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ASSESSMENT ON FLEXIBLE FIXTURE SOLUTION AND A NOVEL PIN ARRAY SOLUTION FOR AN INDUSTRIAL APPLICATION

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Abstract

The demand for customisation in today's product assortment challenges the manufacturer to produce unique goods rapidly and economically. Whereas a robot arm performing welding/drilling can be programmed for multiple pieces/functions, the actual standard fixture holding the workpiece in place is not only inflexible, but also lacks the adaptability required to accommodate workpieces of different sizes and shapes. Furthermore, the industry demands a more cost-effective holding solution to secure the workpiece during machining, to reduce the typical 20% of the total system cost for dedicated fixtures. The problems lie in the necessity to lock all six Degrees of Freedom of an irregular and unknown shape, and to define a workpiece pose for automatic production. This paper describes the development and implementation of a flexible fixture that can adjust itself to any form and grasp any workpiece securely. The fixture consists of 112 pins embedded in a 100x200x80 mm base and prodding 60 mm from the top. In this fully automated system, a robot places the piece into the pin array, which closes itself automatically. Multiple revolving active pin arrays conform to the surface and clamp the part. a Pneumatically actuated pins combined with a brake enable the fixture to optimally adapt and support all pieces. The built-in revolting mechanism ensures an ideal connection between the pins and workpiece and provides the required holding force. Assessments of the prototype showed great potential for the method, but also demonstrated the need for high precision parts and fine control of the pins. The pin array presented great adaptability, and the rotating mechanism could significantly increase contact points. Therefore, a future project phase should build on and add to the valuable inside information gathered during this paper to refine the prototype.

Keywords: automated production; fixtures; manufacturing

1. Introduction

Due to changing consumer demand for more customisable and personalised goods, manufacturers adapted their portfolio to accommodate greater variety and shorter product life-cycle. Additionally, the rise in global competitors demands a lower unit cost, higher production quality and shorter lead times. Therefore, producers face the challenge of automating low-volume, high-mix production, which traditionally is expensive and inefficient [1,2]. One essential part, which still lacks an industrial-grade solution, is a flexible fixture of the workpiece.

Commonly used solutions are changing dedicated fixtures, which are specially made for each specific part, between production items. However, every dedicated solution can account for 10-20% of the total system cost due to the need for careful design and high work experience (Wang et al., 2002). Flexible fixtures would eliminate the effort of manufacturing multiple dedicated fixtures and enable the possibility of grasping any item, regardless of its form. This paper describes the development of such a flexible fixture relating to the Morobot [3] production at the Technikum Digital Factory at the UAS Technikum Wien. The aim is to compare different approaches to flexible fixtures currently in development in the science community and further develop the most promising method into a physical prototype. The main focus lies in the explore their uses and problems in an industrial environment. With the aid of the physical prototype, possible problems for a fully automated process should be explored and documented.

2. State of the Art

One essential but often overlooked part of any assembling, manufacturing, inspecting process is a fixture. The primary purpose of fixtures is to fixate, position and support the workpiece during manufacturing operations. Therefore, fixtures are essential to ensure high quality and low variability in parts and often reach 10-20% of the total system cost alone. Moreover, poor fixture design is the source of about 40% of the rejected part because of dimensioning errors [4]. Initially, fixtures were designed for one specific workpiece in mind, which are called dedicated fixtures. These can consequently only be used while producing this piece, which constricts the whole production process. On the other hand, dedicated fixtures also present some benefits, like high rigidity and low tolerances. Current development and production practices demand a new flexible approach to fixtures. Flexible fixtures aim to hold a wide range of workpieces, to adjust to the massive increase of CNC and robot-based manufacturing [1,5-8].

2.1. Purpose of Fixtures

As mentioned, the objectives of fixtures are to fixate, position and support a given workpiece. To achieve these objectives, three main functions must be fulfilled by fixtures, which are clarified in the following paragraphs [9]. In addition, a fixture can also provide various additional functionalities like fast loading and unloading of parts, constant disposal of chips and coolant, be durable and easy to operate by a machinist or automatic [5,8]

Locating: Locating in the context of fixtures describes the positioning of the workpiece inside a 3D workspace at a specific pose (position and orientation). This is necessary to machine part automatically, which depicts the majority of produced industrial goods. For such automatic processes, the parts must be placed at the exact same pose every time to ensure fast, reliable, and precise operations on a workpiece. Furthermore, the correct positioning of the part inside the machine directly influences the reject rate. For example, if a cut or drilling is off by a few millimetres, the part cannot be used in further assembly and must be discarded [5,8,9].

Holding: Holding describes the fixation of the part at the pose in the work area. The held item must not move during the process. If the workpiece moved during the processing, its pose would be incorrect, and the same problems mentioned before would occur. Most of the time, this is achieved by clamping the workpiece between multiple surfaces. The complexity of clamping lies in the supply of sufficient clamping force and in limiting the strength to prevent damage to the part. The necessary clamping power guarantees a rigid and stable fixture of the workpiece in a 3D area and prohibits the movement in the three directions (X, Y, Z) and rotations (RX, RY, RZ), and thereby removing all Degrees of Freedom (DoF). By providing too much force, the part could be damaged or deformed, which would lead to further problems, described in detail in the next paragraph [5,8,9].

Supporting: The last primary function is the support of the whole workpiece against external forces. The part must be supported to prevent the elastic and plastic deformation of the workpiece due to the clamping forces or the machining. This is especially important by thin or fragile workpieces, like Metal sheets or plastics. Errors due to deformation can range from wrong dimensions, tolerances or even damage to tools, and therefore must be minimised to reach a reliable workpiece quality [5,8,9].

2.2. Flexible Fixtures

The change in consumer demand and the growth of global competitors led the producer to increase product diversity, shorten product life cycle and lead-time, lowering unit cost in combination with higher quality and a need to innovate constantly. To be recognised on the global market, manufacturers must be flexible and automated, leading to strife for Flexible manufacturing systems (FMS). FMS enable manufacturers to produce a vast accumulation of different part, varying wildly from each other efficiently and effectively. FMS attain this variation by combining hardware and software components to adapt and react to a changing demand rapidly. The most common implementations of FMS are CNC Systems and robotic manufacturing.

2.3. Types of Fixtures

This paper aims to design and implement a Flexible Fixture System for a mobile mover in the Technikum Digital Factory at the UAS Technikum Wien.

It is compulsory to examine current development in this area and actual industrial applications to make an informed decision. The Categorisation in Fig. 1 is based on Bijan Shirinzadehs [10] grouping of Flexible Fixtures and is cumulated and curtailed. This results in the five main types, where four are described in the following paragraphs.

