Investigation on the Convergence of the Genetic Algorithm of an Aerodynamic Feeding System Due to the Enlargement of the Solution Space

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Abstract. To meet the demands for flexible assembly technology, an aerodynamic feeding system has been developed. The system autonomously finds the optimal configuration of four parameters – two angles of inclination, nozzle pressure and component speed – using a genetic algorithm, which has been presented in earlier work. To increase the flexibility of the feeding system, an actuator was implemented, that enables the variation of the nozzle position orthogonally to the moving direction of the components. This paper investigates the effects of the more flexible flow against the components on their behavior when passing the nozzle. Additionally, the nozzle position was implemented into the genetic algorithm as a fifth parameter. Therefore, the impact of the enlargement of the solution space of the genetic algorithm due to the implementation of a fifth parameter is investigated in this paper as well.

Keywords: Assembly · Genetic algorithm · Aerodynamic feeding

1 Introduction

The buyer's market is changing, which places new demands on products. These demands include individual design, a high standard of quality and a minimum price. Added to this is the shortening of the product's lifespan [1]. Production must adapt to these demands while the industry is pursuing cost reduction in order to maximize profits. Secondary processes that do not make a direct contribution to assembly must therefore be kept lean, reliable and inexpensive. Apart from organizational and constructive measures, automation is one way to rationalize assembly processes [2].

The costs of an automated production line are largely generated by feeding and transport systems. The actual assembly process is responsible for about 20% of the costs [3]. Feeding plays an important role, as the objects are transported as bulk material for cost reasons. Bulk material is cheaper and easier to handle [4]. For the following process, however, the objects are required in a defined position. For this reason, a targeted orientation from the bulk material must take place so that the next process can be performed [5]. The feeding process can be divided into four subtasks [3].

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- Separation: The objects are sorted from the bulk material.
- Transport: The ordered objects must now be transported to the next process.
- Orientation: After the ordering of the objects, each part has an arbitrary orientation. The orientation process aligns the objects into a defined orientation.
- Positioning: The objects are now designed for the next process so that direct processing is possible.

Often, a vibratory bowl feeder is used to perform these tasks. It has a simple design, can be used for a wide range of geometries and is robust in operation [2, 6]. Objects that are not oriented correctly are returned to the process [7]. The configuration of the vibratory bowl feeder depends on the geometry of the objects and takes place experimentally, which is time intensive [8]. One reason for the high amount of time required is that it is not possible to make general statements about the behavior of objects in a vibratory bowl feeder [9]. Therefore, feeding technology has a high potential for optimization.

To meet the demands for a highly flexible and simultaneously efficient feeding technology, an aerodynamic feeding system has been developed at the Leibniz University of Hanover [10–13]. The system uses a constant air jet to exert a force on the components passing the nozzle. Using a genetic algorithm, the system is designed to parameterize itself for an optimal output rate. The principle of aerodynamic orientation as well as the genetic algorithm will be elucidated in the following.

2 The Aerodynamic Feeding System

Basic Principle. The aerodynamic feeding system presented and used in this work operates with only one air jet, which every component passes. In other work, systems have been presented that use multiple nozzles or air cushions to orient and transport parts [14, 15]. Figure 1 shows the process of aerodynamic orientation in the described feeding system. It becomes clear that the component behaves differently depending on the orientation it has when arriving at the nozzle. If the workpiece arrives in the wrong orientation, it is turned over by the air jet, as can be seen in Fig. 1a), whereas it keeps its orientation, if it already arrives in the correct orientation (Fig. 1b)). The reason for the different behaviors of the component depending on the initial orientation lies in the shape and the mass distribution of the workpiece. The exemplary workpiece in Fig. 1 has a varying projected area against the airflow. Therefore, the wider part of the component experiences a higher drag force than the thinner part, which results in a momentum generating the rotation of the component. In the example, the angle of inclination α promotes clockwise rotation and hinders counterclockwise rotation, resulting in the same output orientation regardless of the input orientation.

Apart from the angle of inclination α, the orientation process is primarily influenced by three additional parameters, seen in Fig. 1:

- Angle of inclination β
- Nozzle pressure p
- Component speed v

The angle β influences the force of gravity acting on the component on the one hand and determines the impact of the friction between the component and the guiding plane. The nozzle pressure p directly affects the magnitude of drag force acting on the workpiece. If it is set too low, the component might not rotate at all, whereas a higher pressure can lead to multiple and unpredictable rotations. Lastly, the component speed v determines, how fast a workpiece passes the air jet and therefore how long it is affected by the drag forces. The parameter can be controlled by adjusting the speed of a conveyor located ahead of the nozzle.

