Porto: Engebook (2023).

[38] F. Pereira, L. Magalhães, A. A. Santos, A. F. da Silva, K. Antosz, e J. Machado: Development of an Automated Wooden Handle Packaging System with Integrated Counting Technology, Machines. 2024; 12(2), 122. https://doi.org/10.3390/machines12020122.

[39] Norelem. Fusos. https://norelem.es/pt/Visão-geral-de-produtos/Sistemas-e-componentes-para-aconstrução-de-máquinas-e-equipamentos/24000/Animação-sobre-a-aplicação-dofuso-de-esferas-recirculantes/Fusos-de-esferas-recirculantes-em-miniatura-retificadoscom-porca-flangeada, accessed on 15 June 2026.

[40] Optibelt, Technical Manual Rubber Timing Belt Drives, https://www.ignera.lt/image/catalog/product/OPTIBELT-TM-Rubber-Timing-Belt-Drives.pdf, last accessed 2026/07/19.

[41] Norelem, Guias de Trilhos Perfilados, https://norelem.es/pt/Visão-geral-de-produtos/Sistemas-e-componentes-para-aconstrução-de-máquinas-e-equipamentos/21000/Guias-de-trilhos-perfilados/c/21472, last accessed 2026/07/19.

[42] Santos, A.A., Teles, B., Silva, A.F., Felgueiras, C., Silva, P.J., Pereira, F. Development of a Multifunctional End-Effector for Handling Standardized Cardboard Boxes on Pallets. In: Machado, J., Trojanowska, J., Ottaviano, E., Xavior, M.A., Valášek, P., Basova, Y. (eds) Innovations in Mechanical Engineering IV. icieng 2025. Lecture Notes in Mechanical Engineering. Springer, Cham. 2025. https://doi.org/10.1007/978-3-031-93554-1_34.

[43] Á. Azevedo. Método Dos Elementos Finitos. Facul. Eng. Univ. do Porto. 2003. https://www.academia.edu/31530340/M%C3%89TODO_DOS_ELEMENTOS_FINITOS, last accessed 2026/08/21.

[44] ABB, IRB 5710 Large size robot for material handling, payload from 70kg to 110kg, https://search.abb.com/library/Download.aspx?DocumentID=9AKK108466A6229&LanguageCode=en&DocumentPartId=&Action=Launch, last accessed 2026/08/21.

[45] Terras, N., Pereira, F., Ramos Silva, A., Santos, A. A., Lopes, A. M., Silva, A. F. da, Cartal, L. A., Apostolescu, T. C., Badea, F., & Machado, J.: Integration of Deep Learning Vision Systems in Collaborative Robotics for Real-Time Applications. Appl. Sc.; 2025: 15(3), 1336. https://doi.org/10.3390/app15031336.

[46] Miguel Silveira, Adriano A. Santos, Filipe Pereira *et al*: 3D Vision Object Identification Using YOLOv8, International Journal of Mechatronics and Appl. Mech.; 2024, 17: 7-15. dx.doi.org/10.17683/ijomam/issue17.1.