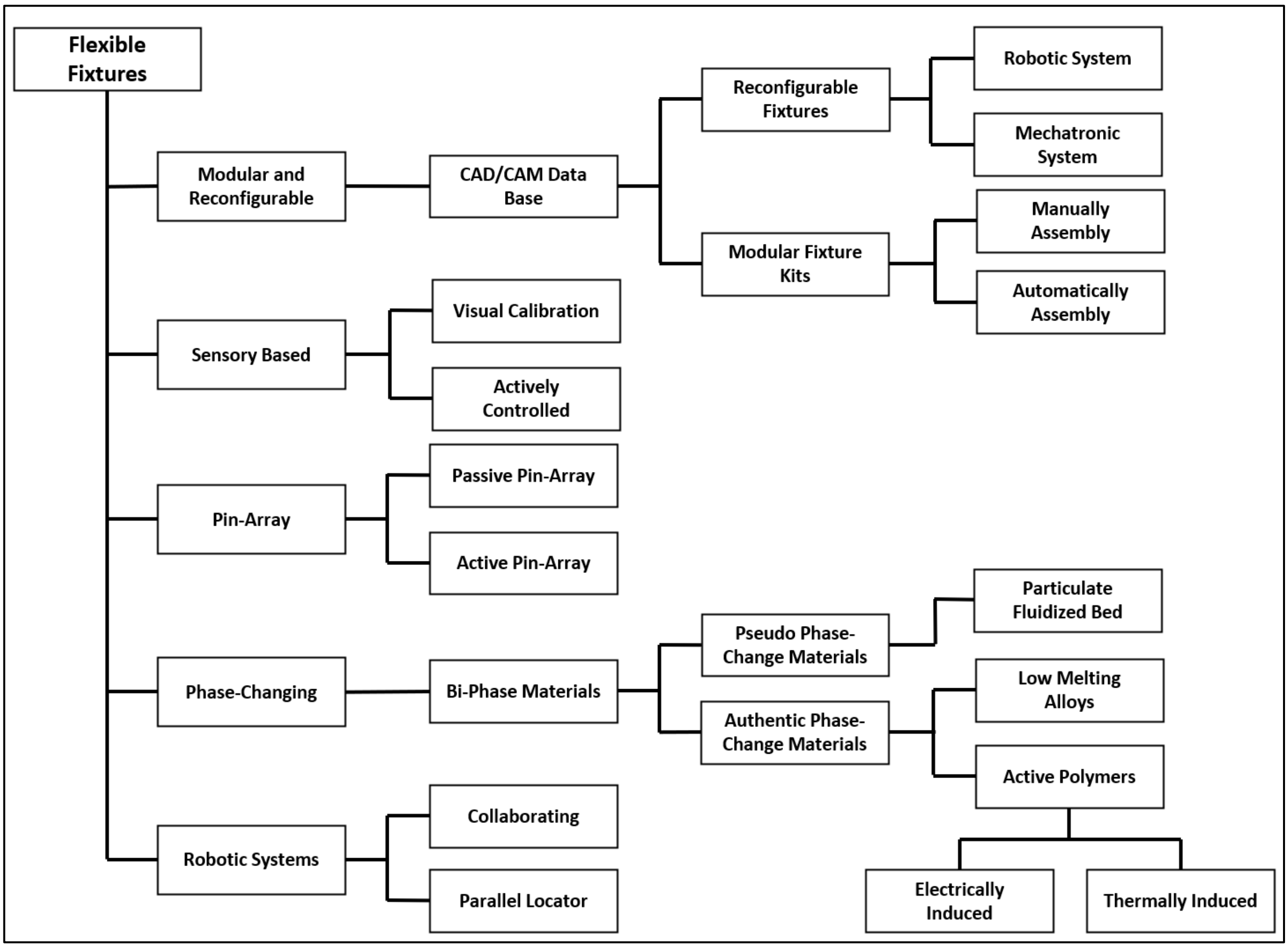

Fig. 1. Categorisation of Flexible Fixtures [10]

2.3.1. Modular and Reconfigurable

Modular and reconfigurable fixtures are descendants of classical systems, splitting the fixtures into multiple parts and making all of them interchangeable. The elements of such a system are grouped into three different types [11]:
Baseplate: A sturdy structure used to connect all parts of the fixture with a single mounting point. Most of the time, it is a plate with multiple parallel T-slots or a hole Matrix System. The baseplate defines the location of the workpiece by attaching the clamping elements at defined positions.
Locating and supporting elements: These elements are placed on the baseplate to align the workpiece onto the fixture and define the pose. In addition, they also support the workpiece during machining by transferring forces to the baseplate.
Clamping elements: Used to clamp the workpiece to the baseplate, thereby restricting the movement during manufacturing processes. The force can be transferred by friction or through a geometric form. They are also used to insert the workpiece into the fixture.

The position of the parts must be calculated or tested for every new part, which should be manufactured. There was a rapid development of an automatic process to design these (CAFD - Computer-aided fixture system [5]), to apply these in an industrial environment [12]. The elements of the modular fixture must be precisely placed on the baseplate before each workpiece change. This is highly skilled and labour-intensive work; therefore, it is often outsourced to a robot system. The robot gathers the needed elements from storage and places them on the baseplate to construct the fixture [10,11,13].

2.3.2. Sensory Based

Sensor-based fixtures are dedicated fixtures, which are enhanced by sensors and software. The information gathered by the sensors is used to compensate for any positioning errors, thereby reducing the fixture's needed accuracy. A "visual fixture" is generated by the computer vision system, which is applied to triangulate the pose of the workpiece in 6 DoF.

With the exact pose of the workpiece, the computer system adapts the manufacturing process to counteract the uncertain mechanical positioning of the fixture. A typical application of this technique is the insertion of windshields into the automotive body [10].

2.3.3. Phase-Changing

One promising idea, in recent years, is the utilisation of materials with phase-changing abilities to change the material from a fluid to a solid and back to a fluid again [14]. A central Obstruction of this technology is the limitation through mandatory functions. The material and process must not harm the workpiece, and the phase change must be simply controlled. The functionality of the fixture can be described in two steps. First, the workpiece is placed in the liquid form of the medium. By triggering the phase-change of the material, the workpiece gets secured in its pose and the manufacturing process can be started. There are currently two different types of phase-changing materials in use.
Authentic phase-change uses the temperature to undergo the phase change. Low melting allowed are primarily used in this category, but even this temperature change can introduce unwanted deformations in the workpiece.
Pseudo-phase-change utilises a particulate fluidised bed, which is a vessel filled with particles (e.g., sand). A controlled stream of air flows through a porous material at the bottom of the vessel. This stream loosens up the particulate material and enables the fluid-like behaviour of the material [10,14].

2.3.4. Pin-Array

Pin-array fixtures utilise the concepts of multiple mechanical contacts to secure a workpiece at a specific location. It consists of multiple pins, also called fixels or fingers, and a base block [15]. The pins can move freely in on direction normal to the base's surface. The workpiece is surrounded by multiple pins, which conforms to the geometry and thereby secures the pose in multiple DoF. Fig. 2 demonstrate the adaptation of a pin array to an irregular workpiece.

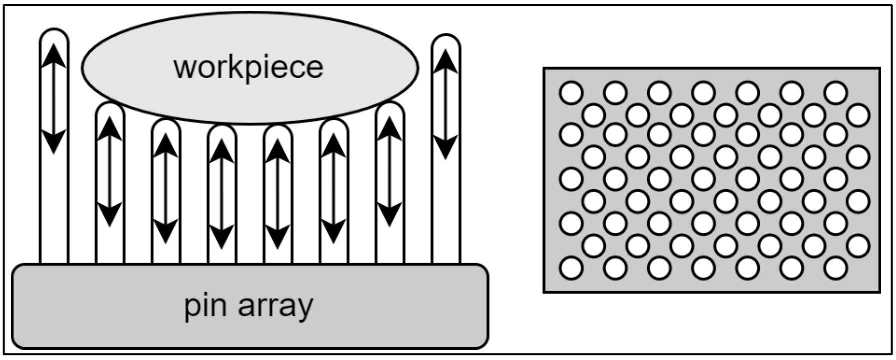

Fig. 2. Schematic of a pin array and representation of its functionality. The right side shows the pins adapt to a workpiece's irregular surface, and the left side is a view from above to demonstrate the pin positioning.

In addition, the workpiece is excellent support over its whole surface. The pin-array is used in two different forms in an industrial setting, a passive and active form. The passive form requires the workpiece to be pushed into the array since the pins cannot be actuated. An active pin-array fixture is capable of moving the pins in a defined direction. This motion is achieved by air or hydraulic pressure or a tiny electric actuator. A friction-based locking mechanism often holds the pins in place [15] to secure their position after adaptation.

Another emerging use of pin arrays are grippers for robots to grab any object and manipulate it. For example, a recent development by Shi [2] utilises a shape-memorable adaptive pin array to grasp any contour. The process consists of two parts. First, multiple objects are learned by pushing them inside a passive pin array, which holds its form through friction. The next step is the clamping part, where the pin rows alternatively move in different directions, which clamps the inserted workpiece. A similar principle is used by the Concentric Rotation Pin Array Gripper [16]. It also uses a passive pin array to conform to the surface, but a twisting motion introduces the clamping forces against multiple revolting parts, which house the pins. Due to the rotational movement, every direction of a workpiece can be grasped.

3. Problem Description

The standard fixture solutions, which are currently in use in an industrial environment, lack the adaptability needed to fulfil the new requirements, presenter to the manufacturer. These requirements consist of a need to produce a small batch size, down to one, to perfectly fulfil all consumer demands, thereby staying competitive in the global market of manufacturing and production. The need for such low batch sizes originates from the consumers' desire for a personalised product that must be customised during production. Moreover, the industry faces the challenge of implementing a cost-effective production process to avert substantial price increases, which the consumer would not accept.