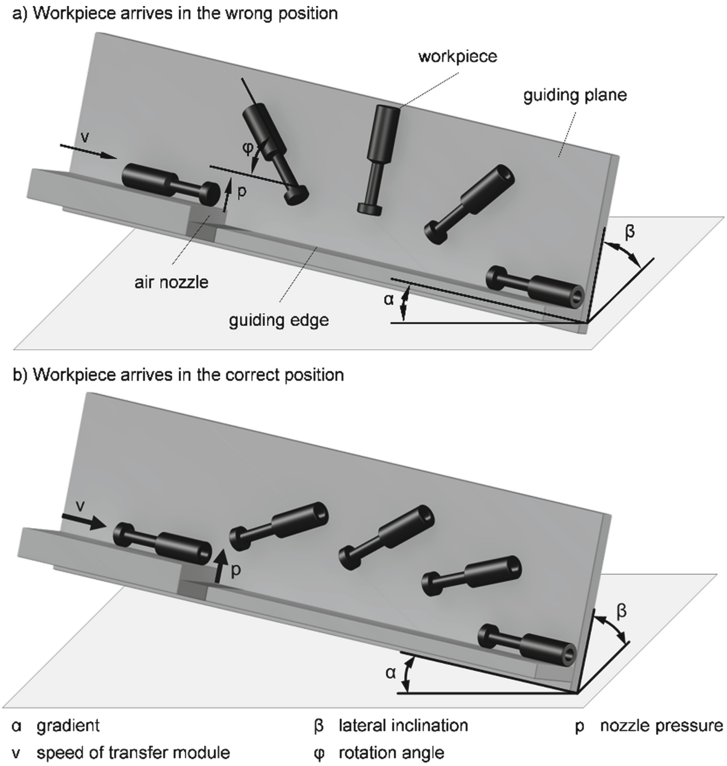

Fig. 1. Illustration of the aerodynamic orientation process [10]

After the orientation process, each component's orientation is determined using a line scan camera. By dividing the number of components in the right orientation by the number of all components measured, an orientation rate between 0 and 100% is calculated. In various experiments, it was shown that the nozzle pressure p has the highest impact on the orientation rate, followed by the interaction between p and v as well as p and β [16]. The identified main effects and interactions are shown in Fig. 2. Even though the effects of parameter changes on the orientation process are known, the parametrization of the feeding system for new components takes a lot of time and expertise with the equipment. To tackle this disadvantage, a genetic algorithm has been implemented in the systems control, which will be presented in the following section.

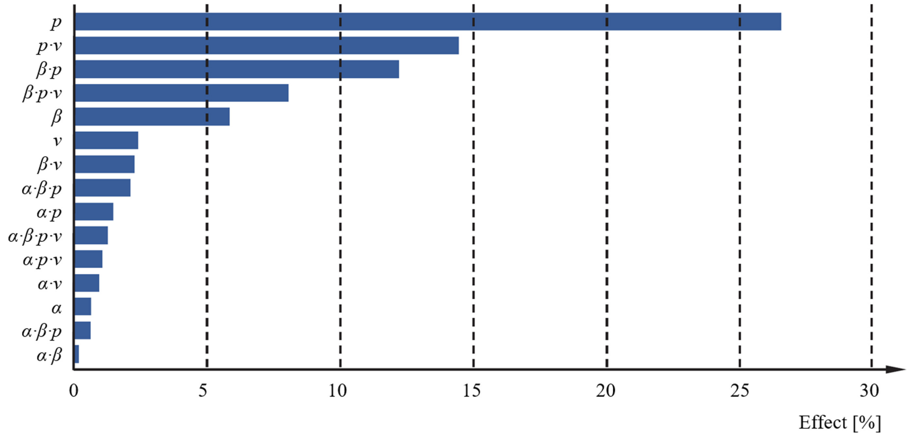

Fig. 2. Values of the main effects and interactions between parameters on the orientation rate [16]

Genetic Algorithm. Finding a set of parameters inducing a satisfactory orientation rate (e.g. >95%) constitutes a non-linear optimization problem. Additionally, the interrelation between input (the parameters) and the output (orientation rate) is not necessarily a continuous function. Therefore, a genetic algorithm (GA) is used as an optimizer [10, 11, 16]. The structure of the genetic algorithm is shown in Fig. 3. One generation contains 4 individuals whose fitness is evaluated by the orientation rate. The parameters of the GA were optimized in previous studies carried out by BUSCH [16]. The best individual is automatically taken over as parent individual in the next generation, the second parent individual is determined by roulette selection. Recombination is done via uniform crossover and the mutation rate is 55%.

