

Breaking the Pneumatic Barrier: Mechanically Actuated 2D Grids for High-Throughput, Energy-Efficient Sensor-based Sorting

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Introduction

In sensor-based sorting, separation is typically achieved by bursts of compressed air that deflect identified particles from the main trajectory. This pneumatic ejection principle has dominated the field for over 30 years (Robben & Wotruba, 2019) with only incremental improvements to design and control. Despite its commercial success, largely due to its ability to achieve adequate sorting accuracy at economical mass throughput, pneumatic separation suffers from fundamental drawbacks in achievable accuracy and operating cost.

The primary limitations of pneumatic sorters stem from their limited temporal and spatial resolution and their high energy consumption. The diffuse and expanding air cones lead to inaccuracies in particle separation, particularly in high mass flow scenarios, resulting in a risk of a large number of accidentally ejected particles (Bauer et al., 2022). Moreover, compressed air generation and distribution account for up to 70% of the sorter's operating costs (Gülcan & Gülsoy, 2018), while ultimately only about one percent of the primary energy is used to alter the particle trajectories (Robben & Wotruba, 2019). These constraints hinder the economic use of sensor-based sorting in new or cost-sensitive markets and threaten the profitability of existing operations in sectors under severe economic pressure, such as recycling.

To address these challenges, we propose a new design of sensor-based sorters that introduces two major novelties:

- (i) the use of a *two-dimensional* grid of actuators for particle ejection, and
- (ii) the replacement of compressed air with *mechanical impact-based* actuators.

In combination, these novelties enhance sorting resolution, flexibility, and energy efficiency, providing a path toward a new generation of high-throughput optical sorting systems.

Our architecture replaces the conventional design consisting of a single line of nozzles spanning the width of the particle stream with a two-dimensional grid of actuators, arranged in multiple, slightly offset rows. Unlike conventional sorters that can eject a particle only at one fixed position and time, the grid architecture allows for choosing the *best-suited* actuator from one of the multiple rows, based on both its spatial location along the sorter width and the expected particle arrival time. Therefore, this geometric configuration significantly increases both spatial resolution and temporal sampling frequency.

Moreover, the two-dimensional layout introduces a new degree of freedom: multiple actuators can potentially eject the same particle. This redundancy in particle–actuator assignment enables optimization of separation accuracy. A

combined particle-tracking and control system can therefore decide which actuators to activate in order *to achieve the best possible separation result*, i.e., to eject as many undesired particles and as few desired particles as possible based on the predicted trajectories of all particles within the separation zone.

The second novelty is the replacement of compressed-air bursts with mechanical impact-based actuators. These actuators are mounted on a chute and deliver short, high-energy mechanical impulses to deflect targeted particles from their trajectories. This substitution fundamentally improves the system's energy efficiency by eliminating the need for compressed air, thereby reducing overall energy consumption by approximately an order of magnitude.

While the use of mechanical actuators in particle separation is not entirely new (Knapp et al., 2014; Robben & Wotruba, 2019; Veras et al., 2020; Wotruba & Robben, 2020), their integration into a two-dimensional grid architecture introduces several synergistic advantages: Although individual actuators are typically larger than air nozzles, resulting in a coarser inherent spatial resolution, the grid configuration effectively compensates for this limitation. Since mechanical actuators produce sharply bounded impact zones, the overall spatial resolution of the resulting system can even exceed that of conventional pneumatic sorters. Additionally, the grid compensates for the time span required between two consecutive activations during which the actuator is not able to eject a particle. We show that the activation time, i.e., the delay between the control signal and the particle impact, and the retraction time, i.e., the duration during which the actuator continues to influence particles after impact, are comparable to those of pneumatic nozzles. Therefore, the system is capable of handling mass flows equivalent to those of state-of-the-art pneumatic sorting systems.

Methods

The use of a two-dimensional grid transforms the separation task into a real-time control problem. For each identified particle, the system must determine

not only when to activate an actuator but also which actuator to use among several candidates that can influence the particle's path.

Therefore, the main contribution of this paper is a simple yet effective control strategy for control of the sorting system that is able to run at 100 fps. The approach is based on a powerful heuristic that generates candidate solutions, i.e., particle-actuator assignments based on the predicted particle trajectories from a multitarget tracker following *the predictive tracking* paradigm (Maier et al., 2021; Pfaff, 2019; Pfaff et al., 2015). These candidate solutions are then validated based on their expected separation success by leveraging an internal model of the sorting system. The most favorable solution is subsequently applied to the sorter.

Experimental Evaluation

We validated the proposed design using a prototype sorter (see Fig. 1) in a real-world separation scenario. Despite being an early-stage prototype, the system demonstrated a sorting accuracy of up to 92% at a throughput comparable to industrial pneumatic sorters, while operating at a fraction of the energy cost.

A [video](#) attached to the paper illustrates the prototype's operation. The results highlight the potential of the proposed concept to redefine the efficiency and precision of sensor-based sorting systems.

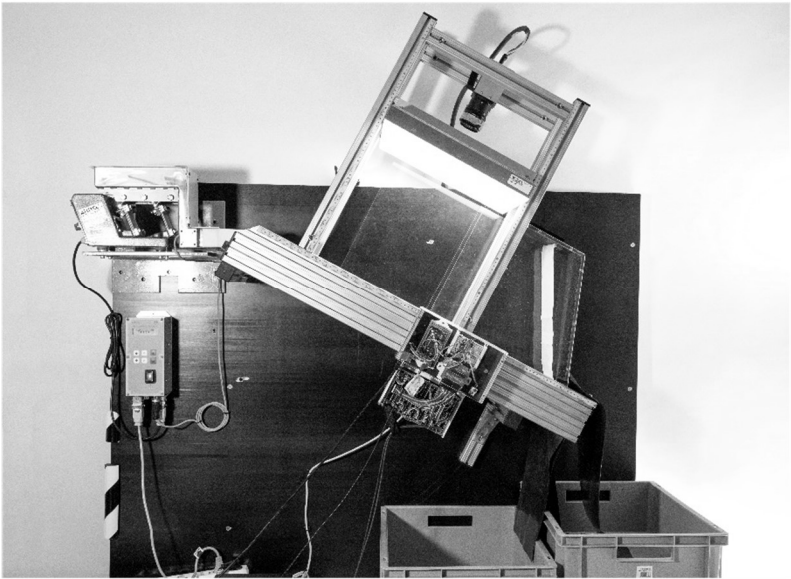


Fig. 1: Prototype of the presented sorting system. Particles are transported via a chute to a separation zone consisting of a two-dimensional grid of mechanical actuators (occluded) while being tracked using images from an area-scan camera. Particles of undesired classes are shot out by momentum exchange when hit by an actuator.

Discussion and Outlook

The proposed design opens new opportunities for deploying sensor-based sorting in markets where energy and cost constraints have so far limited adoption. Future work will focus on scaling the grid architecture, advancing the hardware toward market readiness, and integrating advanced learning-based control algorithms. The presented concept demonstrates that significant innovation remains possible in a field that has been technologically stagnant for decades.

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