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Aerodynamic Feeding 4.1: Simulation Based Parameter Selection for a Flexible Part Feeding Prototype

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Abstract

This work develops on the concept for an aerodynamic feeding system with higher flexibility (regarding the workpiece geometry) and drastically reduced retooling times compared to conventional feeding. The proposed design uses multiple, individually controllable air nozzles to re-orient workpieces. However, appropriate nozzle and feeder parameters would need to be selected before a physical prototype can be built. Design of Experiments is used to identify relevant parameters of the feeding process and minimize the number of simulations. Ideally the parameter selection would maintain high flexibility and low retooling times ensuring that aerodynamic part feeding can maintain personalization at minimal costs.

Keywords: "Design of Experiments; Bullet Simulation; Pose Finding Algorithm; Feeding Technology; Aerodynamic Reorientation"

1. Introduction

Modern production systems face numerous challenges, such as rising production costs and shorter product lifecycles. As a result, it is essential to design more automated and flexible manufacturing equipment [1]. Since part feeding systems are a necessary component of manufacturing, they must be adaptable to accommodate a wide range of workpiece components. Conventional systems, such as vibratory feeders or linear oscillating conveyors, lack the necessary flexibility [2]. For example, a vibratory feeder typically uses a spiral track on a vibratory bowl to reorient components. While the material and resource costs for these systems can be relatively low, the overall design of the bowl is time-consuming and expensive [3]. Even when simulations are used to reduce design costs [4] [5],manual retooling is often required when switching between different workpieces, leading to additional expenses.

The challenges of adapting feeding systems to meet the demands of modern production environments have been explored in various contexts. The majority of part feeding systems used for supplying small parts in automated assembly systems are oscillating conveyors, and particularly vibratory bowl feeders [6]. Vibratory bowl feeders have the advantage of a compact design, simple technical construction, and high feeding performance of up to 200 parts per minute [7]. However, their major drawback is low flexibility, as mechanical chicanes and traps need to be individually designed for nearly every workpiece [8]. This customization requires qualified personnel and substantial experimental effort, making design and construction one of the most significant cost factors for vibratory feeders [9]. More flexible alternatives like pick and place systems involving the use of industrial robots and grippers only deliver a much lower throughput of about 60 parts per minute [10].

To address the challenges of flexible and efficient part feeding, the Institute of Assembly Technology and Robotics at Leibniz University Hannover developed the BiBaZu system (an abbreviation for Image-Based Feeding System) [11]. This is the original Aerodynamic Feeding 4.0 and is the work this paper builds on. This system separates parts from bulk material and feeds them individually onto a conveyor belt. This system does not need any mechanical readjustments between parts

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potentially enabling similar throughputs to a vibratory feeder. At this stage, the parts are separated but remain randomly oriented. The task is then to reorient incorrectly oriented parts into the desired feeding orientation. In the BiBaZu system, this reorientation is achieved by applying controlled air blasts using nozzles, which rotate the parts. Depending on the initial orientation, a sequence of air pulses is required to achieve the desired orientation. Determining these sequences is part of ongoing work. For sequence selection, the system first identifies the part's initial orientation, a task performed by a high-speed camera, as illustrated in Figure 1.

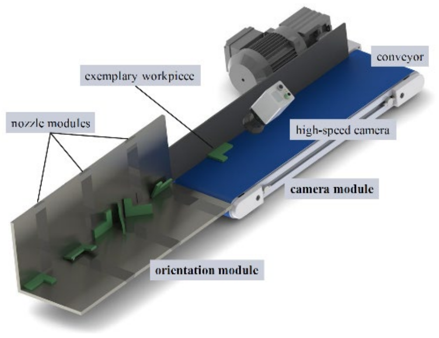

Figure 1: Concept for a flexible Aerodynamic Part Feeding System. A camera detects the initial orientation of the workpiece on a conveyor belt, after which multiple arrays of nozzles within the 'sliding surface' apply pressurized air to reorient the workpiece into its desired final orientation.