With the range and increments of the four "old" parameters, as shown in Table 1, a large solution space with up to 14,214,771 possible configurations is spanned. Nevertheless, the genetic algorithm has proven to be a very effective and time-saving regarding the adjustment of the feeding system to new workpieces [16]. Taking into account the fifth parameter, the solution space would grow to up to 440,657,901 possible configurations. This shows, why it is important to investigate the effect of a fifth parameter to the system and the algorithm on the convergence of the very same.

Table 1. Range and Increments of the aerodynamic feeding systems parameters

Parameter	Minimum value	Maximum value	Increment
α	20°	25°	0.1°
β	39°	50°	0.1°
p	0.1 bar	0.9 bar	0.01 bar
v	50 m/min	80 m/min	1 m/min
z	0 mm	30 mm	1 mm

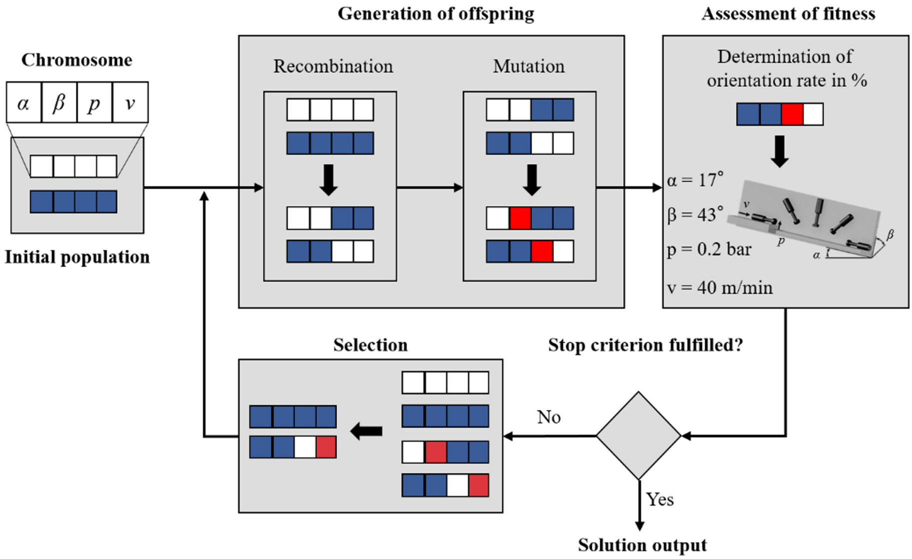

Fig. 3. Structure of the genetic algorithm of the aerodynamic feeding system [10]

3 Implementation of the Nozzle Position as Fifth Parameter

Previously, a fixed nozzle position had to be manually selected for each component, which could be set via a manual positioning table. In the case of rotationally symmetrical components, positioning the center of the nozzle half the diameter of the component away from the guiding plane seems reasonable. This way, the workpiece should receive the maximum amount of drag force, which would lead to a minimal pressure needed. In practice, experiments show that, depending on the dimensions and geometry of the part, a centered air jet can cause an inflow paradox, where the component is aspirated and in consequence slowed down by the air jet. The reason for this lies in Bernoulli's principle, which states that increasing the speed of a flowing fluid is accompanied by a decrease of the pressure [17]. This effect can occur in the gap between the nozzle and the component passing it. Preliminary experiments show, that this effect can be significantly reduced by moving the nozzle orthogonally to the moving direction of the components.

Another problem occurs, when adapting the feeding system to more complex components that have irregular shapes. Manually adjusting the nozzle position can easily become an optimization problem of its own.

In order to expand the spectrum of components the feeding system can handle and reduce the effects of the inflow paradox a linear actor that can vary the position of the nozzle orthogonally to the moving direction of the components was implemented in the feeding system. This parameter, called z, is shown in Fig. 4. The magnitude of z (Table 1) is defined as the distance between the center of the nozzle and the guiding plane.

To automatically control parameter z, a motorized linear positioning table with a preloaded spindle drive was chosen. With this hardware, a positioning accuracy of 0.01 mm can be reached. The stroke is 75 mm. The high precision and stroke are chosen to ensure that the actuator can continue to be used even in future modifications of the feeding system. The position of the nozzle is controlled using an analog output with an output range of 0–10 V DC and a resolution of 16 bit. The trim range of the linear actuator can be specified via setup software. The position of the nozzle can be set either manually by the user or autonomously by the genetic algorithm.

