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Aerodynamic Feeding 4.0: A New Concept for Flexible Part Feeding

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Abstract

In modern production environments, the need for flexible handling systems constantly increases due to increasing uncertainties, shorter product life cycles and higher cost pressure. Part feeding systems are vital to modern handling systems, but conventional solutions are often characterized by low flexibility, high retooling times, and complex design. Therefore, in previous research, multiple approaches towards aerodynamic feeding technology were developed. Using air instead of mechanical chicanes to manipulate workpieces, aerodynamic feeding systems can achieve high feeding rates while at the same time being very flexible and reliable. Still, the complexity of the workpieces that can be oriented relies on the number of aerodynamic actuators used in the system. Previously developed systems either used one nozzle with a constant air jet or one nozzle and an air cushion, allowing a maximum of two orientation changes.

This work presents a new concept for an aerodynamic feeding system with higher flexibility (with regard to the workpiece geometry) and drastically reduced retooling times compared to conventional feeding systems. In contrast to previous implementations of aerodynamic feeding systems, using only one air nozzle or an air cushion, the new concept uses multiple, individually controllable air nozzles. Using a simulation-based approach, the orientation process is divided into several basic rotations - from a random initial orientation to the desired end orientation - each performed by a distinct nozzle. An optimization algorithm is then used to determine an optimal layout of the air nozzles, enabling the feeding system to feed any desired workpiece, regardless of the initial orientation. With the proposed concept, high flexibility, low retooling times and relatively low costs are expected, setting up aerodynamic feeding as an enabler for changeable production environments.

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1. Introduction

Modern production systems have to meet various challenges. On the one hand, high cost pressure leads to increased automation, especially in high-wage locations. On the other hand, increasing uncertainties and shorter product life cycles require flexible manufacturing equipment [1]. Therefore, part feeding systems, being a vital part of automated manufacturing and assembly systems, also have to meet the requirements for flexibility regarding the feedable workpiece spectrum and retooling times. Conventional feeding systems, such as vibratory bowl feeders or linear oscillating conveyors, cannot meet those demands [2]. Different approaches have been made to increase the flexibility of those systems using image processing or specialized actuators, but a holistic approach is still missing.

This work presents a new concept for flexible part feeding, using image processing and active aerodynamic orienting devices. First, related work regarding different approaches of flexible part feeding systems and the basics of aerodynamic part feeding is presented. Then, the new concept is presented in detail and the necessary methods to achieve the goal of a flexible part feeding system that can meet the requirements of modern production environments are elucidated.

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2. Related work

The major share of part feeding systems for the supply of small parts in automated assembly systems in industrial applications is accounted for by oscillating conveyors, especially vibratory bowl feeders [3]. Vibratory bowl feeders can be designed very compact, have a simple technical construction and reach a feeding performance of up to 200 parts per minute [4]. However, they have a low flexibility since the mechanical chicanes and traps for the workpiece manipulation have to be designed individually for almost every workpiece [5]. Due to the need for qualified personnel and a high experimental effort, design and construction are one of the major cost factors for the acquisition of vibratory feeders [6]. Even though the complexity and disruption frequency can be reduced using vision systems to check the workpiece orientation and to sort out incorrectly oriented parts, this can reduce the feeding performance and increases the wear of the workpieces [5]. Another application of computer vision and image processing for flexible part feeding in the industrial use is the concept of pick-and-place using an industrial robot. The Omron AnyFeeder is one example for such an application [7]. Using vibrations, workpieces are separated and spread across a plane. Then, using image processing, workpieces in a favorable orientation are identified, picked up by the robot and placed on a workpiece carrier. Systems like that can feed different components without hardware changes, if the applied gripper can grasp them. Still, due to the intermittent process, the feeding rate is limited to about 60 parts per minute [8]. Other feeding system manufacturers combine conventional, simple vibratory feeding systems with special, vision-based orienting devices in order to increase the flexibility that can be achieved with the same feeding system. The MRW Zuführsysteme GmbH & Co.KG offers a system that uses a vibratory bowl feeder to separate and pre-align components [9]. The last orientation step is then carried out using a special turnover station that reorients incorrectly oriented workpieces by 180°. Rhein-Nadel-Automation offers a similar, but more sophisticated system, using a parallel robot to pick pre-aligned workpieces off a conveyor [10]. These systems can reach a relatively high flexibility with low retooling effort for similar workpieces. Still, they are very complex, coupled systems for specialized applications.

