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DEVELOPMENT OF AN AUTOMATIC CONTROL SYSTEM FOR PACKAGING OF MUNG BEAN

Djurayev Sherzod. S [1],
Fayzullayev Lutfiddin.F [2]
[1] Namangan State Technical University, Namangan, Uzbekistan
[2] Namangan State Technical University, Namangan, Uzbekistan;
f.lutfiddin.98@gmanil.com
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Among legumes, mung bean (Vigna radiata L.) has become a strategic export product for Uzbekistan. According to the Statistics Agency, in the first eight months of 2022, 59.0 thousand tons of mung bean (45 million USD) were exported to 23 countries, of which 47.9 thousand tons were to China [1]. In January-November 2024, the export volume reached 106.6 thousand tons, worth 85.5 million USD [2], and in the first half of 2025, 32.86 thousand tons of mung bean were sold for 30.0 million USD (average price 0.91 USD/kg) [3]. According to a report by the US Department of Agriculture, Uzbekistan is the second largest supplier of mung bean imports to China after Myanmar (121.4 thousand tons in the 2023/24 marketing year) [4].

To meet these requirements, the manufacturer sets the target mass above the nominal. As a result, there is a "give away" in each package: just 3–5 g of excess mass in a 1 kg package means giving away dozens of tons of product for free on one line per year. The main factor limiting the accuracy of gravimetric feeders is the uncertainty in the moment of cut (stopping the feeder). At the time of the cut command, the grain column in the air between the feeder and the weighing hopper, the inertia of the feeder and the delay of the measuring filter cause additional mass to fall into the hopper. In industrial controllers, this mass is compensated by a constant quantity called “preact” or “mass in the air” and is corrected on average for the error of the last few cycles.

The strain gauge–hopper system is a low-damping second-order dynamic system whose output signal is corrupted by vibrations and impact noise. Niedźwiecki et al. improved dynamic weighing based on identification by adaptive pre-filtering of periodic and low-frequency disturbances in conveyor checkweighers. Richiedei [5] proposed adaptive “shaper” filters that compensate for the low-damping poles of the strain gauge, dramatically reducing the settling time. Liu et al. [6] combined wavelet-based noise reduction and metaheuristic-based adaptive identification. In a recent work, Wang et al. [7] achieved measurement in ≈ 38 ms per vial by isolating the effect of airflow in a high-speed filling line and damping the vibration based on Allan dispersion.

The control of the cut-off point in batch weighing is a classic problem, and Nagao [8] proposed a dynamic programming algorithm to reduce the weighing time for an automatic bag-filling scale. An et al. [9] tuned the controller parameters in a steel melting furnace weighing process in a two-level data-driven manner from cycle to cycle. The most recent work for grain agricultural products is by Wang et al. [9]: they achieved an error of up to 0.2% for 600 g of beans using variable-volume weighing containers and iterative learning. Terneus et al. [10] reported an accuracy of ±5 g at 100 g with cascade PI control in a screw feeder.

Therefore, **the creation of a multi-contour system that would control the trade-off between accuracy, speed and excess mass according to a single economic criterion through physically based models and rigorously proven algorithms** is an urgent scientific and technical issue.

According to (6) for h= 0.30 m, v_0= 0.10 m/s, v_t= 5.0 m/s, the fall time t_f= 0.2422 s, the impact velocity v_{imp}= 2.292 m/s. If air resistance is not taken into account, these quantities would be 0.2373 s and 2.428 m/s, respectively. Thus, the quadratic resistance increases the fall time by 2.1% and

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reduces the impact velocity by 5.6%. According to (12) $\delta = 0.0016$ s. This result shows that the impact force for the mash grain almost completely compensates for the air column.

Table 1 presents the results of 8 Monte Carlo experiments in which the regulators were tuned according to the nominal model and the object parameters were randomly varied.

Table 1.
Robustness under parametric uncertainty

Indicator	S2 (industry)	S5 (AKKB-O)
σ_M, g	1.56 ± 0.09	2.09 ± 0.15
Excess mass G, g	4.90 ± 0.05	4.54 ± 0.32
Productivity, pcs/min	10.49 ± 0.24	15.14 ± 0.16
The worst σ_M, g	1.67	2.22
The largest G, g	4.96	4.87

(8 Monte Carlo experiments, 150 cycles each; mean ± standard deviation)

In all experiments, the productivity of the S5 strategy was higher than that of the S2 (average 15.14 and 10.49 pieces/min). The average excess mass was 4.54 g for S5 and 4.90 g for S2. The uncertainty of the parameters affects the accuracy of the S5 more, since λthe errors in the upstream and transition process have a greater weight. However, the NLMS adaptation and the risk-based target ensured that the metrological requirements were met.