The implementation of the nozzle position into the genetic algorithm was achieved by expanding the chromosomes from four to five alleles. The processes of selection, recombination and mutation also had to be adapted to the extended chromosomes while the principles – e.g. one-point-, two-point- and uniform-crossover – remained unchanged.

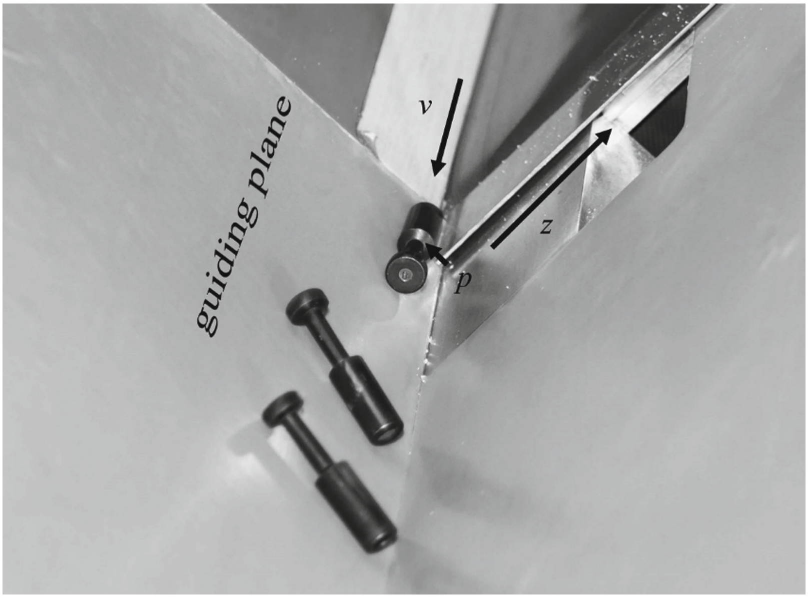

Fig. 4. Orientation process of exemplary workpieces with the parameters v (conveyor), p (nozzle) and z (linear positioning)

4 Effect of the Nozzle Position on the Orientation Process

To assess the effect of the variation of the nozzle position on the orientation process, the behavior of the workpieces at a varying inflow is evaluated. The entire orientation process of one workpiece, from the first contact with the air jet to the impact on the chute, takes about 0.2 s. To allow for the analysis of the orientation process, it is filmed with a frame rate of 240 fps. This way, the behavior of the workpieces can be reviewed properly. In the following, two exemplary components are examined for their behavior under different inflow conditions.

Pneumatic Plug. As first exemplary part, a plug for pneumatic pipes is used. The part can be seen in Fig. 4. The workpiece is well suited for first experiments, as it has a simple geometry due to the rotational symmetry. In addition, due to the strongly varying projected area, it is a component that is generally very well suited for aerodynamic orientation. The measurements of the component are shown in Fig. 5.

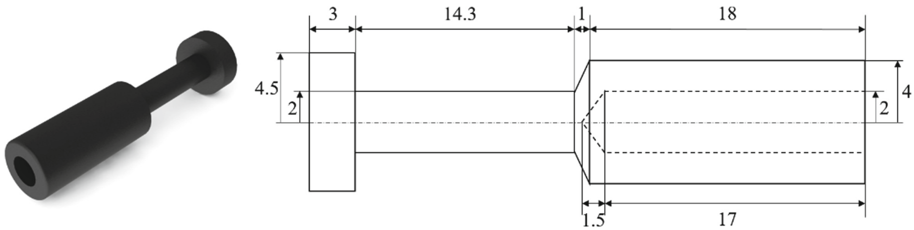

Fig. 5. Measurements of pneumatic plug

Since the nozzle pressure has the strongest influence on the orientation process, to reduce the testing effort, only the parameters p and z are varied. The step size of the pressure p is chosen relatively high, with 0.05 bar to reduce the testing effort. Usually the system controls p with a resolution of 0.01 bar, because the workpieces have a low weight and the orientation process is sensitive to pressure changes. The resulting experimental plan is shown in Table 2. For each measurement, five workpieces were delivered to the nozzle in the wrong orientation and five workpieces were delivered in the right orientation. The orientation process of each workpiece is then evaluated to determine the orientation rate presented in Table 2. Entries with a dash indicate, that no orientation process takes place, which means, that neither the workpieces arriving at the nozzle in the right orientation nor those arriving in the wrong orientation are rotated by the air stream. A value of 0.9 means, for example, that 9 of 10 workpieces leave the orientation process in the right orientation.