Therefore, a lot of research is conducted with the aim of enabling flexible feeding of entirely different workpieces from bulk material. Some approaches aim to reduce the effort for the design and construction of conventional feeding systems with the use of simulation models, while others aim to enable part feeding systems to dynamically adapt to different workpiece geometries. As an example of the former, Mathiesen et al. developed a model based on physics simulation that allows the optimization of four different chicane types for different workpieces [6]. Hofmann also used physics simulation to thoroughly simulate the behavior of workpieces in a vibratory bowl feeder, also considering the vibration behavior of the bowl feeder itself [11]. The aim of this work was to reduce the experimental effort during the design and development and at the same time increase the efficiency of the feeder. In an exemplary use case, the feeding rate was increased from 107 to 478 parts per minute [11]. While these approaches lower the development effort for new feeding systems, the developed systems are still part specific. Therefore, as aforementioned, further research aims to create inherently flexible feeding systems. Zhang et al. presented an approach, which uses adjustable pins to manipulate simple workpieces by toppling them when they come in contact with the pins [12]. The position of the pins can be determined beforehand by simulating the workpiece behavior for different arrangements of the pins. However, the approach is limited to workpieces that can be toppled around defined edges. Joneja and Lee also experimented with adjustable chicanes for vibratory bowl feeders, decreasing the effort for design and construction of the feeders while at the same time increasing the flexibility [13-14]. Still, the chicanes have to be adjusted manually for every new workpiece to be fed.

In order to reduce manual retooling effort and counteract the disadvantages of conventional, mechanical chicanes, Lorenz, Rybarczyk and Busch, in consecutive works, developed an aerodynamic part feeding system and enabled it to adjust itself to previously unknown workpieces autonomously [15-18]. The concept of the aerodynamic feeding system has proven to be very flexible, efficient and reliable. Since it forms the foundation for the new concept for flexible part feeding proposed in this work, the basics of aerodynamic part feeding is presented in the following section.

3. Basics of aerodynamic part feeding

The first work on aerodynamic part feeding was carried out by Lorenz, who investigated different methods for the feeding of workpieces, using pressurized air instead of mechanical chicanes [15]. One example is shown in Fig. 1: The workpieces slide down an inclined plane, which is equipped with different aerodynamic actuators, emitting a constant air flow. Due to the specific arrangement of the actuators, workpieces arriving in the wrong orientation are reoriented in multiple steps, while workpieces arriving in the correct orientation pass the chicanes without manipulation.

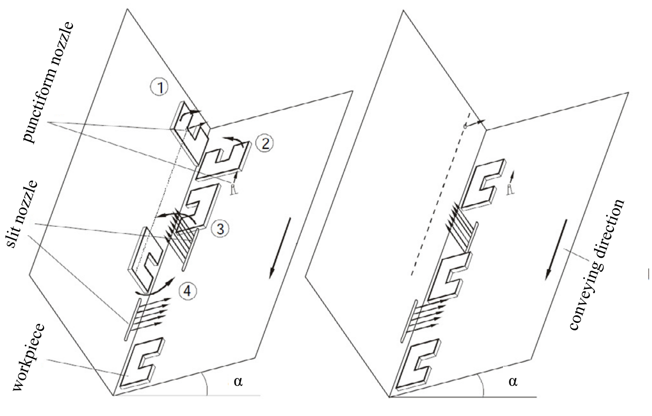
a) Workpiece arrives in wrong orientation b) Workpiece arrives in correct orientation

Fig. 1. Actuator design and arrangement for an exemplary workpiece [1]

The open design without mechanical chicanes allows for a high feeding speed and reduces blockages, increasing the reliability of the feeding system. Nevertheless, the design of the inclined plane requires extensive knowledge of the feeding process and the actuator arrangement is always part specific.

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Therefore, in his work, Rybarczyk developed a method for designing and constructing aerodynamic feeding systems [16]. He identified and investigated two different methods for aerodynamic orientation: Using an air cushion, workpieces can be radially oriented, while with the use of a defined air jet, workpieces can be oriented axially (impulse method, cf. Fig. 2). Combining these two methods, workpieces can be fully oriented with high speed and reliability. Furthermore, Rybarczyk used mathematical and numerical simulations to predict the behavior of the workpieces and the airflow from the aerodynamic actuators (e.g. nozzles) depending on parameters like the nozzle pressure, the workpiece velocity and the inclination angles of the inclined plane. Based on the impulse method developed by Rybarczyk, Busch developed a working prototype of an aerodynamic feeding system that can be adapted to different workpieces by adjusting only four parameters of the system [19]. Fig. 2 shows the principle of the aerodynamic feeding system, with the workpiece behaving differently depending on the orientation it is entering the orientation module in. The behavior of the workpiece is primarily determined by the setting of the four system parameters α, β, p and v. In order to reduce the retooling effort (finding a suitable combination of the four parameters), Busch enabled the system to set itself to different workpieces without any hardware changes, using a genetic algorithm [19]. The average setting time of the genetic algorithm for different workpieces was less than ten minutes [17].