After orientation detection, the part exits the conveyor belt onto an inclined 'sliding surface' equipped with nozzles beneath and along its sides. While the part slides down this surface, pressurized air is delivered through the nozzles to generate impulse forces that rotate the component. For complex parts, achieving the desired exit orientation from the initial random orientation may require multiple sequential rotations. These are executed by several nozzle modules placed along the sliding surface.

To prototype this concept, two primary steps were undertaken in this work:

1. **Identifying Natural Resting Orientations:** The first step was to determine the natural resting orientations of sample components. Since a part typically settles into a natural resting orientation after each rotation, these orientations form critical waypoints for the sequence planning algorithm. The algorithm must establish a "roadmap" through these resting orientations to determine the optimal sequence of orientation changes required to reorient the part into the desired final orientation.
2. **Defining Design Parameters for the Sliding Surface:** The second step focuses on defining key design parameters for the sliding surface in the BiBaZu prototype. Parameters such as the chute's inclination, nozzle module spacing, nozzle positioning, and the required impulse force were identified based on previous studies. These parameters are systematically analyzed using Design of Experiments (DoE) methods. Kolditz et al. [12] emphasized the importance of employing DoE to explore the interaction between geometric component properties and physical parameters like nozzle pressure and inclination angle in aerodynamic feeding systems. This systematic DoE approach serves as a baseline for comparison with other optimization methods that may be applied in future work, as it provides a comprehensive "brute force" exploration of parameter combinations.

By following these steps, the BiBaZu system aims to achieve a flexible, adaptable solution for part feeding that can handle diverse components with varying geometric and physical properties.

2. Related Work

The concept of determining natural resting aspects of workpieces is a notable area of research. Boothroyd and Ho [13] introduced a model-based approach using energy barriers to determine the stability of resting aspects for components. Although their work showed promising results for simple components, it lacked scalability for complex geometries. Ngoi et al. [14] introduced the Centroid Solid Angle (CSA) method, which improved upon Boothroyd and Ho's approach by considering the solid angle from the centroid to different component aspects. This method was further refined with the Critical Solid Angle (CRSA) method [15], which introduced a more nuanced probability calculation for components at rest. Chua and Tay [16] proposed the stability method, which factored in both the contact area and the distance of the centroid from the resting surface to evaluate stability. Numerical simulations were also introduced to model component behavior during drop tests, offering an adaptable approach to analyze natural resting aspects [17] [18]. Kolditz et al. [19] expanded on this concept by using a physics engine (Bullet) to simulate drop tests of arbitrary components, which were then validated with experimental results. This combined simulation and experimental approach provided a more accurate understanding of workpiece behavior under diverse conditions, particularly in determining natural resting aspects. However, their analysis assumed two key simplifications: an initial working speed of zero and a horizontal plane for the simulations.

In contrast, the design presented in Figure 1 introduces additional complexities. The component falls onto a V-shaped angled sliding profile that is inclined relative to the horizontal plane, where it slides toward the bottom. It also possesses an initial velocity imparted by the conveyor belt. These factors - inclination and continuous movement - affect the component's motion dynamics and stable orientations, necessitating a more nuanced analysis. By incorporating these factors into a similar simulation environment, this work seeks to extend and refine the foundational insights from Kolditz et al. [19], ensuring the reorientation process is effective under practical operating conditions.

3. Simulation Model Design

Building on Kolditz et al.'s [19] findings, the BiBaZu system's workpiece pose determination simulations were implemented using the PyBullet Application Programming Interface (API) in Python. PyBullet is a fast and highly configurable open-source physics simulator, making it an ideal choice for large-scale simulations where computational efficiency is critical. Compared to more accurate but computationally intensive FEM-based simulators like Abaqus FEA, PyBullet offers a significant advantage in speed. The BiBaZu simulation model in Bullet incorporates numerous parameters, with some predefined based on earlier work and others treated as variables to be optimized through DoE

3.1 Variable Model Parameters

The BiBaZu design features a V-shaped slide inclined relative to the horizontal plane (see Figure 3). The key variable parameters for this model include:

- **Inclination angles:**
  - α : Inclination around the x-axis.
  - β: Inclination around the y-axis.
- **Nozzle offset**:
  - x_n: Lateral offset of the nozzle from the slide seam in the x-direction in $(CS)_S$.
  - $y_{wp,n}$: Vertical offset between the nozzle and the workpiece at the moment the impulse is applied
- **Impulse force:**
  - p_z: Strength of the applied impulse.
- **Feed speed:**
  - $v_{z,0}$: Initial speed of the conveyor belt.