Table 2. Orientation rate of pneumatic plug depending on nozzle pressure and nozzle position with $\alpha = 22°$, $\beta = 45\,°$ and $v = 70$ m/min

	0 mm	2 mm	4 mm	6 mm	8 mm	10 mm
0.10 bar	–	–	–	–	–	–
0.15 bar	–	–	0.9	0.8	0.8	–
0.20 bar	–	0.9	0.6	0.5	0.5	–
0.25 bar	–	0.9	0.1	0.5	0.5	–
0.30 bar	–	0.6	0.0	0.2	0.2	0.1

The examination of the results in Table 2 shows that good orientation rates can be achieved even with the nozzle not aligned to the centerline of the workpiece. The variation of the nozzle position allows for high orientation rates even at nozzle pressures that would normally lead to poor orientation rates. This can be seen when comparing the second column of Table 2 (z = 2 mm) to the third column ($z = 4$ mm): While the orientation rate rapidly drops with pressures above 0.15 bar with $z = 4$ mm, a high orientation rate can be achieved at pressures of 0.2 and 0.25 bar, when the nozzle is at $z = 2$ mm. This leads to the conclusion that although the solution space becomes larger due to the addition of a fifth parameter, new parameter combinations with a high orientation rate arise.

In addition to the evaluation of the orientation process via the orientation rate, a qualitative evaluation of the process is also carried out in the following by considering the trajectory of the components. Figure 6 shows the trajectories of four components during the orientation process. They differ by the set of system parameters and the incoming orientation as described in the subframes.

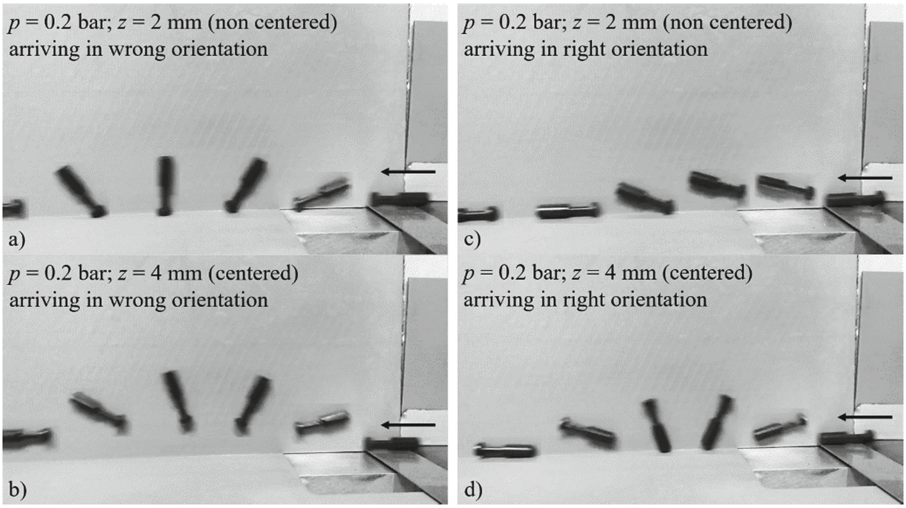

Fig. 6. Trajectories of pneumatic plugs with different parameters p and z

It becomes clear, that the position of the nozzle has decisive influence on the trajectory of the workpieces. The comparison of Fig. 6a) and b) shows that a very stable reorientation of the component can be achieved even with a non-centered nozzle position. The fact that the component in Fig. 6a) does not lift off the chute is to be seen as a major advantage. When the component hits the chute out of flight as seen in Fig. 6b), the impact impulse can lead to uncontrolled jumping of the component on the chute, thus preventing optimal exploitation of the orientation process.

Particularly noteworthy is the stable behavior of those components, which already arrive at the nozzle in the correct orientation. It was observed in all tests, for which Fig. 6c) and d) are exemplary, that the components exhibit a much more predictable and reproducible behavior when the nozzle position is not centered. With a centered nozzle position, a small pressure range must be found in which the incorrectly arriving components are still reoriented but the correctly arriving components are not reoriented yet. With the non-centered nozzle position, on the other hand, the varying projected area of the component against the inflow can be utilized much better. Therefore, a higher range of nozzle pressure can be harnessed, which has a positive effect on the convergence of the genetic algorithm.