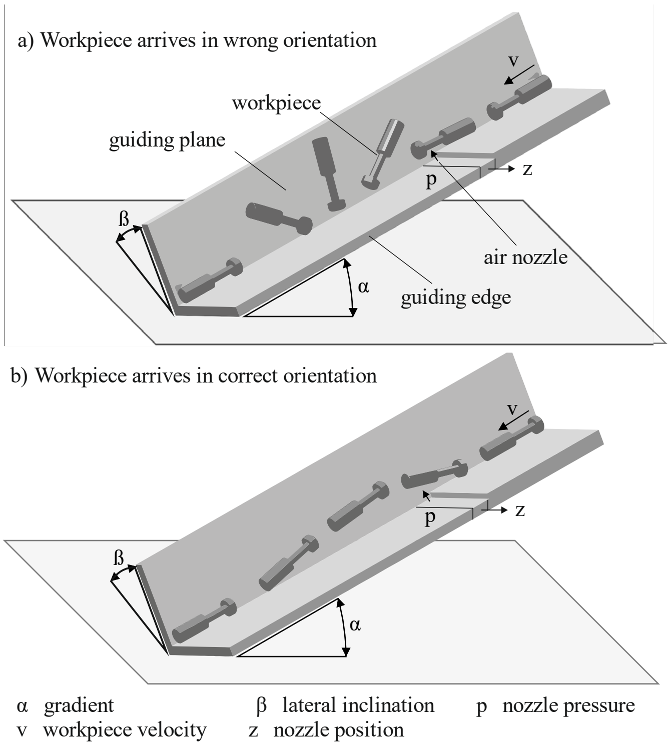

Fig. 2. Principle of aerodynamic feeding using impulse method [2]

In the latest research, Kolditz et al. added a fifth parameter (cf. Fig. 2, parameter z) to the aerodynamic feeding system, in order to increase the flexibility with regard to the workpiece geometry [20]. Despite the larger solution space for the genetic algorithm, the setting time of the genetic algorithm could thereby be reduced, resulting in faster retooling. To further reduce retooling times and make retooling more plannable, Kolditz et al. also extended an existing simulation model (introduced by Busch et al. and based on the work of Rybarczyk [16-17]), which allows to predict start values and to narrow parameter ranges for the genetic algorithm, based on the geometrical data of a workpiece [21].

The development shows the enormous potential of aerodynamic feeding technology for flexible, efficient and reliable feeding. However, in the current state of development, there are still constraints regarding the feedable workpiece spectrum. When using the impulse method, the workpieces must have an eccentric center of gravity along the longitudinal axis of at least 5 % or a varying inflow area. Similar constraints apply to the air cushion method. For a stable process, the workpieces also have to be elongated, meaning the length to diameter ratio should be above two. Regarding the workpiece geometry, the method introduced by Lorenz, shown in Fig. 1, allows for more complex workpiece geometries. Nevertheless, the design of the actuator arrangement is very complicated and specific.

In this work, Lorenz's method is adapted to a new concept for flexible aerodynamic feeding. Exploiting technical advances in the past 20 years, the actuators with continuous airflow are replaced with individually controllable, fast-switching valves and combined with modern image processing for real-time decision-making.

4. A new concept for flexible aerodynamic part feeding

This section introduces the design and operating principle of the new concept for a flexible aerodynamic feeding system. Then, the methods that need to be developed to realize the concept are elucidated.

4.1. Design and operating principle

Fig. 3 shows a simplified representation of the new concept for a flexible aerodynamic part feeding system. The depicted functional model consists of a camera module and an orientation module. The separation of the workpieces from bulk material is not explicitly considered in this work, but can be achieved by simple and flexible systems like centrifugal feeders or hopper feeders. In the camera module, a conveyor accelerates the workpiece to a defined velocity, before a high-speed camera and the corresponding image-processing unit determine the orientation of the workpiece. Determining the workpiece orientation after the acceleration reduces the impact of slip on the conveyour and increases the accuracy of the estimated workpiece position in the following processes. With known orientation and velocity, the workpiece is transferred to the orientation module.