The sliding surface is defined relative to a coordinate system aligned with the world coordinate system. The inclination angles α and β determine the rotation of the slide's coordinate system, as shown in Figure 2.

3.2 Static Model Parameters

All other parameters in the BiBaZu simulation were defined as static. These include:

- **Surface friction coefficients:**
  - $\mu_S = 0.05$: Sliding surface friction (the slide is PTFE-coated)
  - $\mu_{WP} = 0.5$: Workpiece surface friction. Parts are made of high-resolution resin.
- **Slide geometry**
  - $l_S = 10$ m: The slide consists of two intersecting planes forming a V-shape. Each plane is 10 meters long, ensuring the component reaches a stable orientation by the slide's end

3.3 Components

The workpieces modeled in the simulations are based on five representative components from Kolditz et al.'s experiments [24]. These components (Figure 2) offer simple geometries with flat faces, resulting in a discrete number of stable orientations. Their simple design facilitates easy fabrication, reproducibility and experimental validation.

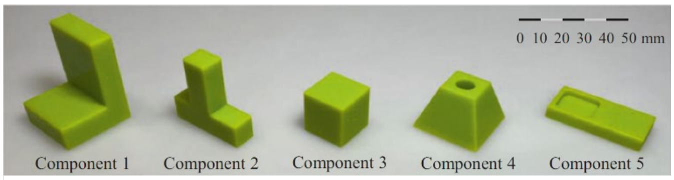

Figure 2: Representative 3D-printed workpieces used in [19]

3.4 Simulation Procedure

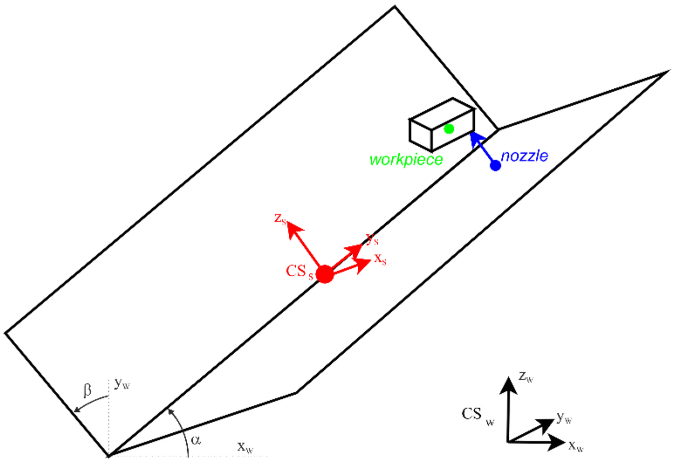

Figure 3: The surface is bound to a co-ordinate system relative to the world co-ordinate system. The angles alpha and beta influence the rotation of the surface co-ordinate system. The workpiece (*wp*) and nozzle (*n*) components are initialized relative to the surface (*S*) co-ordinate system.

Each simulation begins by loading the BiBaZu model into the Bullet physics engine. A component is spawned at the top of the slide in a random orientation at a fixed position x_{WP}, accelerated to the specified feed speed $v_{z,0}$, and dropped onto the slide. The component stabilizes into a stable orientation based on the slide's inclination, feed speed, and its initial orientation.

Once stabilized, the component reaches the nozzle, where an impulse force (p_y) is applied perpendicular to the slide surface. The effectiveness of the impulse depends on the nozzle's lateral x_n and vertical $y_{wp,n}$ offsets and the impulse's strength. Depending on those factors, the component may rotate, lift, undergo multiple uncontrolled rotations, or not be affected at all.