In addition, if a product is custom-made, it cannot be produced in advance and shelved, thereby increasing the delivery time for the client drastically. Therefore, the production process must be as fast as possible to prevent enormous lead times. The necessary machining equipment is often already in use to achieve all these requirements. For example, CNC machinery can produce a variety of different products by just adjusting the program code without additional setup times. Moreover, robots execute multiple different tasks in an autonomous production line, like welding, drilling, and part handling, because they provide an adaptable and programable base framework. In combination, the machining side of a production line is often already suited to manufacture multiple parts without any additional production time and costs besides the initial programming. Whereas the machining part can be programmed for multiple pieces/functions, the existing standard fixture holding the workpiece in place is inflexible and lacks the adaptability required. The fixture fulfils the task to hold the workpiece in place during any kind of processing. Therefore, all the parts six degrees of freedom must be locked to prevent any movement, which would alter the workpiece's dimensions and render the process useless. Traditionally, every part, which can be manufactured at a production line, has its dedicated fixture to fulfil this role, but this is not an option with the need for adaptation and customizability. A dedicated fixture would present the manufacturer with massive additional costs and time for each part. Therefore, a fixture solution is needed to accommodate workpieces of different sizes and shapes. The problem with the standard dedicated fixtures is demonstrated on a vice in Fig. 3. When an irregular shaped object is placed in a fixture there can only be a limited amount of contact points, which highlighted as red dots in the image.

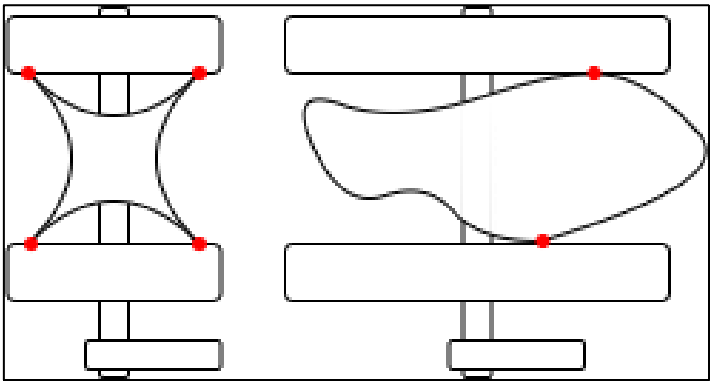

Fig. 3. Limited contact points resulting from an irregular shaped workpiece

Additionally, the fixture should support the part during machining to prevent deformation, ensuring a suitable workpiece. The limited contact points counteract this function and can even cause the part to move during machining and loosen itself, by rotating in the fixture, as seen in Fig. 4. This would lead to a rejects part or could even damage the production machine, which results in additional delays and costs. The third task of a fixture is the introduction of clamping forces to counteract the forces produced by the machining. However, with such a low contact point count, these areas of the workpiece are stressed extraordinary which can lead to damage.

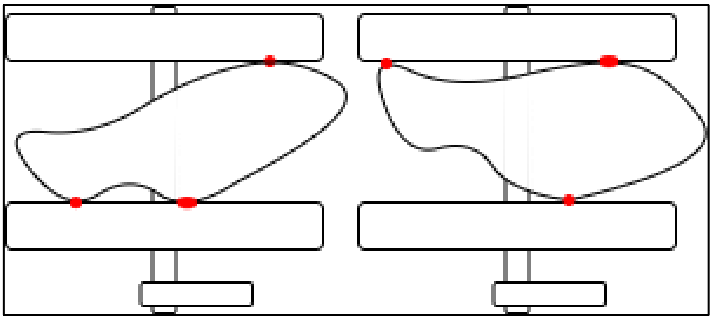

Fig. 4. Uncertain orientation of the workpiece, due to limited contact points between fixture and piece

4. Materials and Methods

The overarching idea was to develop a new flexible fixture for the use in a fully automated industrial setting. The digital factory of the UAS Technikum Wien provides a fully automatic production line of miniature robots in which this fixture is implemented in a future project, to be more precise. This paper provides the groundwork and conceptional design for such a flexible fixture. To achieve that, three promising concepts were compared in their versatility and scope of functions. An evaluation matrix was developed, and the solutions examined and assessed in detail. The best concept was further developed and adapted to the needed requirements.

Lastly, a prototype was manufactured and tested. Selective laser sintering (SLS) 3D printing was utilised to manufacture the prototype, which enables internal mechanical structures but limits the material selection to a thermoplastic polymer. The prototype consists of a subpart of the complete fixture and was only used to examine the developed fundamental concept. The focus during testing lay on the general fulfilment of the desired functionality and not on the performance of the fixture, due to the fact that this project provides the groundwork for a flexible fixture.

5. Practical Realisation

Despite their incredible benefits, flexible fixtures are not yet a widespread part of the industry. Nonetheless, some ideas and concepts could provide a solution to this problem. These notions often come from other industry fields and can be adapted to create a flexible fixture solution. The conceptualisation of the proposed solutions starts with examining and evaluating the most promising concepts. To compare different solutions, we first define what requirements a flexible fixture must fulfil to meet the needs of the industries. The three essential aspects are explained in detail in 1 and must be fulfilled by all fixtures, providing an excellent parameter for comparing these concepts. Next, different qualities and functionalities of a fixture are weighted as additional benefits for the solution and are explained in their corresponding sections. Six specific qualities of fixtures are evaluated to provide a quantified and comparable picture of each concept to quantify these aspects. These examined features are as follows:

- *Complexity*
- *Control*
- *Stress to the workpiece*
- *Position accuracy of the part*
- *Repeatability*
- *Automation*

These characteristics are a general matrix for flexible fixtures and not adjusted to the compared one. Therefore, additional concepts can be included in the comparison without any further adaptation or re-evaluation of the presenter concepts in future developments. This paper covers three concepts, presenting a unique approach to adaptation and flexibility. The concepts are a variation of a fractal vice (Section 5.1), a modular fixture system (Section 5.2) and a pin array (Section 5.3). All solutions are examined individually, using the before defined features. After ranking and comparing the concepts, the best idea is the basis for further developing a flexible fixture in Section 5.5.

5.1. Fractal Vice

A fractal vice is an early 20th-century evolution of the vice jaws, which enables a vice to hold irregularly shaped objects and was patented by Mantle & Co [17]. An excerpt of the patent, where the construction of the vice is demonstrated, is shown in Fig. 5.

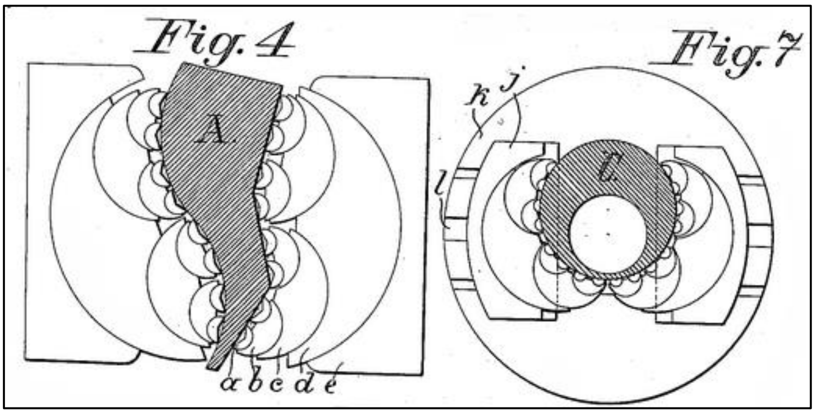

Fig. 5. Excerpt of the patent of the original fractal vice, demonstrating the adaptability of the jaws (Source: [17])

This technology was pushed into the background with the rise of mass production and standardisation, but it currently has an upswing in the 3D printing community. The vice utilises multiple semi-circular jaws to change its form and conform to the shape of the workpiece. To achieve this adaptation, the jaws are placed in a series of linked shrinking semi-circles, most of the time in four steps. The individual jaws can swivel about 45 degrees in each horizontal direction. This system is a passive mechanical chain and is only actively moved at the base of the jaw. The joints between the parts are sliding contact bearings. Therefore, they must meet specialised requirements, like surface quality and lubrication. Nonetheless, the mechanical system of the fractal vice is comparatively straightforward and proven.

The only attention must be given to the design of the joints between the part, due to their before mention needs, yet they are no hinders with today's manufacturing qualities. Fig. 6 shows the 3D printed prototype of the design to evaluate the system better.

