https://doi.org/10.55343/CogSust.133

Design and Construction of a Handling Station to Interlace PCBs

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Abstract

This study discusses the design and construction of an automatic handling station to interlace two-part printed circuit boards (PCBs), with special attention to the methodology of constructing its handling nodes. The valuable result of this work is a presentation of the acquired cognitive experience with centric grippers and a new approach to gripping fingers. At the same time, the work describes an overview of the current state of the mechanisms of single-purpose machines. The task is to design a structure of a horizontal manipulator, a stopper for the PCB bed plates, a two-axis manipulator and a gripping head focusing on a sustainable production process. The concept of individual parts' arrangement, interactions, and resulting parameters have been developed following the stated requirements. The design meets all requirements in terms of simplicity of construction, adjustment, reliability of grasping, non-damage of the manipulated part, and sustainability of the whole manufacturing process.

Keywords
manipulator, engineering design, analysis, printed circuit board plate, requirements, cognitive experience, sustainable production

1. Introduction

New technologies constantly emerge, posing new requirements for production and development daily. For that reason, industrial manipulators have become an essential part of most production lines (Blatnický et al., 2020a; 2020b). A significant advantage of manipulators is their possible continuous operation and high accuracy, power, and speed, in contrast with significant physical limitations for humans. This way of operating companies allows manufacturers to reduce the production costs of their products, which significantly increases competitiveness. In the production of devices intended for work in the automatic production process, great emphasis is placed on the reliability and fault-freeness of the device (Blatnická et al., 2018; Blatnický et al., 2018a).

The presented research is focused on the design of the main structural units of an automatic handling station. This station will interlace two-piece printed circuit boards (PCB). PCBs are essential modules incorporated in a wide range of industrial equipment to control or signal manipulation applications. These boards are subjected to various loads, such as vibrations, shocks and static loads (Homza et al., 2024; Zhang et al., 2024). PCBs are applied to connect components to form a working

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circuit; thus, they play a crucial role in modern electronics. Integrating more components onto PCBs is becoming increasingly common, which presents significant challenges for quality control processes (Kahn et al., 2024). One of the main challenges in factories that use robotic manipulators for "pick and place" tasks is object orientation because the robotic manipulator can misread the object's orientation and thereby grasp it incorrectly. Object segmentation solves this problem (Glucina et al., 2023). The assembly of PCBs is one of the standard processes in chip production, directly contributing to the quality and performance of the chips. In the automated PCB assembly process, machine vision and coordinate localization methods are commonly employed to guide the positioning of assembly units (Peng et al., 2025). Regarding recycling, Naito et al. (2021) present the development of a system for recycling PCB boards through classification, recovery and management of electronic parts. The considered new technologies are applied in many engineering fields and are used to improve the processes in manufacturing and production (Szalai et al., 2023a; 2023b).

The design is based on the authors' long-term acquisition of knowledge and skills. All needed functionalities, demands and limits were understood and taken into consideration. At the same time, the engineering design also focuses on the requirements of a sustainable process of production and operation. The effectiveness of operation and sustainability of the design were among the most important factors considered during the design procedure.

Different types of drives are used in single-purpose machines. Manual, pneumatic, electric and hydraulic drives are known. Logically, their choice depends on the individual requirements of the machine. Table 1 summarizes drives' analyzed advantages and disadvantages for designing an automatic handling line (Chen et al., 2021; D'Souza Costa, Pires, 2020).

An analysis of its components is necessary to design a single-purpose machine successfully. These are mainly manipulators, conveyors, sensors, pneumatic cylinders and effectors. Manipulators in single-purpose machines are applied in any product manipulation (Blatnický et al., 2020c). Manipulators can be manual, electric, pneumatic or pneumatic. Electric manipulators use servomotors or stepper motors for manipulation. Their significant advantage is the achieved transmission speeds (Festo, 2024). Pneumatic manipulators are structurally simple because they use combinations of pneumatic cylinders, and their main advantage is the low purchase price (Venkatesan and Capelleri, 2017; Zhang et al., 2022).