In the orientation module, aerodynamic impulses from different types of nozzles (e.g. punctiform nozzles with different diameters, slit nozzles) are used to manipulate the workpiece. For higher flexibility, the nozzles are designed as interchangeable modules. Contrary to the aerodynamic feeding systems presented in sec. 3, the air flow from the nozzles is not constant. Instead, the nozzles are only activated by fast-switching valves when the workpiece is in the correct position over the nozzle. The position of the workpiece is estimated based on the camera data, the velocity of the conveyor and the

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friction on the orientation module. The renunciation of a constant air jet decreases the consumption of pressurized air and reduces the dependency on specific workpiece properties (e.g. eccentric center of gravity or varying inflow area) as described for the state-of-the-art aerodynamic feeding system described in sec. 3. Using the short, but precise aerodynamic impulses from the nozzles, the workpiece is re-oriented from the initial orientation to the desired orientation at the end of the orientation module in multiple steps. Dependent on the determined initial orientation, different sequences of aerodynamic impulses are activated by the system control.

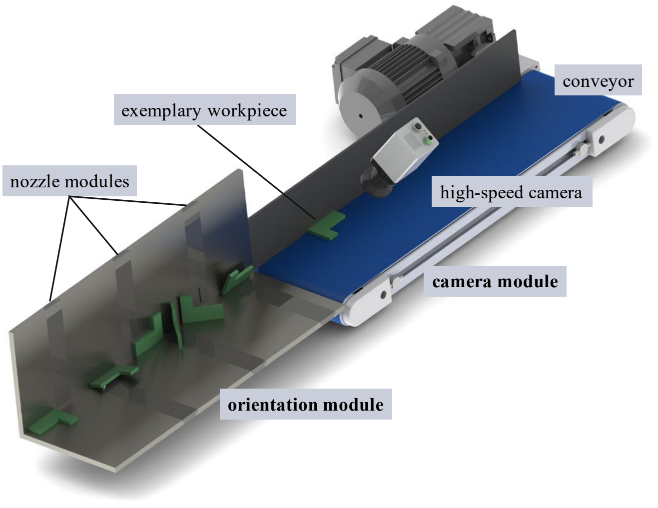

Fig. 3. Concept for a flexible aerodynamic part feeding system

In order to determine the different impulse sequences without disproportionate experimental effort and therefore to minimize the retooling time, a simulation-based method for the prediction of the workpiece behavior in the orientation module has to be developed. The goal is to create a number of predefined sequences entirely offline without any impact on the real feeding system. Those predefined sequences then only have to be executed during the feeding process (online) depending on the initial orientation in which the workpieces are entering the orientation module. The complete process flow is shown in Fig. 4. As aforementioned, the initial orientation is determined in the camera module by a high-speed camera and high-speed image processing. Therefore, the concept for the camera module will be presented first, before elucidating the concept for the aerodynamic orientation module.

4.2. Image processing

The image processing development aims to enable real-time determination of the workpiece poses using a high-speed camera and digital image processing methods. The real-time capability is necessary because the pose identification takes place immediately before the workpiece enters the orientation module. Therefore, the acceptable latency for the pose determination and the consecutive activation of the aerodynamic actuators is very low. In contrast to light barriers or line scan cameras, the use of a high-speed camera offers the advantage of high flexibility with regard to the shape of the workpieces. However, for a classification of different workpiece poses, image processing requires training data (images), which usually has to be recorded at the plant. To avoid the resulting unproductive downtimes, a method that enables the image processing for new workpieces to be trained offline using artificial (synthetic) image data has to be developed.

These images can be generated with modern CAD-Software or specialized rendering software like Blender [22]. With the material properties known, photorealistic images of the workpieces can be rendered. However, an important factor, which must be considered is the domain gap, which arises when the training data (rendered images) and the actual process data (camera images) differ from each other. The domain gap can be reduced by mapping the camera parameters, the camera position, the background and the illumination in the virtual environment according to the real environment (feeding system).

