

DESIGN AND EXPERIMENTAL VALIDATION OF FLUTED ROLLER FOR FERTILISER METERING SYSTEM

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Abstract. Autonomous field robots enable plant-based nutrient management in perennial crops, but their agronomic benefits depend on reliable and low-power granular fertiliser dosing. In this study, a compact fluted roller-based dosing module for a blueberry farm robot operating on depleted peatland was developed and validated. The original fluted-roller dosing device leaked, and the dosage amount drifted, prompting a redesign: a compact fluted roller is designed to mitigate internal clearance. The mechatronic drive was built on a 12 V gear-reduced DC motor and an incremental encoder providing 768 counts per output shaft revolution, enabling angle-controlled dosing. Particle flow was modelled in Ansys Rocky using the discrete element method (DEM) for three commercial fertilisers, and the model was calibrated based on measured particle size, sphericity, and bulk density. Ten repetitions per fertiliser were performed on a test bench with one full revolution, and the emitted mass was determined gravimetrically. The experimental mean mass per revolution was 10.37 g for Substral, 10.26 g for Agro NPK, and 7.78 g for Agro Organic; the coefficient of variation ranged from 6.38% to 9.60%. DEM predictions recovered the mean dose with relative error ranging from -2.9% to +14.5% depending on the fertiliser. Based on the measured calibration, the target plant-level doses of 13.3-40.0 g correspond to output angles of 466° to 1852°. The proposed module demonstrates preliminary bench-scale feasibility for integrating fluted roller precision fertilisation into agricultural robots, providing a validated baseline for future multi-revolution and field-level testing.

Keywords: precision fertilisation, agricultural robotics, discrete element method, berry cultivation.

Introduction

The use of mineral fertilisers remains indispensable to ensure yields, but nitrogen losses to air and water are a persistent sustainability constraint [1]. Global analyses show that optimised agricultural management can significantly reduce nitrogen losses from arable land without a proportional yield loss [1]. Economic studies also indicate that the profitability of variable rate nitrogen fertilisation improves when prescriptions are consistent with spatial heterogeneity and decision uncertainty [2].

In Northern Europe, blueberry plantations are increasingly established on depleted peatlands, where optimising nitrogen inputs is critical to prevent greenhouse gas emissions and nutrient leaching [1; 3].

Agricultural robots are shifting from prototype-based platforms to culture-specific platforms, including platforms for berry crops [4]. The most recent platform is the Agrobot Gari platform, which includes sensor and actuator modules for blueberries [5]. Beyond productivity, agricultural robots also provide the opportunity to achieve agroecological objectives through small-scale, frequent, and targeted operations [4]. Surveys of robotic arms and field manipulators also describe rapid advances in reliable actuation and tool-tip solutions for agricultural tasks in the field [6].

An important ability provided by the robots is the plant-based fertilization, in which each plant is given the amount of fertiliser it needs based on the soil conditions [7]. Combined robotic location-based seeding and nitrogen fertilisation has been demonstrated as a pathway towards precise input distribution and reduced total fertiliser use [7]. Such approaches increasingly rely on digital technologies including water and nutrient management workflows [8].

However, the success of plant-based fertilization depends on the reliable and low-power-demanding dosing of granular fertilisers in variable field conditions [9]. Variable rate control systems for granular fertiliser spreaders show that the stability of the feed rate is sensitive to the drive dynamics and dosing geometry [9]. Ongoing engineering development of granular fertiliser spreaders, simulation-supported fertilization processes, and dosing concepts for blueberry robots emphasises the importance of the topic [10]. The selection of initial simulation parameters for robotic fertilization [11] has a key role to evaluate and choose the best dosing system for a given blueberry plantation using various mineral fertilizers.