Table 1 Advantages and disadvantages of individual drive types

Style name	Manual drive	Electric drive	Pneumatic drive	Hydraulic drive
Advantages	High reliability Simple design Low procurement costs Low failure rate	Precise positioning Good positioning speeds Simple assembly	High movement speed Simple construction Low price	High lifting and clamping forces High accuracy and reliability
Disadvantages	Low lifting and clamping forces Low positioning speeds Short-term operation	Cost	Poor positioning Low lifting and clamping forces Sensitivity to loss of pressure	Low movement speed Ecologically objectionable (possibility of leakage of working fluid)

Conveyors are used in single-purpose machines to transport products over longer distances. Widely used conveyors in single-purpose machines are belt conveyors, which stand out for their simple installation and regulation. In addition, less standard types of conveyors are also used. An example is a vibrating conveyor that is driven by a vibrating drive. Its disadvantages include that it is only available for horizontal transport and the demanding initial optimization for the moved material (Callegari et al., 2020; Ciubucciu et al., 2017; Han et al., 2022).

Sensors serve as feedback for the controlled element. They are used, e.g., for location, temperature, humidity and motion sensing. In machines, they are used on drives, where they sense individual positions, and for any operations where it is necessary to detect the presence of a part. Both touch and non-touch sensors are used in practice. Examples of sensors are inductive, ultrasonic, capacitive, optoelectronic and magnetic. The leading manufacturers are Balluff, Turck and SICK (Euchner.cz, 2024a; Euchner.cz, 2024b; Linear drives, 2024).

Compressed air as an energy carrier is considered the oldest form of increasing physical performance in pneumatic cylinders. In the past decades, pneumatic systems have come to the fore, mainly thanks to the automation of production processes. A pneumatic cylinder is a mechanical device used to convert the force of compressed air into mechanical motion. It is a system of energy transmission between two or more places in space. Usually, the system's pressure is 2 to 16 bar. At a pressure lower than 2 bar, it is impossible to ensure stable movement of the piston due to the frictional resistance of the

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piston in a cylinder. For pressures higher than 16 bar, using air as a medium for energy transfer is not economically advantageous compared to hydraulic cylinders (Linear drives, 2024).

An effector is a functional part of a manipulation unit. It allows the machine to grasp or otherwise work with manipulated objects. The effector is in direct contact with a manipulated object. A unique effector is proposed for each application. The design can be implemented directly by the manufacturer of the robot/single-purpose machine or the user of the manipulator. When designing the effector, it is crucial to consider that it can perform manipulative and technological tasks. The manipulation task mainly means executing operations to ensure the change of position and orientation of the manipulated object, secure its position, and clamp it. In the technological task, the effector performs welding and assembly operations (Blatnická et al., 2018).

Operational practice led to a request to design a handling station to interlace two-part PCB boards. The main requirement in the station's design and its gripper is that the gripping of the two-part board is stable, repeatable and does not damage the board. Automatic adaptability to dimensional inaccuracies in PCB board production was also required. The presented research aims to design suitable solutions for handling NX Siemens 12 program nodes that will meet all requirements.

2. Requirements for the proposed device

The proposed OPR30 station (Figure 1) is to be integrated into an automatic line whose task is the fully automatic assembly of a servo motor. In addition to manually loading parts and removing the finished product, the process is fully automatic. At the other stations, various activities are performed, such as bending electrical wires, applying the heat-conductive paste, dispaneling and loading the two-part PCB board onto the pallet, screwing the PCB board, pressing contacts, resistance welding, turning the electronics part onto the motor part, applying glue, loading and then pressing the cover Multiple cameras are also installed for controlling the process. All requirements for the proposed manipulator are listed in Table 2.