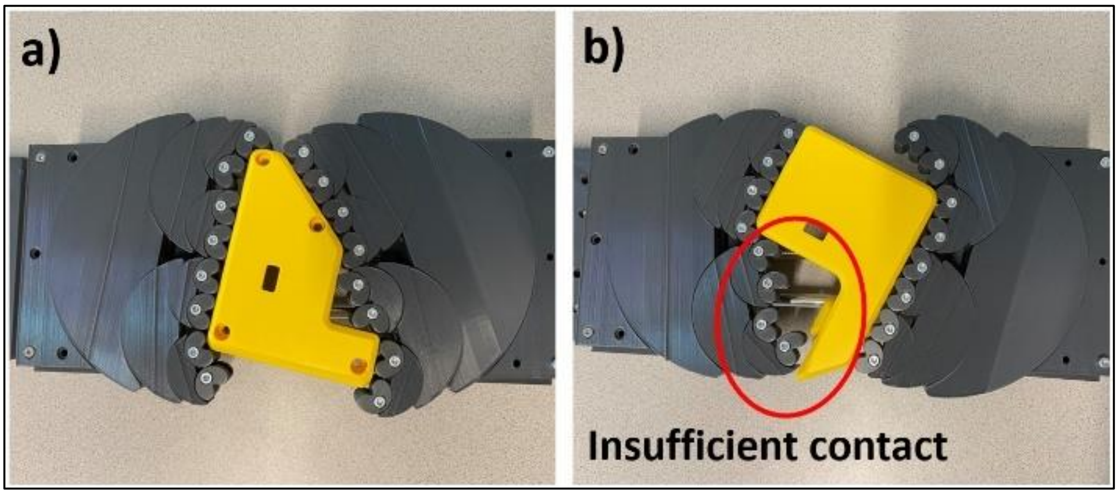

Fig. 6. 3D printed prototype clamping irregular shaped objects. a) Demonstrates a good grasp of the part and b) shows an insufficient contact due to the workpiece geometry

The control of the system is done through a single driveshaft, which can be powered manually, with a handle or automatically with a stepper motor and torque sensor. Therefore, the fractal vice qualifies for an autonomous industrial setting due to the low implementation requirements for the manufacturing plant. The production line must provide power and a digital I/O connection to control the vice. However, the fractal vice presents difficulties in an autonomous environment due to its poor position accuracy and repeatability. It is impossible to say how the part will align itself in the vice during the closing, thereby complicating further workpiece processing. Moreover, as seen in Fig. 6 b, it can occur that the part and vice do not form a sufficient contact and thereby limit the functionality of the vice. These problems can be limited by adjusting the jaw positioning and adding an additional jaw pair 90 degrees rotated, but not wholly prevented, which is needed in an autonomous industrial environment. Another drawback of the concept is the reliability of clamping forces to move the vice parts and conform to the workpiece. These might not be a problem with sturdy materials like metal or plastic but limit the concept's application range. The before-defined criteria assessment can be found in Table **1** in Section 5.4.

5.2. Modular Fixture

The most common solution currently used in an industrial environment is a modular fixture system. However, only specialised manufacturers offer these and often contribute high costs to the production line. Moreover, they do not wholly characterise as flexible fixtures but present a great middle-ground between total flexibility and precision. This section examen its potential as a flexible fixture and what disadvantages hindered its universal adoption. Section 1 describe the general functionality and construction of modular fixtures. Thus, this section concentrates on their implementation and functionalities in an autonomous industrial environment. As mentioned previously, the fixtures consist of multiple parts, like support, locator, clamps, and mounts attached on a baseplate, which has holes or grooves as a means of mounting the part to it. Consequently, the fixture must be assembled and reconfigured for every new part in the holding solution. A highly skilled worker often does this. However, this is not a suitable solution for autonomous production. Manufacturers often overcome the problem by storing the assembled and configurated fixtures separately and changing them with the workpieces. If a new part is designed, an additional fixture is configured, or a previously used one gets adopted. Another promising approach is to outsource the fixture assembly to a robot system. It can place the part precisely where they are needed, and the robot can prepare the following configuration of the fixture during machining of the current part. A modular fixture combined with a robotic reconfiguration station presents the manufacturer with some challenges during implementation into a production line. First, the fixture parts must be stored and accessible to the robot, occupying variable production space. Moreover, this process takes time and could present itself as a bottleneck of the production line. Last, the fixture configuration must be designed, which presents additional work. There are tools to generate these fixtures automatically, but these are often experimental and costly. These implementations challenges mean that the whole system, consisting of the fixture, the robot assembly station, and part storage, are taken into account in the assessment. The individual passive part reduces the complexity of the fixture substantially, but the addition of the assembly station in combination with a configuration tool makes it very time-consuming and error-prone. Likewise, the control of the fixe is the simplest one because it consists entirely out of passive components and is used as a dedicated fixture, but the robotic systems present a significant amount of work.

The modular fixture outperforms in stress of the workpiece, position accuracy and repeatability. If sufficiently well-built and assembled, it competes with dedicated fixtures and presents no problem in these categories at all. As mentioned before, the system can be fully automated, but only with substantial additional work, space, and cost.
Moreover, due to the fixture's design, it cannot accommodate every possible shape of the workpiece. The individual parts of the fixture are off-the-shelf, and the flexibility is only achieved by combining these parts. Therefore, the modular fixture can adjust itself only in small defined steps. The assessment of the criteria once more can be found in Section 5.4.

5.3. Pin Array

The last examined concept of a flexible fixture in this paper is the pin array. It has only a limited application in today's industrial production, but several projects are currently developing. This section only describes the variations and adaptations of pin arrays. The basic functionality and structure are described in section 2.3.4 in detail. Moreover, Fig. 1 in this section is used as a reference here. As it shows, a pin array consists of multiple movable pins. There are two main types of pin array, active and passive. Active pin arrays can actuate the pins and control them. The passive pin array relies on a spring system to push the pin into a before defined position and introduce a force into the workpiece. This type of pin array requires heavy parts to function properly and is sometimes used in engine block manufacturing. For that reason, an active pin array is evaluated in this scope. There are multiple possible variations of actuation, but to two most common ones are a pneumatic system and a linear electric motor. A pneumatic system presents itself as a suitable fit in an industrial environment due to its low implementation cost since nearly every production line has a pressure air system and the great potential power to area ratio at the pins. That means that each pin could introduce more power to the workpiece with a pneumatic system than with an electric one. A pneumatic system with many pins in an array presents a rather complex system to produce and control. Each pin must be treated as a cylinder, with small tolerances and sealing rings. Moreover, the piping inside a small footprint presents its own challenges. The control of the system is achieved through multiple valves and a controller. The pneumatic control and the multiple pins enable the system to be fine controlled and only strain the workpiece with minimal force. An aspect, which standard pin arrays could improve is the position accuracy and repeatability. It is dependent on the minimal distance between the individual pins, but a system can be implemented to additionally move the pins against each other to counteract this disadvantage. This system adds significant complexity but presents a near-ideal performance of the fixture system. If a pin array should be implemented into an autonomous environment, it can be done quickly by adding a robot to position the workpiece into the array. When the piece is placed at the correct location, the pin array locks its form, grasping and holding the workpiece ideal. Moreover, a pin array is arbitrary expandable without losing its ability to hold a small part.

5.4. Comparison

This section provides a direct comparison between the examined concepts (5.1-5.3), providing a solid base to make an educated decision on which solution should be used for further development. The categories the assessment is based on can be found in the first paragraph of section 5. "Complexity" describes the overall difficulty and expenditure of the mechanical and electrical design and manufacturing of a prototype. The scope and complexity of the control, including programming, number of actors and types of power supply, are considered in "Control". "Stress to the workpiece" evaluates the forces acting onto the workpiece during clamping, which are unnecessarily high or unwanted. These forces limit the potential to grasp delicate and soft workpieces. "Position accuracy of the part" and "Repeatability" have the same meaning as in robotics but are applied to the workpiece inside the fixture after clamping. The last metric evaluated is "Automation". It depicts the overall difficulty and expenditure to implement the fixture into a completely automated production line. Important factures here are the footprint, control interface, power supply and speed.