Printed Sleeve. In addition to the pneumatic plugs, the effect of a flexible inflow was also investigated on plastic sleeves. The sleeves are rotationally symmetrical parts as well. However, in contrast to the pneumatic plugs, the sleeves have a completely homogenous projected inflow surface. Because of these characteristics and the higher diameter, it was expected that the inflow paradox caused by Bernoulli's principle would have an impact on the orientation process. This assumption was confirmed during the evaluation of the tests. The dimensions of the sleeves are shown in Fig. 7. The sleeves were manufactured using a 3D printer and the eccentricity is 10%.

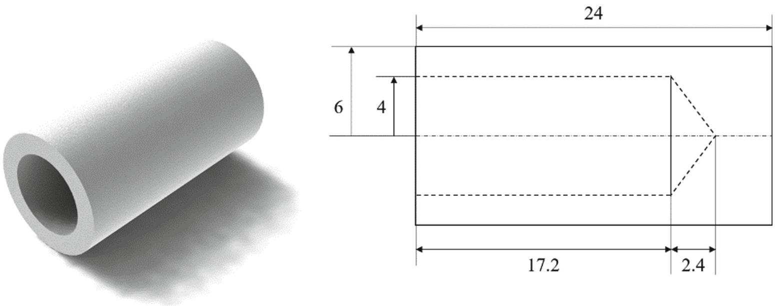

Fig. 7. Measurements of plastic sleeve

The trajectories of the components during the orientation processes with different parameter settings are shown in Fig. 8. To better illustrate the orientation of the cylindrical sleeves, the end with the center of mass has been digitally marked with a + symbol. Considering Fig. 8a), it becomes clear, that a nozzle pressure of 0.2 bar is enough to reorient the plastic sleeve with $z = 2$ mm. Nevertheless, with $z = 6$ mm (centered) no reorientation takes place (Fig. 8b). The different amounts of uplift on the components also becomes clear by comparing Fig. 8c) and d): When the sleeve arrives at the nozzle positioned 2 mm from the guiding plane, it is slightly lifted but does not rotate more than a few degrees. The component arriving with the nozzle centered ($z = 6$ mm) passes about half of its length over the nozzle without getting any lift. This circumstance is attributed to the Bernoulli Effect. When the sleeve passes over the nozzle, it creates a gap between itself and the nozzle carrier. Therefore, the flow path of the air jet is narrowed with results in a higher velocity of the fluid. This, according to Bernoulli's principle, leads to a decrease of pressure between the sleeve and the carrier and results in the part being dragged down.

This is contrasted by the behavior of the component when the nozzle position is not centered. On the one hand, this increases the distance between the nozzle and the workpiece. On the other hand, the air jet does not hit the workpiece inside the narrow gap between workpiece and nozzle carrier, which prevents the acceleration of the air flow and therefore a decrease of pressure.

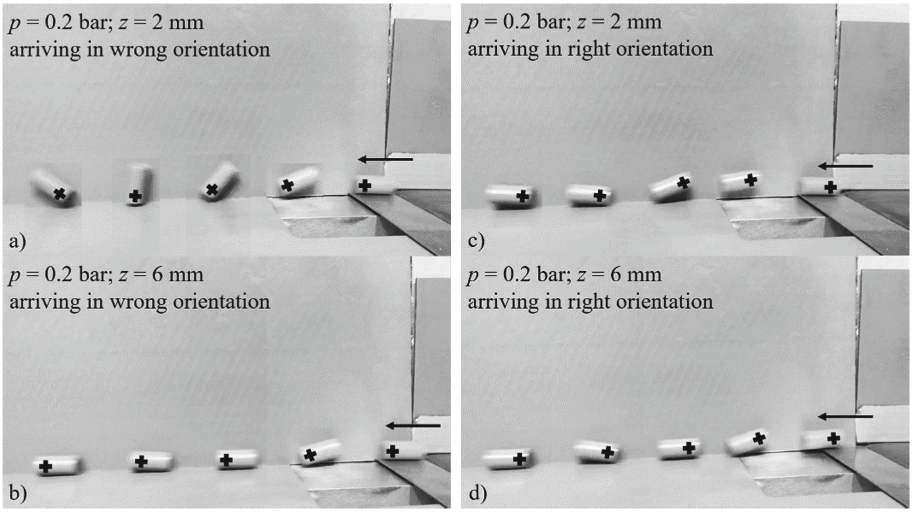

Fig. 8. Trajectories of plastic sleeves with different parameters p and z

Analysis of all trajectories of the experiments with the pneumatic plugs and the plastic sleeves shows the advantages of the variable nozzle position even with geometrically simple components. Essentially, four findings can be derived:

1. Even at higher pressures, the trajectory of the workpiece is lower when the nozzle position is not centered. This is an advantage, because the impulse at the impact on the slide is lower. This in turn leads to less jumping of the components on the slide and thus, finally, to a more stable and reliable feeding process.
2. Components that already arrive at the nozzle in the right orientation are reoriented easily, when the nozzle position is aligned to their centerline. When the nozzle position is not centered, components arriving in the right orientation have a much lower risk of being inadvertently reoriented. The reason for that is, that the varying projected area of the component can be exploited much better, when the core of the air jet is not aligned with the centerline of the component. This way, during the passing of the thicker part, much more momentum is generated than during the passing of the thinner part.
3. With the nozzle position at extreme values ($z = 0$ mm or $z = 10$ mm) very little lift is generated. Therefore, it is concluded that the nozzle bore must be positioned in the range of the measurements of the fed component.
4. The unwanted effect of Bernoulli's principle can be significantly reduced by varying the nozzle position. Reducing this effect leads to a more stable orientation process that can be achieved with lower nozzle pressures.

5 Convergence of the Genetic Algorithm

In order to investigate and evaluate the impact of the fifth parameter on the convergence and setting time of the genetic algorithm, additional trials needed to be carried out. To do so, the genetic algorithm was run five times with and five times without a variable nozzle position. The tests were carried out alternately to compensate for the influence of environmental influences like changes in ambient pressure or non-measurable variables like pollution of the slide by dust or abrasion of the components. To determine the orientation rate of one individual, the orientation of 100 components is measured. With a feeding rate of about 200 parts per minute for the experimental feeding system (limited by the centrifugal feeder) two individuals can be tested per minute. As exemplary component, the pneumatic plug from previous testing was chosen. The range of the parameters α, β and v was chosen according to Table 1. Based on the preliminary tests in Sect. 4 the minimum and maximum values of p were set to 0.1 and 0.3 bar respectively. Also, the range of the nozzle position was set from 1 to 9 mm in accordance with the aforementioned preliminary testing.

Figure 9 shows the distribution of the number of individuals needed by the GA to reach an orientation rate of 95% or higher. It becomes clear, that with a variable nozzle position, the genetic algorithm needs far fewer individuals to find a satisfying solution. The longest setting time with the variable nozzle position is about as long as the shortest setting time with fixed nozzle position. Additionally, the deviation of the maximum and minimum setting time from the average setting time is much smaller with a variable nozzle position.

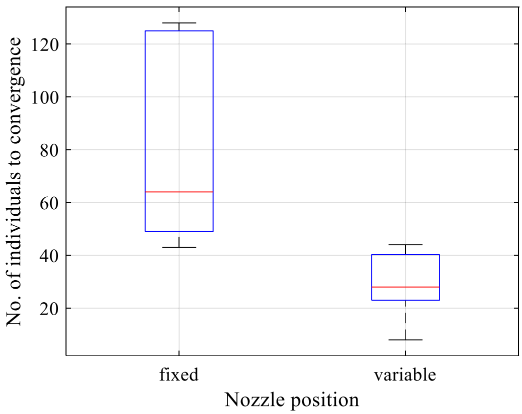

Fig. 9. Distribution of number of individuals needed by the GA to reach an orientation rate of 95% or higher with fixed and variable nozzle position.

The advantages of the variable nozzle position as fifth parameter also become clear when looking at Table 3. The average number of individuals, which correspond directly to the setting time is reduced by 64% with a variable nozzle position compared to a fixed nozzle position. Also, the maximum number of individuals of five runs with variable nozzle position corresponds approximately to a third of the maximum number of individuals of five runs with fixed nozzle position. This is a huge advantage considering that the setting time is directly dependent on the number of individuals and that during the setting process the system is not productive. All in all the experiments clearly show, that adding the fifth setting parameter does not impair the convergence of the GA and therefore the setting time of the feeding system. On the contrary, the average setting time is significantly reduced.