Table 2 Requirements for the proposed manipulator

No.	Feature Requirements	Importance	Explanation
1.	Speed of handling	Required	The clock of the device is up to 36 seconds
2.	Rounded/chamfered edges	Required	All edges of manufactured parts are rounded at least R2 – for sheets thinner than 2.5 mm, edging/edge protection is preferred.
3.	Surface treatment of sliding parts	Required	Nitriding or coating the surfaces of contact surfaces of moving parts
4.	Damping movements	Required	Ensuring damping of end positions during movements
5.	Use of commonly available springs	Required	Guaranteed availability of spare parts
6.	Maximum weight of the product	Required	It must not exceed 15 kg
7.	Easily replaceable preparation	Required	Replacement of the preparation without the use of tools
8.	Simple construction of the preparation	Optional	
9.	Pneumatic elements	Required	All pneumatic elements from Festo or Schunk
10.	Pneumatic cylinders	Required	The cylinders must contain end position sensors and damping
11.	ESD ionizers	Required	Air ionizers will be placed in the part of the equipment for loading and unloading components.
12.	PCB loading position sensing	Required	In the basic position of the horizontal manipulator, ensure the correctness of the loading of the PCB.
13.	Repeatability of PCB sampling	Required	The design of the effector prevents the risk of PCB slipping
14.	Preventing dirt build-up	Required	The frame construction is made up of closed profiles of the NVS type
15.	Spring-loaded fingers of the gripping head	Required	The fingers of the gripper placed in a linear guide are pressed by a compression spring.

As it emerged from the requirements, the supporting structure was designed from aluminium profiles closed from the outside by Bosch Rexroth (Bosch Rexroth, 2024). Lightweight profiles with dimensions of 90 × 90 mm, 45 × 90 mm and 45 × 45 mm were used. Since the entire device is placed on the support structure of the lower frame (Figure 1), the structure should have sufficient load-bearing capacity and rigidity.

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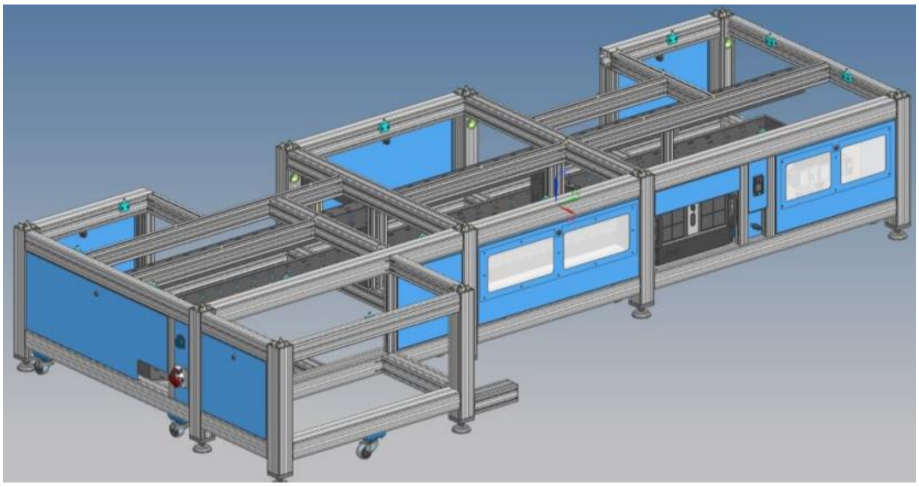

Figure 1. 3D CAD model of the lower frame of the proposed manipulator

The choice of profile geometry resulted from experience constructing similar devices with similar loads (Blatnický et al., 2018a; Blatnicky et al., 2018b). The used aluminium profiles are very advantageous in price and weight, while they have relatively high strength (Bosch Rexroth, 2024). A significant advantage is the grooves along the entire length of the profiles, on which any accessories can be placed with the help of special rotating nuts. Pin connectors connect the profiles themselves. In addition to the adjustable legs, the lower part has swivel wheels for transportation. The lower frame also includes a pneumatic component that controls the pneumatic part of the station. A sheet metal box for milled panels is also included in the lower part of the frame. See the red part in Figure 2a. The panels fall out of the dispaneling device near the station via a conveyor and fall through the base plate into the box by a gravity slide.

(a)

(b)

Figure 2. Scrap box placed on the linear guide (a) and 3D CAD model of the upper frame of the proposed manipulator (b)

The upper frame is fixed to the base plate of the station. There are three doors to access the OPR30 station, as shown in Figure 2b. All doors are blocked by an electronic security lock that prevents unauthorized entry into the station during operation. Safety locks on station doors are essential parts of every automatic station to ensure the safety of operating personnel. The inner part of the door is filled with 5 mm thick transparent antistatic polycarbonate. The upper part of the frame is covered with a 2 mm thick anodized aluminium sheet.