	Fractal Vice	Modular Fixture	Pin Array
Complexity	Average	Good	Fair
Control	Excellent	Poor	Good
Stress to the workpiece	Average	Excellent	Excellent
Position accuracy of the part	Poor	Excellent	Good
Repeatability	Poor	Excellent	Good
Automation	Excellent	Poor	Excellent

Table 1: Comparison of the three flexible fixture concepts

Table **1** lists the individual ratings of the systems split into the defined categories. A grading metric from 1 to 5 (Poor/Fair/Average/Good/Excellent) is used as a rating system. The fractal vice presented two significant problems in the scope of this paper. On the one hand, the aim is to design a holding solution for an autonomous industrial environment, demanding a high position accuracy and repeatability to function correctly. Moreover, a misaligned part can halt the whole production line, resulting in additional problems. On the other hand, the vice must be built with a specific dimension range of the workpiece in mind.

If the object is too small, the vice cannot adjust itself due to the size of its smallest semi-circular jaws. Additionally, when the part is too big, the vice cannot open wide enough to fit the part, and only a small area of the workpiece would be in contact with the fixture, limiting the force transmission and clamping capabilities. The modular fixture convinced with its performance but presents too many obstacles during implementation at a smaller scale. Moreover, the paper's aim is a fully adjustable fixture that can grapes any shape securely, requiring massive modifications and substantial changes to the existing and proven system.

The pin array could not outperform in any category but achieve a relatively good and consistent rating in all groups. Moreover, most aspects, which lowered the score can easily be rectified by minor adaptations and additions to the solution, as elaborated in section 5.3. Therefore, the pin array was chosen as the basic concept of the flexible fixture. The following sections describes the design, adaptation and additions needed for a fully automated flexible fixture.

5.5. Development of a Flexible Fixture

This section covers the development and implementation of the new approach to fixate a part in an industrial environment. The aim is to hold any shape and form securely in place, exert enough holding forces to process the workpiece and provide an automatic process of insertion and closing of the fixture to avoid any need for human interaction. To accomplish this, two new techniques are adapted and combined. These are an active pin array to conform and support and a rotating mechanism to hold and secure the workpiece, which are explained in detail in Section 3 and 5.5.2. In addition, the pneumatic and power supply system and control design are examined in their corresponding paragraphs 5.5.3 and 5.5.4. Finally, a smaller prototype of the complete flexible fixture system was made and tested based on the adaptations and new ideas. The results of these tests can be found in section 6.

5.5.1. Active Pin Array

As elaborated in the previous comparison between different concepts in section 5.4, a pin array was chosen for this fixture. Despite the excellent capabilities of classical pin arrays, some adaptations had to be made. The first significant addition to existing pin array concepts was the active manipulation of each pin. Existing concepts of pin array fixtures depend on springs and the pushing force of the workpiece to adjust their pins. This constricts the capability of the fixture to adapt to any form without unnecessary additional forces. Each spring exerts a specific force depending on its characteristic curve, which cannot be adjusted easily after installation, if at all. Therefore, a spring-based fixture can only accommodate a limited range of materials and workpieces without a spring change. If a process demands soft and hard materials handling, such a fixture is not suitable. Hence, the present solution allows adjusting the force exerted through the pin onto the workpiece, thereby making it possible to grasp a delicate soft piece without damaging it, directly after holding a rigid part during heavy machining like drilling or milling, which demand high holding forces. This great adaptability is achieved by replacing the spring with a pneumatic system. Each pin acts like a miniature cylinder and possesses the same functionality. Therefore, the force applied by the pin is linked to the pressure inside the cylinder. Consequently, by adjusting the pressure, the force on the workpiece can also be varied. To provide an even better control, the pins are designed as a double-acting cylinder. This means the pin can be extended and retracted by the controller without any external interactions. In addition, if both chambers of the cylinder are pressured, the position of the pin is locked. This comes from the fact that both sides of the piston have the same pressure and thereby exerting the same force on the piston in the opposite direction. Thus, the pin does not move in any way and even can absorb some force, corresponding to the internal pressure used.

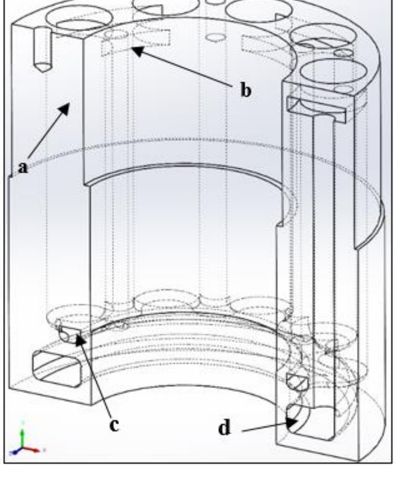

Fig. 7. Section view of the outer housing of a module. Visualisation of the internal air piping and double-acting cylinder construction. a: Cylinder tube, b: Piping and splitting for two top pressure chambers, c: Distribution for all bottom pressure chambers, d: Distribution for all top pressure chambers

Fig. 7 shows the design of these described features and how they were realised in this flexible fixture. This paper's functionality and design decisions are demonstrated on the base part of the outer housing and applied with minor adaptations to the inner base part, which can be seen in Fig. 10. The outer part houses ten cylinder tubes which are radial oriented, as seen in Fig. 7 a. They have a diameter of 8,4 mm, a length of 42 mm and are placed at a distance of 39 mm around the centre. In each tube sits a pin splitting the cylinder into two parts. These are the two pressure chambers needed for extension and retraction. Internal piping is needed, to actuate the pins by filling the chambers with air pressure. The top chamber is supplied with air by five internal tubes between the cylinders (Fig. 7 b). At the top of each tube, it splits up and supplies two top pressure chambers. All five internal tubes are connected through a distribution chamber at the bottom of the part, which can be seen in Fig. 7 d. The bottom chambers of each cylinder are also combined by a separate distribution chamber (Fig. 7 c). Therefore, all cylinder in the outer housing of each module work in unison, regarding extension and retraction of the pins. Hence only two pneumatic tube connections are needed per module, one for the top and one for the bottom chamber, which reduces complexity and piping effort inside the fixture without losing significant flexibility. That is because the position of the individual pins is not linked with this connection. The position of the pin is a combination of the pressure in the chambers and the connection point of the pin with the workpiece. During extension, the pressure of the bottom chamber is higher than in the top chamber, and the pin has no physical resistance, therefore moving up. As soon as the pin connects with the workpiece, the pressure inside the chamber rises to the set air pressure and exerts the force through the pin onto the workpiece. Since the maximum pressure reached is the set pressure, the pins can undergo this sequence without interfering with each other.

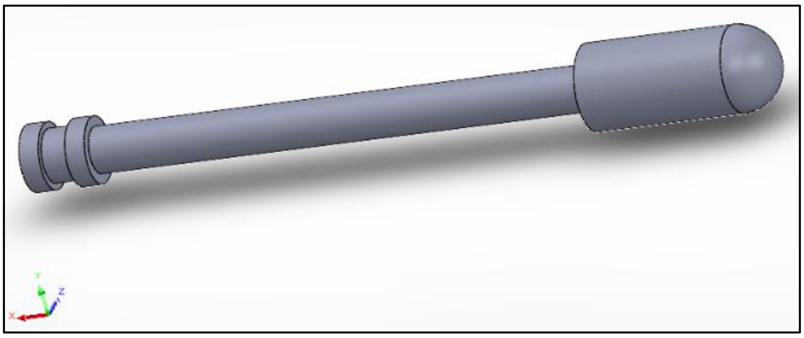

Fig. 8. Single pin, which is used multiple times in the flexible fixture. Additionally, the optional pinhead is also displayed

The pin, which is placed inside each cylinder tube, can be seen in Fig. 8. Every pin is made of two parts, the pin itself and an optional pinhead. The pin functions as the piston of the cylinder, where one side sticks out of the top and contacts the workpiece. It has a diameter of 4,5 mm at the rod and extends at the bottom to hold a gasket. For the gasket, an O-ring with an inner diameter of 4,5 mm, is used to seal the pin and the cylinder walls. This sealing also provides the separation of the top and bottom pressure chamber. The total length of the piston is 70 mm, which allows the pin to extend 60 mm. To ensure a smooth movement of the pin and prevent wedging, the pin is guided by the gasket at the bottom and an additional O-ring in the lid of the housing. This additional O-ring also provides the sealant between the outside and the top pressure chamber. To further prevent any cramming and provide a better connection between the pin and the workpiece, the top of the pin is rounded. Due to the physical space required by the double-acting cylinder and gaskets, the distance between the pins reaches a maximum of 7,5 mm. To reduce this distance, additional pinhead can be installed. These are 3D printed caps, which hold on top of the pins by friction. In this way, the distance can be reduced to 3,6 mm. If a passive movement of the pins is desired, or additional forces should be compensated, there is the possibility to add a spring in the bottom chamber as well as in the top chamber. However, in the majority of use cases, these springs are not needed.