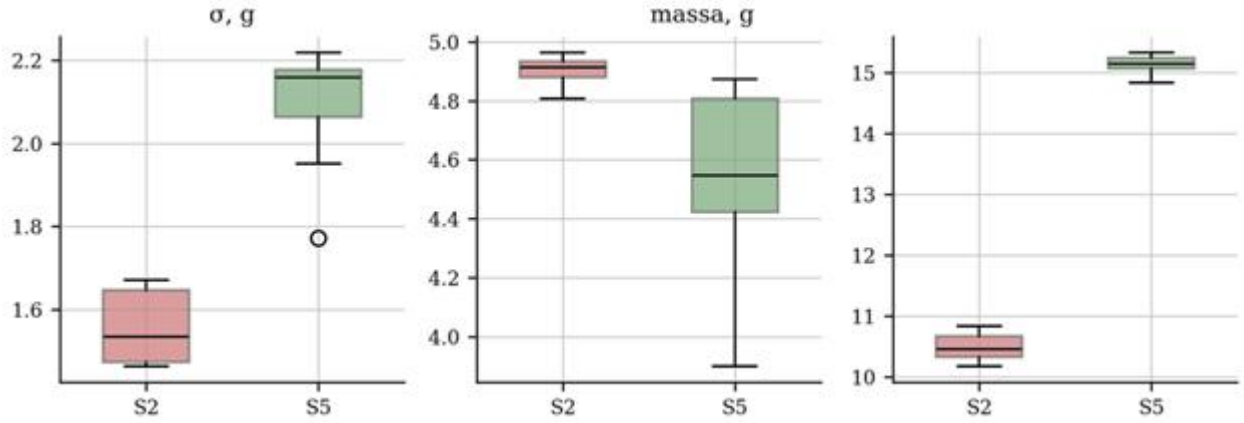


Figure 1. Performance of strategies S2 and S5 in Monte Carlo experiments.

Table 2.
Annual economic indicators for one line

Strategy	N, pcs/min	Annual volume, million units	G, g/piece	Excess mass, t/year	Excess mass value, million soums/year
S1	10.88	3.13	4.31	13.5	144.7
S2	10.84	3.12	4.96	15.5	166.0
S3	11.20	3.23	5.03	16.2	173.9
S4 (AKKB-A)	11.21	3.23	2.39	7.7	82.8
S5 (AKKB-O)	15.38	4.43	3.97	17.6	188.5

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(4800 hours/year; product price 0.91 USD/kg)

As can be seen from Table 10, switching to the precision mode of the AKKB (S4) while maintaining the S2 operating mode saves 8.0 tons of product per year on one line. This is equivalent to 7,295 USD or 85.9 million soums at a price of 0.91 USD/kg. The economically optimal mode (S5) increases the annual capacity of the line by an additional 1.31 million packages. At the same time, even in this mode, the excess mass remains below the industrial level (savings of 3.1 tons/year). The proposed system requires only a change in the controller software, so additional capital costs are minimal.

To implement the AKKB: a PLC with a weighing module (IEC 61131-3) with a 24-bit ATO measuring frequency of at least 1 kHz is sufficient.

Future work includes: experimental testing of the proposed system on a real line for packing grains; testing the Poisson hypothesis by modeling the grain flow using the DEM method; λpredicting (forwarding) moisture by measuring it with a near-infrared sensor; extending the AKKB to multi-head combination scales; creating a digital twin of the line; generalizing the results to other legumes (beans, peas, lentils).

6. Conclusion

A four-loop (feeder, mass dosing, cycle-to-cycle adaptation, and packaging machine) adaptive automatic control system has been developed for the batching and packaging process of grains. Its physically based model includes the dynamics of the feeder, Poisson flow of grains, free fall with air resistance, impact force, and strain gauge resonance.

In the economically optimal mode (q^{*}= 90.1 g/s), the line efficiency increased by 41.8%, while the excess mass remained below the industrial level. The feedforward of the efficiency to the temperature contour reduced the temperature deviation from 0.67 °C to 0.36 °C when the speed changed. The SIMC tuning, however, maintained stability even when the object parameters were uncertain.

The results show that AKKB can be implemented as a software upgrade to existing gravimetric feeders. The next step is experimental validation in a real production line.

Authors' contributions. [Author 1] – idea, mathematical model, proofs; [Author 2] – software, simulation experiments, analysis. All authors have read and approved the manuscript.

Conflict of interest. The authors declare no conflicts of interest.

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