3. Structural design of a horizontal manipulator

The operation of relocating the PCB board from the dispanelisation device to the pallet proceeds as follows. After dispanelisation, the PCB board is inserted into the bed fixed by a linear pneumatic drive. With the help of this drive, the bed moves between three positions: PCB loading position, dirt extraction and PCB board unloading. The assembly of the horizontal manipulator in the PCB board unloading position is shown in Figure 3.

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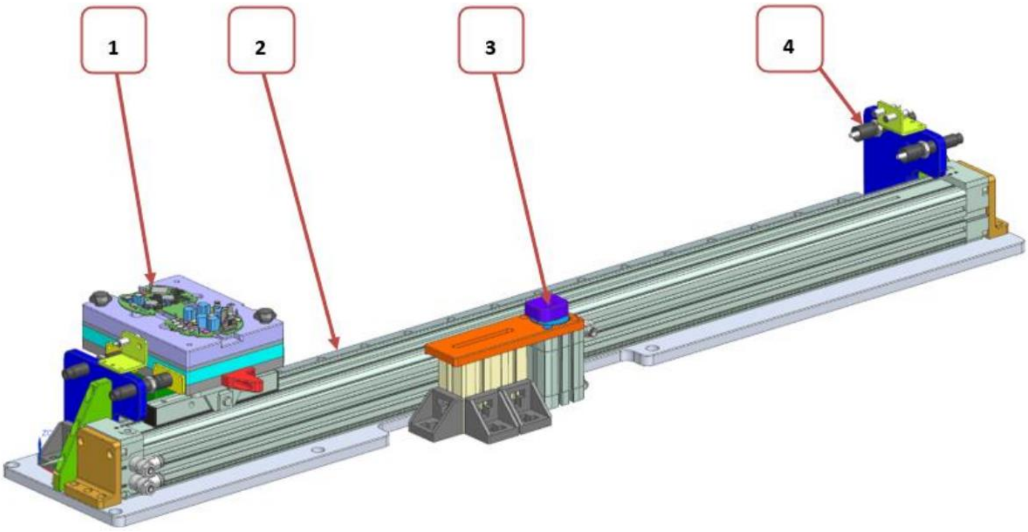

Figure 3 An assembly of the horizontal manipulator: 1 – a bed with the PCB board, 2 – a linear drive, 3 – a stopper, 4 – a damper

The role of the bed is to hold and centre the PCB board. It consists of a shaped bed that corresponds to the board's dimensions. The shaped bed is made of POM ESD material because it conducts an electric discharge. If an electric charge occurs during the folding of the PCB board, the bed will safely dissipate it. In this way, protection against electrostatic damage to sensitive electronics is ensured. This shaped bed contains two nitrided steel centring pins that ensure the repeatability of the part's placement. It also contains two centring bushings for centring the gripping head of the two-axis manipulator. The manufactured parts used to ensure the accuracy and repeatability of the interlacing are stored in precise holes of H7 tolerance and screwed with an M4 screw. This bed is screwed onto a duralumin plate with a thickness of 5 mm because the POM ESD material deforms over time. This bed is replaceable if part modifications occur or a new version is added. Figure 4 shows a picture of the bed and a pair of optical sensors.

Figure 4. A detail of the PCB board bed

The sensor located on the left side of the sensor holder is used to detect the presence of a piece. The sensor located on the right side is used to detect the correct loading of the piece. If the plate is loaded incorrectly, this sensor will send a signal to the station's control unit and prohibit the removal of the piece.

The research team has used the POM ESD material several times in previous designs. Therefore, the experiences with this material and its properties, such as excellent machinability, abrasion resistance and, in this particular case, the conduction of electric current, have predetermined it for its further direct application presented in the work. The entire plate serving as a bed for the product (PCB board) can be dismantled and, if necessary, replaced with another piece or a different material design.

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The replaceable fixture is placed on a duralumin plate with a thickness of 16 mm, on which a washer is screwed together with a rail carriage of size 25 BR from Bosch Rexroth. On the other hand, this bed is attached to the movable carrier of the pneumatic pistonless cylinder Festo DGC-K40-900-PPV-A-GK-FK. It has a lift of 900 mm, a low-moving dead weight and a symmetrical construction. The driver is equipped with a pin to compensate for alignment errors when using an external guide. The linear drive is fixed with the help of a pair of identical duralumin holders on a duralumin plate firmly mounted on the base plate of the station. Its position is secured by a pair of purchased pins with a diameter of 8 mm and a tolerance of H7.