The simulation records the timestep and orientation when the impulse is applied. It also records the component's angular velocity until it stabilizes into a final resting orientation, at which point the final timestep and orientation are saved. This process is repeated for various parameter combinations with 100 random initial orientations each, enabling a comprehensive analysis of the interactions between slide inclination, feed speed, and nozzle settings and the reorientation rate.

4. Design of Experiments

DoE is a method that can be used to determine a suitable range of parameters with the application of repeated experiments. In this paper, a full factoral analysis is performed as there are too many unknowns in the interaction between the workpieces and the surface to eliminate some of the parameter range. This means all possible parameter combinations were simulated. 100 simulations were performed for each parameter combination to ensure the results are repeatable. The generation of each experiment was parallelized using the multiprocessing package in python to minimize time taken as in total 576,000 parameter combinations are possible.

Parameters used in the DoE analysis

α	Gradient angle of the sliding surface
β	Inclination angle of the sliding surface
p_z	Force of the expelled air from the nozzle
$v_{z,0}$	The velocity that the workpiece is fed into the slide at the beginning of the simulation
x_n	The position of the nozzle on the surface in the x axis
$y_{wp,n}$	The displacement between the nozzle and the workpiece at time of actuation in the z axis

Table 1: The table below outlines the range of these key design parameters selected as well as the reasoning behind the upper and lower bounds selected.

Parameter	Range	Step	Reasoning
α	5-85 °	5°	The lowest angle that allows the workpiece to slide past the nozzle. The highest angle where the workpieces are still in contact with the surface.
β	5-45 °	5°	the smallest angle that ensures that the workpiece can slide down to the seam of the slide after feeding. The largest tilt that allows for the workpiece to rest on the same plane of the surface slide as the nozzle.
p_z	0-4 N	1 Ns	No nozzle force impulse to the highest force applied on the workpiece when the other parameters are at the nozzle, where the workpiece remains on the slide after actuation.
$v_{z,0}$	0-4 ms^{-1}	$1ms^{-1}$	No feeding velocity to an input velocity value which is comparable to the feeding velocity of a vibratory bowl feeder.
x_n	0-0.05 m	0.005 m	The nozzle position ranges from the seam of the slide to being offset by the longest diagonal length out of all of the tested workpieces. Beyond this value the nozzle will be unable to actuate the settled workpieces.
$y_{wp,n,k}$	0-0.025 m	0.005 m	The point where the force is applied ranges from the geometric center of the workpiece to the longest diagonal length of all of the example workpieces.

For the simulations to be meaningful in the DoE and the workpiece pose finding framework, clear and measurable outcomes are required. The raw outputs from the simulations are then converted in python into these measurable outcomes. The first measurable outcome is the number of simulations where the workpiece is 'successfully' reoriented, which means three key criteria are met:

- **New Orientation:** The workpiece must achieve a sufficiently different orientation compared to its pre-impulse state. Based on the design of the selected components, all stable orientations differ in at least one axis by more than 45°. Therefore, the criterion is satisfied if the pre-impulse orientation and the final orientation differ by at least 45° in one axis.
- **Settled State:** After reorientation, the workpiece must reach a stable state with minimal angular velocity. Specifically, the maximum angular velocity in any axis must be below a threshold of $\max(\omega^{wp}) < 0.01\ rad/s$. This threshold accounts for numerical effects in the simulation, which prevent the velocity from reaching exactly zero.
- **Remaining on the Slide:** The workpiece must stay on or above the slide throughout the simulation. Certain parameter combinations, such as high inclination angles combined with high impulse forces, may cause the workpiece to fly off the slide, which constitutes a failure.

These qualitative criteria are converted into two quantitative metrices to facilitate analysis:

Successful Reorientation Rate (SRR): This metric represents the proportion of simulations that meet all three success criteria. It is calculated as the number of successful simulations divided by the total number of simulations. While the SRR does not directly assess whether the achieved reorientation matches the desired orientation, it provides insight into whether a rotation is possible under the given parameter combination. This metric is particularly useful for identifying parameter ranges that enable reorientation, forming the basis for further optimization.