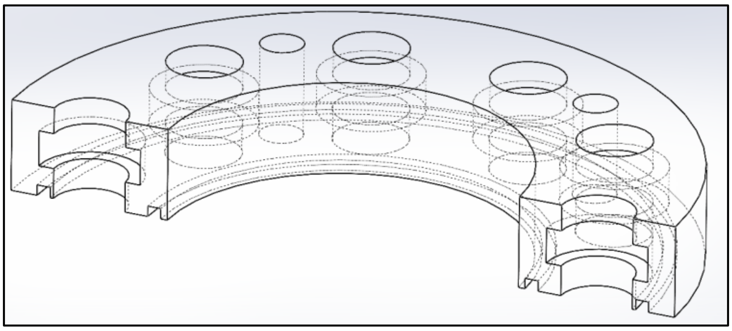

Fig. 9. Section view of the outer housing lid of a module

The final part of the outer housing is the lid, which can be seen in Fig. 9. It is made of a ring with an inner diameter of 27 mm, which surrounds the inner housing and an outer diameter of 51 mm, which is also the maximum dimensions of a module. Ten holes, one for each pin, encircles the centre corresponding to the ten cylinder tubes in the base. Additionally, these holes present a groove for the before mentioned O-rings. These serve the purpose of guidance for the pins and sealant for the upper chamber. Additional O-rings are placed between the lid and the base part to seal this connection and prevent air leakage. To mount the lid to the base, five M3 through-holes are placed rotational symmetrically to ensure an even mounting pressure, which is needed for the O-rings.

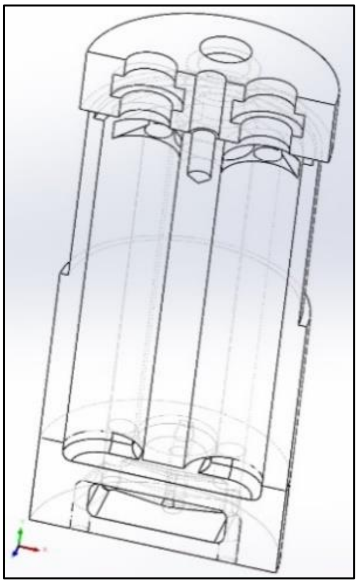

Fig. 10. Section view of the inner housing of a module. Depicts the base part and the lid, without the enclosed pins for better visibility

Fig. 10 presents a section view of the inner housing. The same design process was used, and many similarities to the outer housing are visible. The structure is the same: two distribution chambers at the bottom, a double-acting cylinder in the middle, and a lid with guidance and gaskets at the top. The connection for the top pressure chamber consists of four internal tubes, which are linked into all four top chambers together. A single M3 Screw in the middle is used to assemble the part. The inner housing is placed in the hole of the outer housing and connected with a barring, making it possible to move the inner part around its axis. Section 5.5.2 describes the rotating mechanism and its use in greater detail. A physical prototype of such a module was made and tested. The results and examination methods can be found in section 6. 3D printing was utilised for the prototype due to the complex internal geometrics and piping. The SLS (selective laser sintering) process presented itself suitable to print the parts. It provides relatively good accuracy and can produce small footprints reliable. This is needed because some walls require only 2-3 mm thickness, which is not feasible with a commonly used FDM (fused deposition modelling) printer.

5.5.2. Rotating Mechanism

This section describes the functionality of the rotating mechanism and what benefits it provides. The mechanism addresses the limited number of contact points between the workpiece with an irregular shape and the fixture. The issue is described in detail in section 3 and states the main difficulty with flexible fixtures. If just a static pin array is used, the number of contact points is very limited and often, only 1-3 contacts can be achieved, as seen in Fig. 11 on the left side. The number of contact points highly depends on the exact location of the part inside the pin array. It may even happen that no contact point occurs, which means the workpiece is not supported and moves slightly until a connection can be made. Moreover, a minimum number of contact points is needed to prevent any movement in the six degrees of freedom. Therefore, the number of contact points must be maximised at the precise location of the workpiece. To achieve this, the pins move in the direction of the workpiece to make contact. However, linear movement of the pin could result in special cases where no improvement is achieved. This is the situation when a narrow part is orientated parallel to the movement direction of the pins. As a result, the pins do not move in the direction of the workpiece and, therefore, cannot make additional contacts. The proposed solution is a rotating pin array. This means that two sets of rotationally oriented pins rotate in opposite directions, as seen in Fig. 11 on the right side. By doing that, it is assured that every line drawn through the fixture have at least 2 pairs of pins, which move together, clamping the line in the middle. Additionally, the position of the part inside the fixture is defined by its placement since the pins move onto the part. Thus, the number of contact points and position accuracy can be significantly increased, as seen in Fig. 11 by comparing the left and right sides.

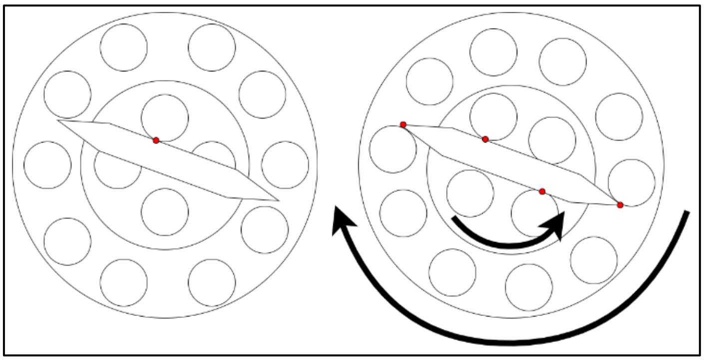

Fig. 11. Contact point between fixture and workpiece with (right) and without (left) rotating

The rotation of a module's inner and outer housing was realised with a pneumatic cylinder. The pneumatic system was chosen since the active pin array already uses an air supply, reducing system complexity. The installed actuator is a spring-loaded single-acting cylinder with a diameter of 4 mm and a 10 mm lift. Fig. 12 demonstrates the mechanism used to move the flexible fixture.

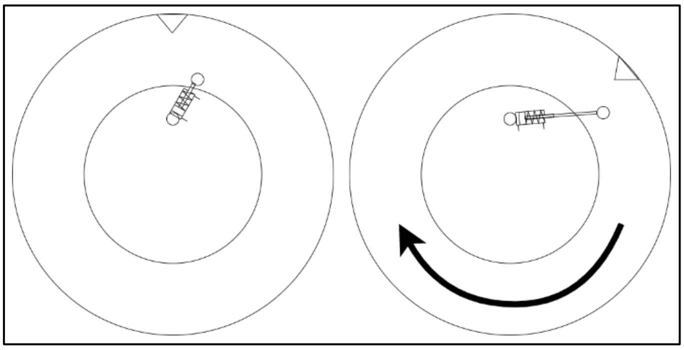

Fig. 12. Transforming a linear motion into a rotation motion to move the inner and outer housing against each other

The rotational movement in opposite directions is achieved by placing the cylinder between the two parts. If the cylinder extends, it pushes the components apart and introduces a force, which rotates the parts in opposite directions since neither the inner piece nor the other part is fixated. Because the movement of the cylinder would interfere with the air pressure fitting, it was lifted above those, and angel fittings were chosen. As a result, the cylinder is mounted on two stilts, which must be able to rotate, as seen in Fig. 13. This is necessary because, during expansion, the cylinder rotates, and the mounts must stay normal to it. Therefore, a friction bearing with two washers is a space-efficient and reasonable approach.