In Figure 5, shown in yellow, stop plates serve for direct contact with the motion damper and the stop nut. They are made by cutting with a laser beam from material STN 12 050 with a thickness of 3 mm, and then they are nitrided. Each time the bed is moved, they transfer the impact force to the bed. Both the surface treatment and the choice of material were chosen to maximize the service life of the functional parts of the station. Also, the stop pin, depicted in Figure 5 and shown in red, is nitrided. Two screws are inserted in the upper part of the model, which allows the replacement of the fixture without the need for tools.

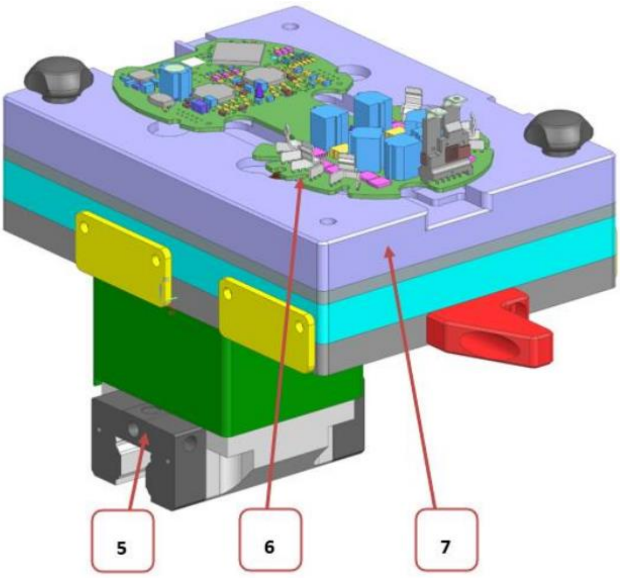

Figure 5. A horizontal manipulator bed: 5 – a carriage, 6 – a PCB board, 7 – a plate

Damping the end positions of the device was one of the essential requirements. A pair of ACE MC150MH dampers serve to dampen the kinetic energy of bed movements in extreme positions. On their outer thread, which also serves as a mounting element of the damper, a stop nut is screwed, which can be seen in Figure 6. Its task is to touch the stop plate.

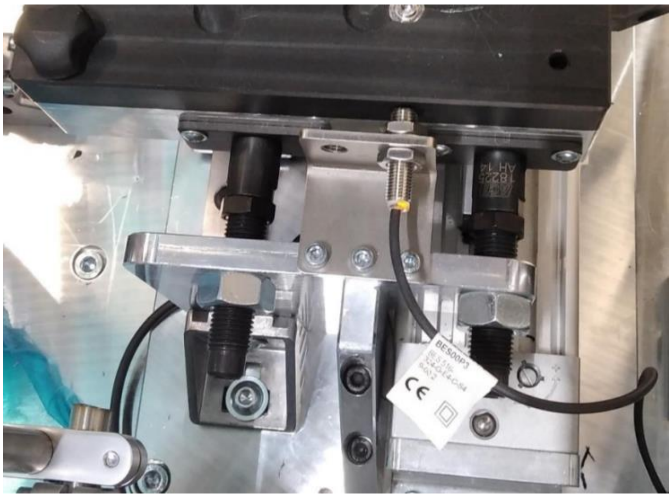

Figure 6. External damping with the end position stop

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The pneumatic drive has its end damping and stop, but for use in this application, its repeatability is insufficient, and therefore, it was necessary to make external damping with a stop. Fixing the threaded body of the shock damper in a duralumin plate allows the operator to set the end positions in the longitudinal direction. The damping path can be adjusted by tightening or loosening the stop nut. A Balluff BES00P3 inductive sensor with a range of 2 mm is placed on the upper part of a 10 mm thick duralumin plate. It is fixed with the help of a 3 mm thick sheet metal holder and AISI 304 material. The task of the induction sensor is to detect whether the bed has reached the end position and is in the secured position, which is ensured by the constantly pressurized chamber of the pistonless cylinder.