Settling Distance: The second key metric is the Settling Distance, which is calculated as the total displacement of the workpiece along the slide, from the point where the impulse is applied to the point where it reaches a settled state. This value accounts for the effects of the applied impulse (p_z), as well as the dynamics of the system, including the slide's inclination angles (α,β), friction coefficients (μ_s/μ_{WP}), and initial feed speed ($v_{z,0}$).

5. Evaluation of Results

To parse out the individual effects of the key slide parameters on the Successful Reorientation Rate (SRR) and the Settling Distance main effect plots (Figure 4 and Figure 5) were created for all of the workpieces and for their average.

5.1. Successful Reorientation Rate

The simulations indicate that the geometric slide parameters, such as inclination and nozzle position, have minimal impact on the Success Rate of Reorientation (SRR). As long as these geometric parameters fall within a specific range, the SRR remains relatively stable. A similar observation applies to the feed speed ($v_{z,0}$);

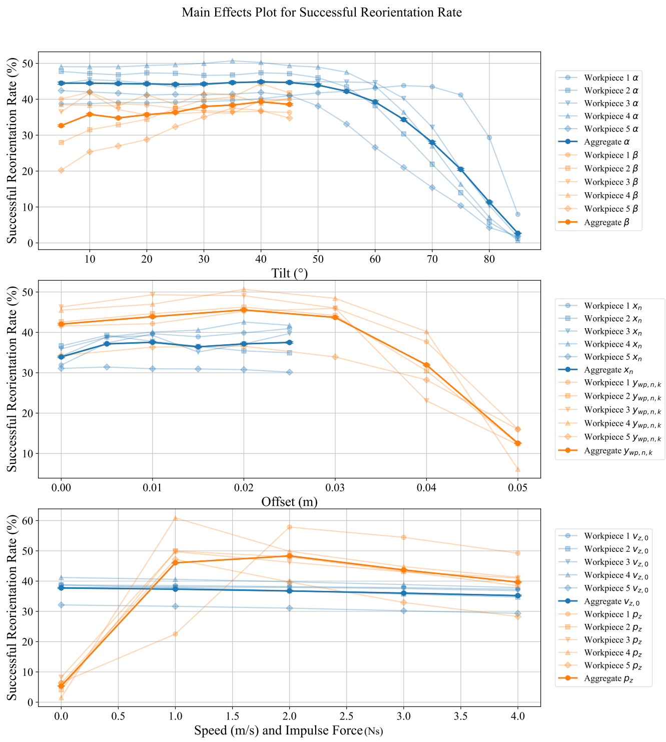

Figure 4: The mean Successful Reorientation Rate is found for a range of input parameters and is plot on a set of three axes, where parameters of similar scale are plot in a smaller subplot. This main effects plot aims to demonstrate the individual effects of the parameters on the Successful Reorientation Rate.

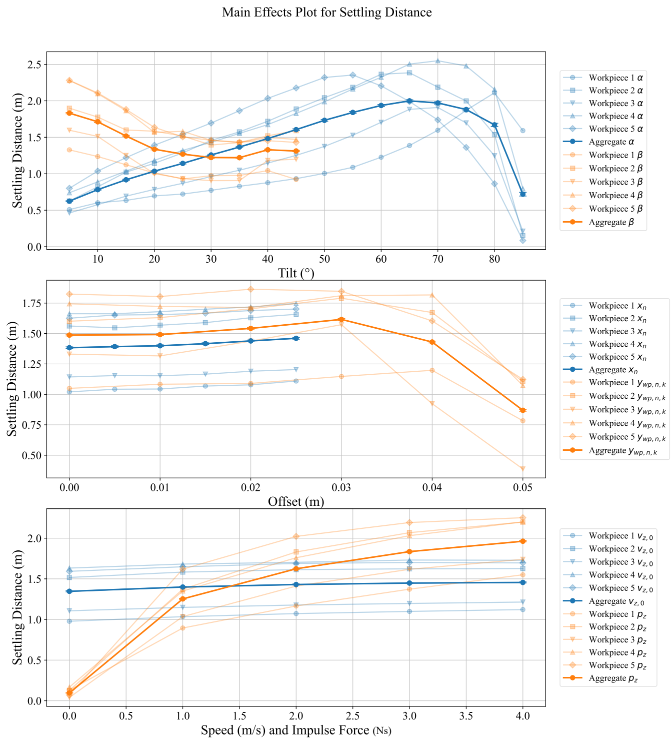

Figure 5: The average workpiece settling distance for re-oriented components was analysed individually for each component.