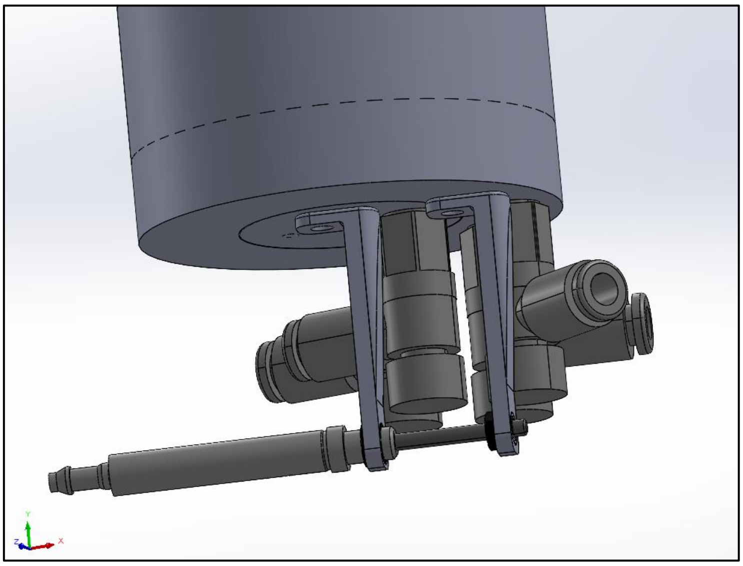

Fig. 13. Assembly of the rotation mechanism without piping to enhance visibility

5.5.3. Pneumatic System

The pneumatic system of the flexible fixture is the primary power source and responsible for all physical movement of the fixture. As elaborated in the previous sections, both the pins and the rotating mechanism are powered by air pressure. Therefore, an air pressure supply is needed to use the fixture. It is common in an industrial environment that a production line-wide air system is present. Thus, the flexible fixture system was designed to be connected to such a system with a single connection. All controls and routings are done inside the fixture, which eases the implementation into the production line significantly. The internal air system consists of a valve terminal, fittings, manifolds and tubes. A schematic of the layout is shown in Fig. 14. The valve terminal contains a distribution rail and five valves, which are controlled by 5V. The valves regulate the following parts individually: The top and bottom chamber of the other housing, the inner housing's top and bottom chamber, and the cylinder for the rotating mechanism. Each valve feeds a manifold, enabling a single valve to control multiple modules. For the fittings and tubing, a range of diameters from 4-6 mm are in use, depending on their expected throughput. The tubes which lead into a manifold are larger than the outgoing ones. The fittings are equipped with flow control, through which the extension and retraction of the pin can be fine-tuned.

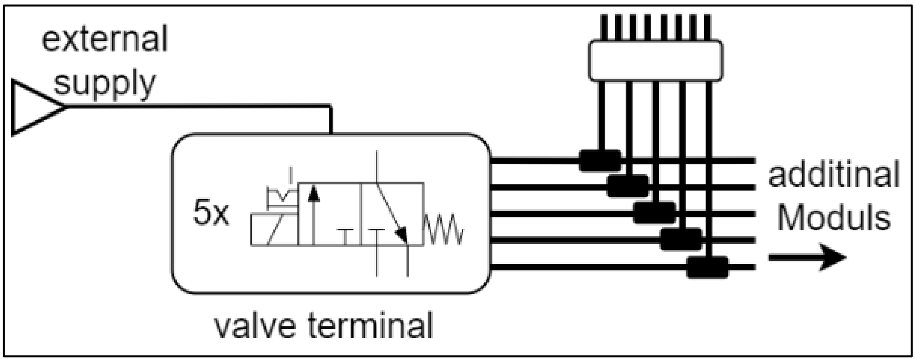

Fig. 14. Schematic of the internal air supply and piping in the base of the flexible fixture

5.5.4. System Control

This section discusses the control system of the fixture and what must be present for implementation into an autonomous process. Additionally, the individual steps performed by the fixture during clamping are listed and described. For the main process unit an Arduino Uno [18] is used, which is a microprocessor with an integrated I/O shield. It provides multiple 5V digital input/output ports and supports varies different serial transmission protocols. As mentioned in section 5.5.3, the pneumatic control is handled by a valve terminal. This terminal is controlled by the 5V digital outputs of the microcontroller, for each valve an individual output. The valves are normally closed (NC), therefore open, if a high signal is present on the corresponding pin. The microcontroller needs a supply of 7-14V to function property, which must be provides by the production line. Hence, the flexible fixture must only be supplied externally with pressured air and 7-14V power. The interaction between the manufacturing plant and the fixture is realised with a digital input, which triggers two different processes. "Low" state starts the opening process of the fixture to release the workpiece and hold the fixture open, while waiting for a new part. The "high" state signals the fixture to close itself and grasp the workpiece. This signal is provided by the plant controller, which also is responsible for the coordination with the placement of the workpiece inside the fixture.

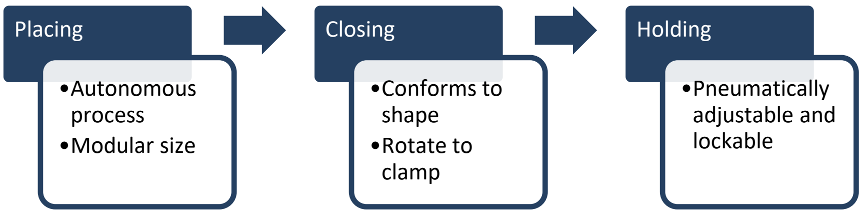

Fig. 15. Sequence of the complete clamping and holding procedure of the proposed flexible fixture

Fig. 15 visualises the steps the fixture undergoes to receive and hold a part. The opening process has the same steps but in reversed order. The first step is to place the workpiece inside the fixture. That means that, the pins are extended (bottom chamber pressurised) and a robot or similar mover places the workpiece at the exact position and orientation. By pressing the part into the fixture, some pins compress to make way to the part and conform to the surface of the part. In the next step, the rotating mechanism activities and rotates the fixture part against each other. In that way, a maximum number of pins contacts the part and exert a force to secure it in place. Last, the pressure in all chambers (top and bottom) rises and the workpiece can be released from the robot gripper.

The additional pressure strengthens the support of the underside of the workpiece, to achieve a higher absorption of manufacturing forces. With the pressurisation of the top chamber, the pins are locked into position, to prevent any unintentional forces.

6. Results

The main focus of this work was to evaluate the concept and create a knowledge base for a future project. Therefore, the fixture's performance was measured by the functionality and not by specific performance parameters. Fig. 16 shows the finished prototype of a single module inside a mounting for evaluation purposes. The complete fixture consists of eight modules inside a joint base, which also houses the tubing and control system. However, in this project, only a single module was manufactured and tested. The 14 pins can be seen in their retractive position in the upper part of the image. The whole fixture is mounted with a bearing in the middle to test the fixture without outside interferences. At the bottom, the four connection ports for the pressure chambers are noticeable, but the tubes were removed for better visibility. Moreover, the small cylinder, responsible for the rotational movement can be seen behind the connectors.

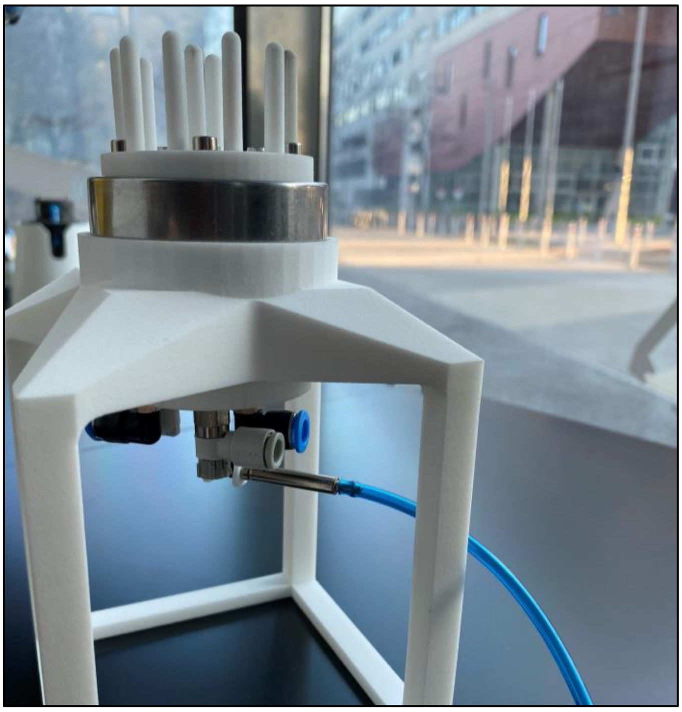

Fig. 16. Prototype of a single module of the proposed flexible fixture

The first part tested was the pin array and how it interacts with irregularly shaped objects. The assessment evaluates, the holding performance in regard of general functionality. Two pictures of an inserted part inside the fixture can be seen in Fig. 17. In Fig. 18, the adaptation to horizontal irregular shapes is demonstrated. The pins underneath the part extended until they contacted the workpiece and then stopped and supported. This functionality was desired and is one outstanding feature of the pin array. Therefore, the general functionality of the pin array was quite good, and the part could be held in place by the fixture. However, some significant problems occurred with this prototype and the manufacturing methods. The SLS printing procedure could not achieve the dimensional accuracy needed for such a small and precise tool. Moreover, the surface quality was not as desired, which led to additional friction inside the cylinders. This results in two noticeable downfalls. First, the pressurisation of both chambers (top and bottom) could not be accomplished due to the inaccuracies and the resulting leaky seals between the pins and the outside.