In general, its application must be justified if a high-speed manipulator is equipped with an external damping mechanism. If the reason is increasing the stabilization (or arresting) of the final position of the product, then there is a certain difference in the specifics of individual cases. In our specific case, the life of the integrated solution (consulted with Festo as the manufacturer of the specific implemented drive for the needs of a single-purpose machine, OPR 30, with the required frequency of work cycles) plays a decisive role. Therefore, integrating an external damping mechanism will ensure a longer and more reliable operation for the user of the proposed line.

Another component proposed here is the so-called stopper. The task of the stopper is to stop the moving bed. The Festo DFSP-Q40-15-DF-PA stop cylinder plays the main role in this assembly, as shown in Figure 7. It is a double-acting pneumatic cylinder in the design with a pin with an internal thread with protection against overturning.

Figure 7. A bed stopper in a basic position

This is a primarily custom-made version with a stroke of only 15 mm. Such a small lift was necessary due to the mounting dimensions of the entire assembly between the base plate of the station and the stop pin. Stop cylinders work like classic pneumatic cylinders but are designed to stress the piston rod in the radial direction. This means in the direction perpendicular to the direction of the cylinder's extension. Therefore, such cylinders have a reinforced and adapted piston rod to guide the cylinder in withstanding this type of stress. The stop cylinder is working (extended) when the bed returns to the dispaneling station. The bed hits the stopper and is acted upon by the force of the pistonless cylinder. This centre position is necessary to stop the bed to allow blowing and suction of debris from the bed after milling the PCB board from the panel.

On the piston rod of the cylinder, a shaped member is screwed, which has a recess in the lower part that copies the shape of the groove of the piston rod, with an M8 screw, which is in direct contact with the stop pin after the cylinder is extended. Since it was a requirement that the movements be damped even at this intermediate position, no damping occurred apart from guiding the stop cylinder piston rod; throttle valves were fitted to the pistonless cylinder. With the help of throttle valves, the filling speed of the air chamber in the cylinder can be continuously regulated. This way, we can achieve smooth truck operation at a low speed. At the manufacturing station, the practical bed speed was less than 0.3 m/s. The plate on which the piston is screwed has a groove in the longitudinal direction of the bed displacement. This enables fine-tuning of the stop point of the bed. To reduce production costs and simplify the device's design, the stopwatch assembly is designed to produce only three manufactured parts, as seen in Figure 8. These are the stop cylinder holder, the shaped member and the stop mandrel.

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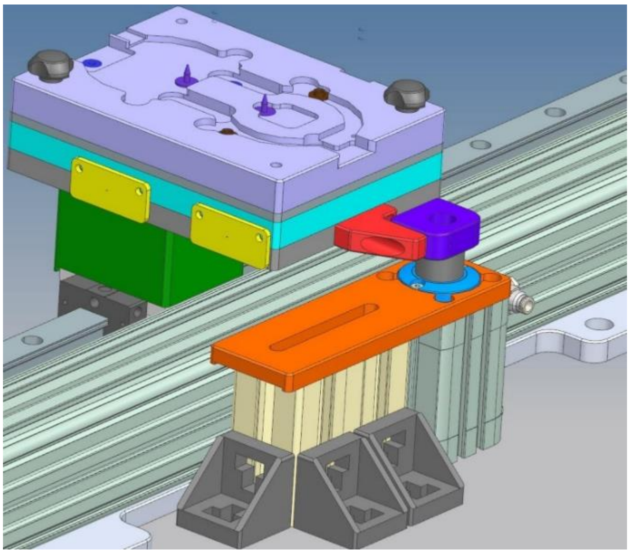

Figure 8. A stopper with a bed in a suction position

Cleaning the empty bed of the PCB board is an essential part of the handling process, as dust particles are created by milling the printed circuit board. The bed cover, i.e., the suction head, is shown in Figure 9.