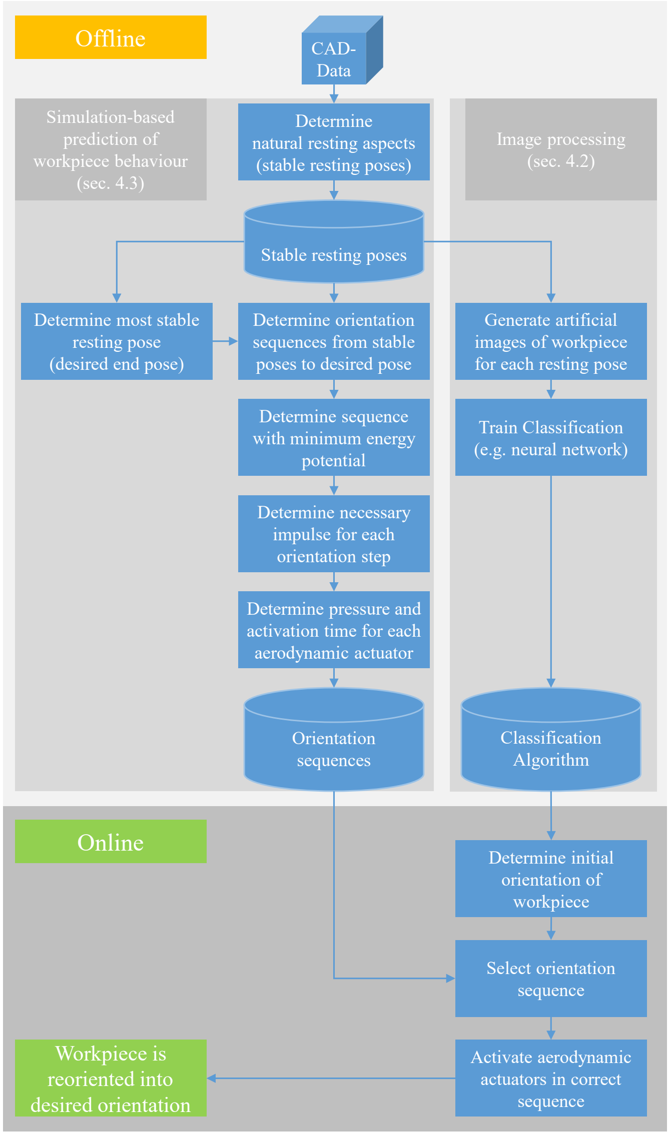

Fig. 4: Process flow of flexible aerodynamic part feeding system

Once the virtual environment has been set up, a classification algorithm compares the artificial images with the images recorded by the camera during operation. It has to be investigated whether artificial neural networks or simpler, deterministic classification algorithms are better suited for this use case. Since the number of possible workpiece poses is limited (cf. sec. 4.3), a continuous 6DoF pose estimation, e.g. by edge detection, is not necessary in this case. Instead, only a discrete number of workpiece orientations needs to be classified. The necessary synthetic image data for this classification is generated and labelled using the virtual environment. To increase the robustness of the classification, the aforementioned parameters like the illumination or the camera position are slightly varied in the virtual environment during the creation of the artificial data set. To evaluate the suitability of synthetic data for training the classification, the reliability of a conventionally trained classifier is compared with that of a classifier trained with synthetic data in experimental trials.

To be able to render the artificial images, the possible, inital poses, in which the workpieces can enter the process have to be known beforehand. Therefore, the determination of the possible initial orientations is one aspect of predicting the workpiece behavior described in sec. 4.3. Furthermore, the workpiece behavior in the orientation module, determined by the aforementioned sequences of aerodynamic manipulations, has to be simulated.

4.3. Simulation-based prediction of workpiece behavior

In order to determine the possible initial orientations and the desired orientation at the end of the process, the stable workpiece orientations (natural resting aspects) are derived from the CAD-Data (e.g. STL-file). The determination of the natural resting aspects of arbitrary geometric bodies without the need for extensive drop tests has been the objective of different research works. Ngoi et al., Lee et al., and Udhayakumar et al. developed and tested a mathematical method to determine the most probable resting aspects of different components [23-25]. This centroid solid angle method showed good results for simple geometries, but requires manual definition of possible resting aspects. Therefore, a modern, open-source physics engine that enables script based simulation of drop tests with arbitrary components, is used. Examples for such physics engines are Blender or Gazebo [26]. Using a python script, the investigated geometry can be placed in the virtual space in any desired position and orientation and then be dropped on a rigid plane. When the object has stopped moving, the final orientation can be determined and saved. This process is repeated several thousand times (script based) in order to emulate a real series of drop tests. The acquired end orientations are then assessed and clustered using MATLAB, in order to determine stable resting poses and the respective probability of occurrence. By default, the pose with the highest probability is selected as desired pose at the end of the orientation process, since it is assumed to be the most stable pose. Of course, other end poses can also be defined, depending on customer requirements. Since the workpiece can enter the orientation process in any of the previously determined stable poses, for each possible entering pose, a sequence of workpiece rotations, which leads to the desired end pose, has to be identified.