The aim of this study was to develop and validate a compact, low-power fluted-roller dosing module for a blueberry field robot. The specific contributions include: mechanical redesign motivated by the internal leakage of a ribbed-roller mechanism; implementation of an encoder-based angular dose

control; preliminary bench-scale validation of one-revolution discharge using three commercial fertilisers with DEM support. The scope of this paper is limited to bench-level metering behaviour and does not yet assess field-level agronomic outcomes.

While recent studies have explored the discrete element method (DEM) optimisations for grooved-wheel metering and variable-rate applicators for perennial crops, challenges remain in scaling these down to fit the tight spatial and energy constraints of autonomous field robots. Furthermore, typical robotic applicators rely on screw or pneumatic dosing, making the compact fluted roller a specific mechanical alternative that requires rigorous parameter calibration.

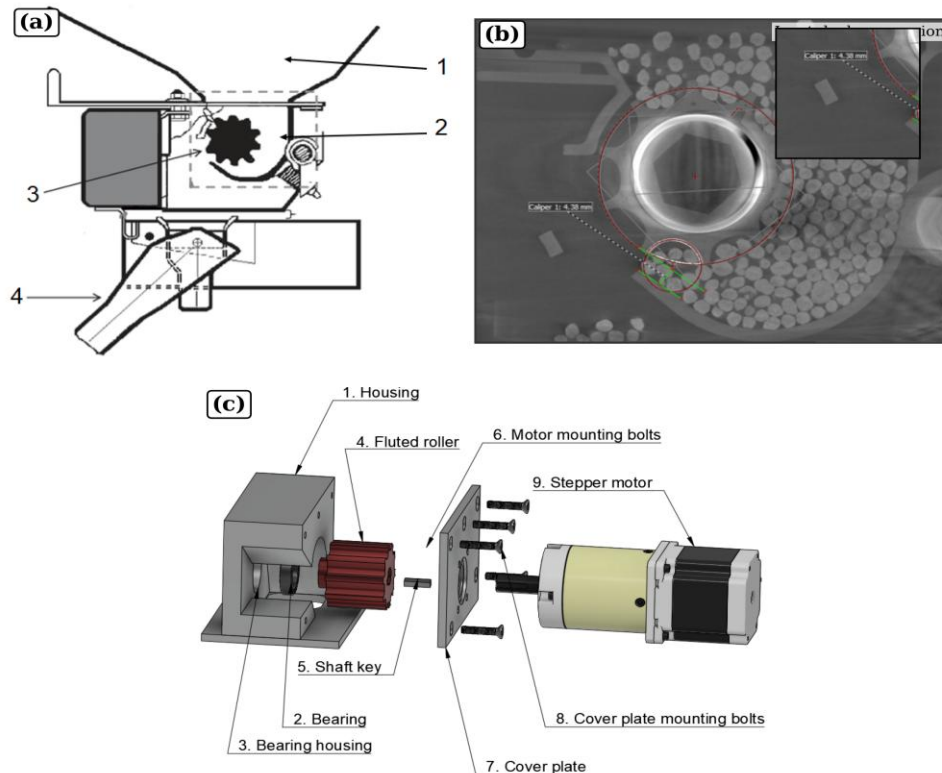


Fig. 1. **Failure mechanism and redesign rationale:** a – grooved-roller volumetric-feeder principle; b – CT cross-section of the original fluted roller showing the 4.38 mm internal clearance and leak path, with a zoomed inset of the critical region; c – redesigned fluted-roller assembly

Materials and methods

The development process involved redesign of the dispensing device, implementation of mechatronic control, modelling with the discrete element method and validation on a test rig. The DEM calibration followed a common approach where the simulated dispensing behaviour is matched to physical measurements by selecting particle properties and tuning contact parameters [12].

The purpose was a robot for plant-based fertilization in blueberry cultivation on ploughed peatland. The existing gauge device used a fluted roller and showed leakage through internal slack; the measured slack was 4.38 mm, which motivated the concept of a compressed fluted roller with an adjustable discharge flap. A commercial Fenix III 18 cc fluted roller unit was chosen as the base mechanism due to its compactness and suitability for drives with low power requirements.