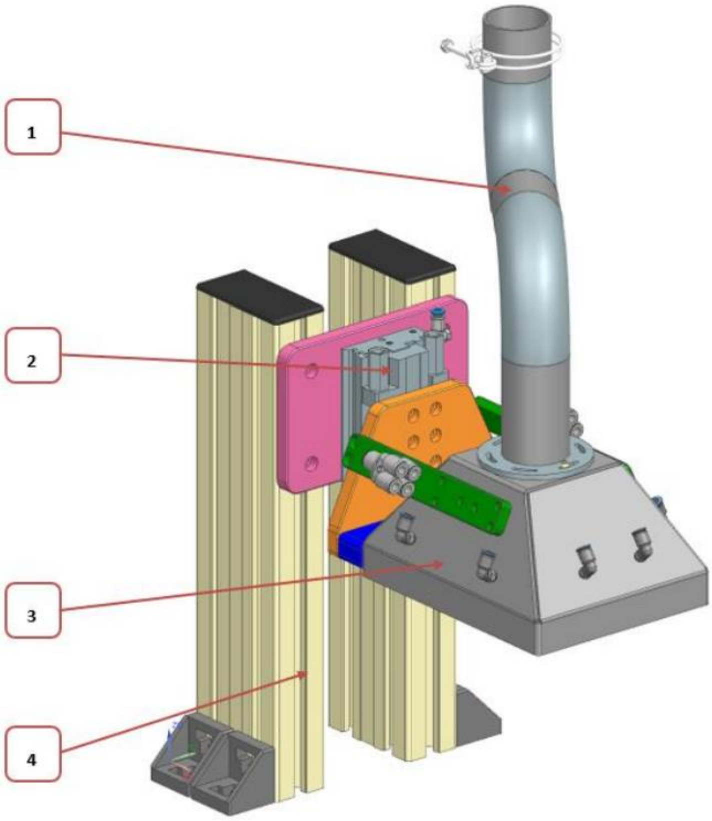

Figure 9. An extraction head with an integrated blower: 1 – an exhaust tube, 2 – a cylinder with guidance, 3 – a cover, 4 – a stand

The dirt extraction stand comprises two aluminium profiles measuring 45 × 90 mm. It is attached to the base plate with the help of 45 × 45 mm angles. The manufacturer designs the mounting holes in a very shape that allows fine-tuning of the position of the stand relative to the base plate in the two axes, X and Y. In the Z axis, the position adjustment is ensured by profile grooves. Fine-tuning of the Z-axis is possible using the integrated adjustment screws in the cylinder body. The stand is loaded for bending because the suction head is placed eccentrically on the assembly's base. For this reason, the orientation of the profiles was chosen, which is more advantageous for the bending load.

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The plate on which the pneumatic cylinder with the guide is located is mounted in the groove of the profile using four M6 screws. The cylinder is also fixed with three M6 screws. The cylinder contains precise recesses of H7 tolerance on its mounting part for centring rings. The mounting plates also contain such recesses with an accuracy of ±0.02mm relative to each other. The centring rings are used for the assembly to be repeatable. In the case of replacing the pneumatic cylinder, it must be placed on the original mounting holes, and the position of the nozzle relative to the stand will be identical. The centring rings are made of ordinary quality steel, and their surface is ground. They are stressed only in the radial direction. In the axial direction, there is always at least 0.1 mm clearance in the mounting plate to ensure maximum contact between the cylinder mounting plate and the holder. Centring rings are also produced in a thin-wall version, with a maximum of 0.2 mm wall thickness. Such undemanding space has a favourable effect on the dimensions of the pneumatic cylinder.

The suction head serves to cover the empty bed of the PCB board. It consists of a 3 mm thick AISI 304 sheet welded cover, which has pneumatic push-in couplings screwed into it, which act as nozzles. They bring clean, compressed air under the cover. The nozzles help swirl the air under the head to remove all debris from the bed. The nozzles are connected in series to compressed air with a pressure of 6 bar. Their connection, the suction head and the pneumatic mechanical valve, can be seen in Figure 10.

Figure 10. The top view of the suction head

Dirt is removed by a vacuum cleaner located outside the station. The transmission of the vacuum is ensured by an air hose VULCANO PUH 09 with an inner diameter of 51 mm, designed for vacuuming up to -0.5 bar. Between the suction head and the pneumatic hose is a welded pipe made of AISI 304 material. A sheet flange with grooves for six pieces of M4 screws is used for mounting this pipe. Their location and length allow smooth rotation of the exhaust pipe to set the most suitable position. The sheet thickness of 3 mm provides a sufficient length of the cut thread for the screws used. A pneumatically controlled valve is used to close the pipe at the end of the exhaust. The role of the valve is to close the pipe and increase the suction power at other suction points because one vacuum cleaner is intended for three suction points. The valve is controlled by a pneumatic double-acting cylinder DSNU-8-50-P-A. The entire production line is located in a clean zone; therefore, the extracted dust is removed outside the premises of this zone.