Table 3. Minimum, maximum and average number of individuals to convergence, Standard deviation and average orientation rate (OR)

	Minimum	Maximum	Average	Std. dev.	Av. OR
Fixed	43	128	82	36.6	0.958
Variable	8	44	29.4	12.4	0.970

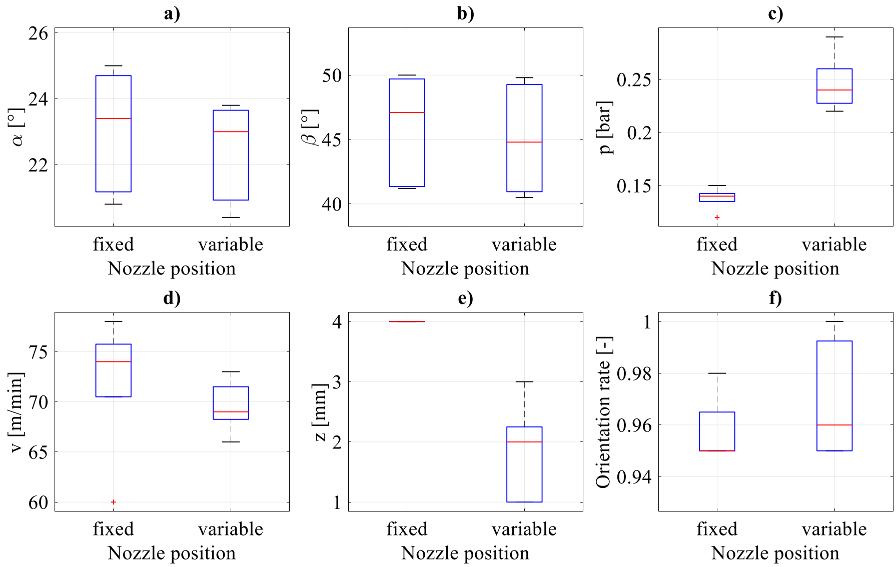

Fig. 10. Distribution of the system parameters in case of convergence for fixed and variable nozzle position.

Figure 10 shows the distribution of the system parameters at the end of each test run, when convergence (orientation rate $\geq 95\%$) was reached. In each plot, the left box shows the distribution for a fixed nozzle position, whereas the right box shows the distribution for a variable nozzle position. While α and β show no significant differences, the nozzle pressure p (Fig. 10c)) is generally higher with a variable nozzle position. At the same time, the range of p is also wider with the variable nozzle position. Considering that for a system configuration with only four parameters, the nozzle pressure p has the highest effect on the orientation rate (c.f. Fig. 2), it is assumed, that the higher acceptable range of the pressure p significantly contributes to the shorter setting time.

Figure 10e) shows that all values for z are between 1 mm and 3 mm with a median of 2 mm. This shows that the fixed nozzle position of 4 mm was not the optimal position and that – using the fifth parameter – the system is now able to determine the optimal nozzle position autonomously, which in turn reduces the setting time. The higher median and range of the orientation rate at convergence (Fig. 10f)) is an indication for a higher process stability that can be achieved with a non-centered nozzle position.

6 Conclusion and Outlook

In this work, the extension of an aerodynamic feeding system was presented. In order to increase the flexibility of the system, the position of the nozzle perpendicular to the direction of movement of the components was introduced as fifth adjustment parameter in addition to two angles, the nozzle pressure and the feeding speed. As a result of the new parameter, the number of possible configurations of the system increased significantly. In order to investigate the effects of the nozzle position on the autonomous adjustment algorithm (GA) of the aerodynamic feeding system, the behaviour of the components in the orientation process was examined in detail. It was found that even with simple components, a flexible inflow can lead to an increased resilience against variation of nozzle and ambient pressure. Since the pressure has been identified as main factor determining the orientation rate, this higher resilience induces an elevated process reliability. In addition, the disturbing influence of Bernoulli's effect could be reduced by means of a displaced inflow.

Subsequently, it was investigated how the setting time of the aerodynamic feeding system changes due to the enlarged solution space of the genetic algorithm. It was found that the adjustment time with a variable nozzle position can be reduced by more than 60% on average compared to a fixed nozzle position, despite the larger solution space. The reason for this is the higher range of possible nozzle pressures, generating a high orientation rate and the higher process stability mentioned above.

Further experiments on the convergence of the GA are to be carried out in future work. The component spectrum and complexity will be varied, expecting to show further advantages of the variable nozzle position. In addition, the analysis of the parameter sets at convergence (Fig. 10) shows that the effects of the parameters on the orientation rate have shifted. For example, the system's sensitivity to pressure changes seems to be lower, while the nozzle position seems to have a high impact on the orientation process. It is therefore necessary to determine the effects of the system parameters on the orientation rate again, using Design of Experiments methods.

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