Depending on the number of orientations necessary to rotate the workpiece from the initial to the desired pose, there may be multiple possible sequences of workpiece rotations that lead to the desired end orientation. Therefore, each of the possible sequences is analyzed with regard to the energy potentials that have to be overcome for each orientation step. This way, the orientation sequence with the minimum potential energy can be identified and selected for the feeding system in order to reduce the required aerodynamic impulses and therefore reduce the consummation of pressurized air. Furthermore, it is assumed that the sequence, where the lowest energy potential has to be overcome will be the most stable orientation sequence.

After the orientation sequences are determined, the aerodynamic impulses necessary to perform the desired orientation steps have to be calculated. In earlier works, the impulse transferred to different workpieces by an air jet has already been simulated successfully [19, 21]. Based on the velocity of the workpiece and the desired manipulation of the workpiece, the necessary impulse that has to be transferred to the workpiece can be calculated. The impulse generated by the air jet is dependent on the nozzle pressure, the workpiece geometry and the nozzle geometry. For example, more pressurized air flows towards the workpiece with a bigger nozzle diameter, creating more lift at the same nozzle pressure. Therefore, with a given workpiece geometry, the nozzle pressure and geometry can be varied reciprocally to produce the same impulse. This is an important advantage for the optimization of the actuator design and arrangement described in the next section.

4.4. Optimization of actuator design and arrangement

This work aims to create an aerodynamic feeding system that can feed arbitrary workpieces with high flexibility and minimum retooling times. Therefore, the actuators' design and arrangement must be optimised so that a large spectrum of workpieces can be fed without changing any nozzle modules (cf. Fig. 3).

To determine the most effective arrangement of the aerodynamic actuators, an iterative optimization procedure is used. Due to the discrete nature of the optimization problem and the expected high number of constraints, a genetic algorithm offers the highest potential for this procedure. For the optimization procedure, a set of workpieces with versatile geometric properties is defined. Those properties vary with regard to the primary shape (rotational, prismatic), the symmetrical properties and features like chamfers, steps, grooves, bores or imprints, following the system for coding small parts for automatic handling by Boothroyd [27]. This way, the spectrum of workpieces that can be fed with the identified actuator arrangement is as diverse as possible.

The genetic algorithm starts the optimization with an arrangement in which all actuators required to manipulate the predefined workpiece spectrum are arranged one behind the other. This guarantees that all workpieces can be fed, but, in reality, would also lead to an extreme length of the orientation module. Therefore, the genetic algorithm creates new arrangements in each generation, where similar or identical actuators are merged or arranged in parallel. The orientation process is simulated with each workpiece for each arrangement and the results are returned to the genetic algorithm’s fitness function. The target values for the optimization are the shortest possible length of the orientation module and the smallest number of actuators. Of course, a fixed boundary condition for

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each arrangement is that all workpieces from the defined spectrum can be oriented as desired. The abort criteria of the genetic algorithm are met either when the number of actuators reaches the minimum required number of rotations of the workpiece or when the fitness function approaches a limit value so that no further improvement is expected.

Using this approach, an actuator arrangement is identified that enables the feeding system to flexibly reorient workpieces with versatile geometric properties. The described workpiece set for the optimization procedure is selected with the aim to represent the diverse spectrum of workpieces found in the industry. Still, it cannot be guaranteed that the identified arrangement is a generic optimum, suitable for every workpiece. Therefore, repeating the optmization for specific product ranges might be necessary in individual applications.

5. Conclusion and Outlook

In this work, the concept for a flexible aerodynamic part feeding system was presented. The conceptualized feeding system is based on the technology of aerodynamic feeding, which has proven to be a flexible and reliable technology. Using multiple, individually controllable aerodynamic actuators, the feeding system can manipulate various workpieces into a desired orientation. To reduce or completely avoid retooling times, the sequences for the actuator activation are predicted simulation-based without the need to interrupt the feeding process. In addition, the necessary classification algorithm for the image processing is trained using artificial images of the workpieces.

At this time, the new aerodynamic feeding system is in a conceptual state. Therefore, future work will concentrate on developing the necessary algorithms for the image processing, the prediction of the workpiece behavior and the optimization of the actuator design and arrangement as described in sec. 4.2, 4.3 and 4.4. Furthermore, a functional prototype of the feeding system, as seen in Fig. 3, will be built in order to evaluate the developed algorithms and the proposed concept in general.

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