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The last assembly member addressed in this work is the gravity slide of milled panels (Figure 11). It is a simple passive assembly with the possibility of adjusting the position with the help of grooves in the X, Y and Z axes ±5mm.

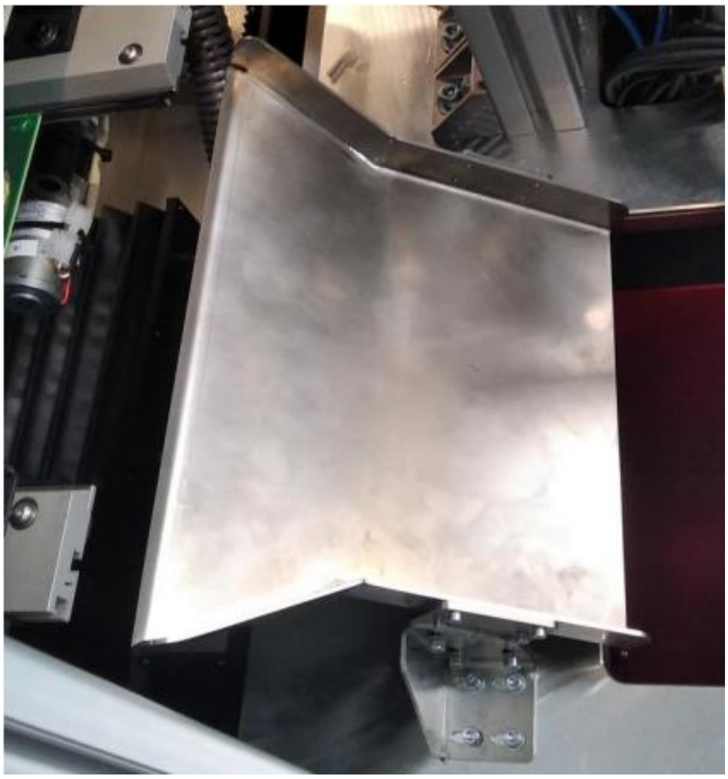

Figure 11. A sheet metal gravity chute

The sheet metal punch bent into a funnel primarily transports empty PCB board panels between the conveyor of the depanelization station and the scrap box. If the camera inspection of the depanelization device evaluates any of the PCB boards as NOK (not OK), it falls into the scrap box along with the panel by gravity.

The entire device is designed as a single-purpose machine for a specific product type. If the shape or dimensions of the PCB board are changed, the shape of the POM bed can also be changed very easily and quickly to the currently required geometry. When only the diameter of the (circular) part of the PCB board, which is gripped by a three-finger gripper (6 fingers in total because the board is two-part and connected only by a flex cable), will be changed, the current design could adapt to this. Changing the shape of the PCB board from a rotating part to a planar part could be considered a challenge. This requirement has not yet been encountered in applied research for practical use. However, this does not exclude the possibility of a solution being needed.

4. Conclusion

The paper aimed to describe the structural design and the development of handling nodes of a single-purpose machine, i.e., an automatic station called OPR30 used for handling two-part printed circuit boards utilized in electric vehicles of various categories by a real engineering company. The work briefly described and provided an overview of the current state of the mechanisms used to construct single-purpose machines. Tasks, i.e., the design of the horizontal manipulator and PCB bed stopwatch, can be considered fulfilled, as evidenced by the documentary images illustrating the arrangement of individual parts and their parameters. These results stem from adhering to the stated requirements. The design meets all requirements in terms of simplicity of construction, adjustment, and reliability of grasping, as well as non-damage of the manipulated part. In further research, the authors will focus on the structural design of the two-axis manipulator and the gripping head to complete the basis of the structural design of this device.

https://doi.org/10.55343/CogSust.133

Acknowledgement

This publication was supported by the Cultural and Educational Grant Agency of the Ministry of Education of the Slovak Republic in the project KEGA 031ŽU-4/2023: Development of key competencies of the graduate of the study program Vehicles and Engines.

"Funded by the EU NextGenerationEU through the Recovery and Resilience Plan for Slovakia under the project No. 09I03-03-V01-00131."

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