variations in this parameter do not significantly affect the SRR. Even the nozzle force impulse (p_z) has little effect on the BiBaZu system's ability to reorient parts, provided that the force is sufficient to induce rotation. The most notable differences in SRR occur between different workpieces. Regularly shaped workpieces, such as cubes, tend to achieve higher SRR with this nozzle and chute design, suggesting they are better suited for this system. Overall, the results are highly promising for the BiBaZu concept, as the system demonstrates stability across most parameters. This without needing to adjust parameters such as inclination or nozzle spacing for different workpieces. suggests that on order to cause a desired rotation it may be sufficient to activate the appropriate nozzles at the correct time, without needing to adjust parameters such as inclination or nozzle spacing for different workpieces.

5.2. Workpiece Settling Distance

The same general trends observed in the SRR are also evident in the Settling Distance. However, there is less variability in Settling Distance across different workpieces compared to SRR. Parameters that increase workpiece speed, such as α, $v_{z,0}$, and p_z, tend to result in larger Settling Distances. To minimize Settling Distance for a more compact slide design, these parameters should be kept as low as possible without negatively affecting the SRR.

6. Proposed Prototype Parameter Ranges

Both the SRR and Settling Distance are highly dependent on the interplay between parameters such as nozzle force, alpha, beta, and nozzle position as well as the workpiece geometry selected. This means that the prototype needs to be adjustable to at least cover the range of parameters outlined below:

- α : A range of 15° to 30° is suggested for alpha. This range balances effective reorientation and sliding behavior while preventing extreme tilting that could lead to instability or improper reorientation.
- β: The beta angle should be in the range of 10° to 25°. This range has shown to produce effective workpiece reorientation, providing enough force to keep workpieces moving while maintaining stability.
- p_z : The optimal range for nozzle impulse force is 3 Nms to 5 Nms. Increasing the force beyond 3 Ns improves reorientation, while forces beyond 5 Ns may cause undesired acceleration and inconsistency.
- $v_{z,0}$: The feed speed should be set between 1 to 2 ms^{-1}. This speed ensures higher re-orientation rates and a high throughput to compete with a vibratory feeder.
- x_n: The recommended hitpoint offset is 0.015 to 0.03 m. This range provides precise interaction with the workpiece, optimizing the timing of impulse application for effective reorientation.
- $z_{wp,n,k}$: The nozzle should be placed between 0.01 to 0.04 m along the x-axis. This range ensures effective interaction with the workpiece. This can be done in the form of a nozzle array with these nozzle positions.

7. Conclusion and Future Work

In this study, a flexible feeding system was proposed and analyzed using a combination of a workpiece pose determining simulation and the Design of Experiments (DoE) analysis. The surface and nozzle design parameters were systematically evaluated to select a range of parameters that ensures a sufficient rate of successful reorientations. Suggested ranges for each parameter were provided to assist in the development of a prototype system. Some parameters such as speed were observed not to have a strong influence on reorientation rate which means that selecting certain parts can be based on availability and price rather than maximizing for performance.

While the DoE approach has proven useful in identifying influential parameters, limitations were observed in the variability of the results. The current analysis highlighted that the DoE framework alone might not be sufficient to fully capture the nonlinear interactions and complex dynamics involved in this feeding system. Therefore, future work should focus on employing more sophisticated methods of analysis, such as optimization techniques or statistical techniques such as a sensitivity analysis to better model and predict the interactions between parameters. This will enable more precise tuning of the system, leading to improved efficiency and adaptability of the feeding process.

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