Furthermore, a higher pressure of 4 bar (58 psi) was needed to extend the pins, which resulted in additional forces acting on the part and a rapid extension. However, a satisfactory extension and retraction process is feasible with better sealing and flow regulators. Additionally, the inaccuracies and surface quality caused the pin to wedge and move horizontally inside the cylinder tube easily. A wedged pin can be seen in Fig. 17 in the left image in the middle. The pin leaned to the right, which led to fewer contact points between the fixture and workpiece. Moreover, wedged pins are often halted in a permanent position, resulting in a required loosening by hand or disassemble in a few major cases. This is unacceptable in an autonomous environment and must be addressed in a future project. Additionally, to the inaccuracies, the pins bend under load, which furthers any wedging and hinders the optimal performance of the fixture. The bending comes from the choice of material, which performs inadequately in such small dimensions. Bending can be observed in both images of Fig. 18, on the right, the outermost pin and on the left, the pins underneath the slant.

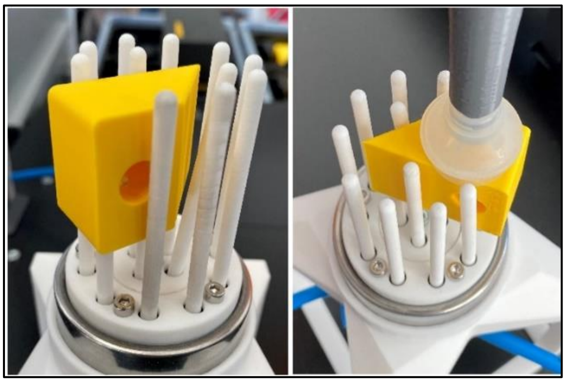

Fig. 17. Irregular part inside the fixture with extended pins. Right: Part is placed by a robot inside the fixture, and it closes around it

Fig. 18. Demonstration of the vertical support of irregularly shaped objects inside the fixture

The second area examined was the rotating mechanism and its performance regarding the workpiece's contact points and position accuracy. A demonstration of the clamping process with the rotating mechanism can be seen in Fig. 19. On the left side is the fixture with an embedded part before the rotating mechanism is activated. The markers show the two potential pins close to the workpiece but not touching it. Therefore, they did not contribute any grasping forces. On the right side, the fixture is shown after clamping the part. By comparing the marked areas, it can be seen that indeed two new contacts could be achieved. Therefore, the hypothesis that a rotating pin array can increase the number of contact points could be confirmed. Moreover, with additional modules, the contact point gain could be further expanded.

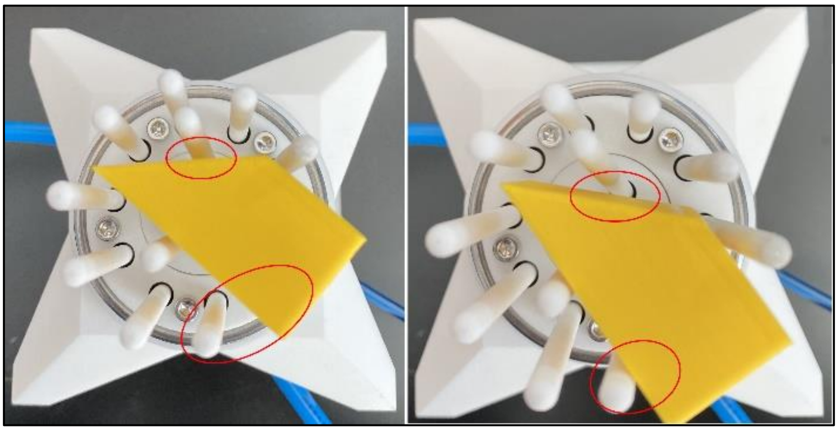

Fig. 19. Experiment to validate the rotation mechanism. The two additional contact points gained by the rotation are marked. Left: Before rotation; Right: After rotation, the workpiece is clamped

Nonetheless, the implemented methods grappled with the same problems as the pin array. The surface quality of the SLS print could be mostly circumvented using bearings between the inner and outer ring and the mounting rack, but the friction bearing used for the stilts are affected, as seen in Fig. 20. The additional friction in combination with the tendency of the material to bend resulted in sometimes in a deformation of the stilts, which hinders the smooth operation of the cylinder, and the linear motion could rotate the fixture with sufficient force.

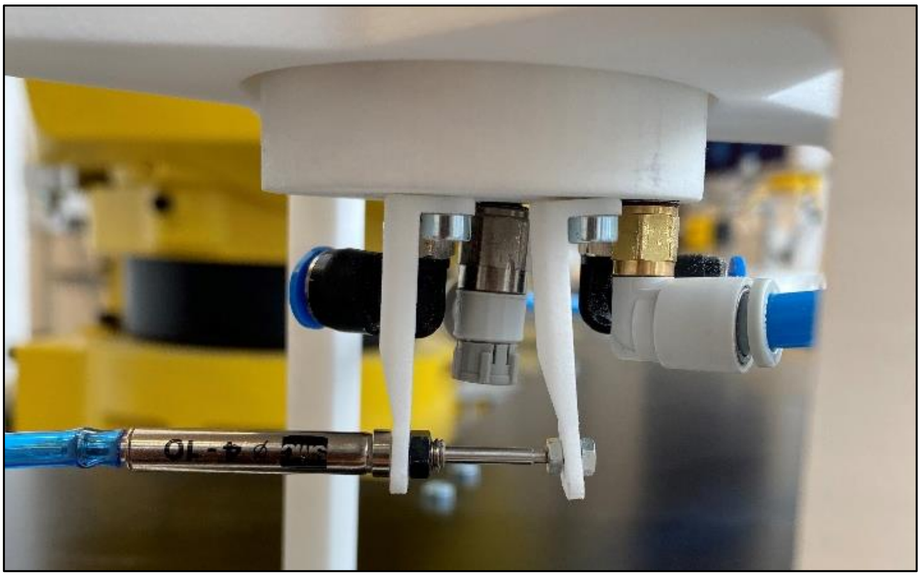

Fig. 20. Close up of the bending of the stilts during rotation of the fixture

7. Conclusion and Outlook

This work tried to develop a flexible fixture and produce a groundwork for a follow-up project. These goals were fulfilled with the improvement for an active pin array combined with a rotating clamping mechanism and the assessments with the first prototype. The concepts functionality could be validated, and valuable knowledge of flexible fixtures gathered for the next iteration. However, the prototype also presented some significant obstacles and challenges, like tolerances and surface qualities. As the results state clearly, SLS 3D printing is not a suitable production method for such a small and precise part. The project's next step is to use other production means, like CNC-routing, to produce a better prototype to test the functionality purely without the before mentioned material limitations. For this purpose, the design must be adapted to accommodate the new production restrictions.

In this process, the flexible fixture can be enhanced with multiple features that provide better functionality and ensure a seamless implementation into a fully automatic environment. The Arduino was a suitable controller for a simple prototype, but a Linux based computer, like the raspberry pi, provides more versatility and better interfaces, which supports standard industrial protocols, and is therefore preferable for the implementation into production lines. In addition, a closer pin configuration combined with individual pin control would ensure a safer grip of the workpiece by the increased number of contact points and more nuanced control of the partially pushed pins. The rotating mechanism is an excellent method for introducing clamping force into a pin array, but the proposed mechanism showed some difficulties and should be improved in future projects to ensure a smooth operation. The pins would also benefit by guiding to accommodate the sideways clamping forces better. Lastly, the flexible fixture could be improved by changing the directional valves with electrically adaptable pressure units and sensors to enable more nuanced control and enhance the controllability significantly. The project revealed the great potential of flexible fixtured and provided the first draft of a possible solution. Despite the semi-successful prototype, the concept looks promising and should be further developed into a fully functional prototype for an industrial application.

8. References

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