The dosing module was driven by a 12 V brushed DC motor with a 64:1 planetary gearbox. A closed-loop rotational control was implemented using an incremental encoder that provided 12 pulses per motor revolution, corresponding to 768 counts per output shaft revolution and an angular resolution of 0.47° per count. The control unit was implemented on an Arduino Nano microcontroller with MOSFET power stage. To prevent motor overrun and ensure precise dosing, a custom closed-loop positioning algorithm was developed using a relay-based dynamic brake. For a commanded full revolution, the motor operated at 100% duty cycle until reaching 340° . Subsequently, a pulsed micro-stepping sequence was initiated: the motor speed was reduced to approximately 60% and pulsed for

10 ms, followed by a full stop (speed reduced to zero and brake engaged) and 100 ms position-verification pause. This sequence was repeated until the exact 360° target was reached, after which the encoder counter was reset for the subsequent dosing cycle.

$$\Delta\theta = 360/N_c, \tag{1}$$

where $\Delta\theta$ – angular resolution per encoder count, deg·count⁻¹;
 N_c – encoder counts per output-shaft revolution, count·rev⁻¹.

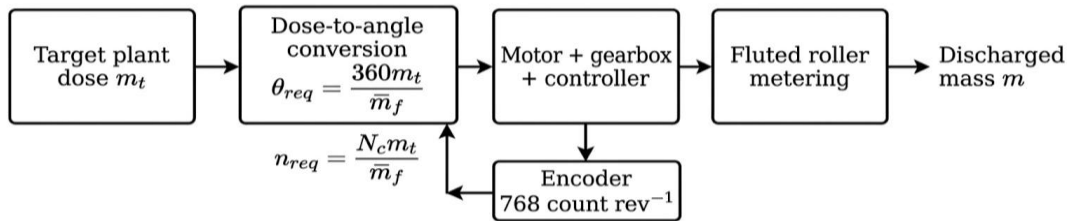


Fig. 2. Encoder-based dose-control logic used to convert a target plant dose into output-shaft rotation and encoder counts for the fluted-roller metering module

Three granular fertilisers used in the robot concept were selected for modelling and validation: Substral, Agro NPK and Agro Organic. For experimental determination of physical parameters, 100 granules of each fertiliser were selected randomly. For each granule, the longest (l), intermediate (w) and shortest (h) orthogonal dimensions were measured, and the equivalent diameter and sphericity were calculated as $d_e = (l \cdot w \cdot h)^{1/3}$ and $\varphi = d_e / l$ [12]. Single-particle mass was determined gravimetrically from the same particle samples and averaged. The mean particle mass was 70 mg for Substral, 80 mg for Agro NPK and 39 mg for Agro Organic. The present DEM model used values shown in Table 1.

Table 1

Physical properties and nominal-volume-derived fill factor of the tested fertilisers

| Fertiliser | Equivalent diameter, mm | Sphericity | Bulk density, kg·m ⁻³ | Nominal mass, g·rev ⁻¹ | Experimental mass, g·rev ⁻¹ | Fill factor η |
|--------------|-------------------------|------------|----------------------------------|-----------------------------------|--|--------------------|
| Substral | 3.15 | 0.99 | 950 | 17.10 | 10.372 | 0.606 |
| Agro NPK | 4.08 | 0.89 | 1030 | 18.54 | 10.264 | 0.553 |
| Agro Organic | 3.54 | 0.71 | 775 | 13.95 | 7.776 | 0.557 |

The nominal mass in Table 1 was estimated from the geometric capacity of the 18cc roller and the measured bulk density. The fill factor was then calculated as $\eta = m_{exp}/m_{nom}$. The resulting values, 0.553-0.606, indicate that the flutes were not completely filled, which is expected for granular materials with inter-particle voids.

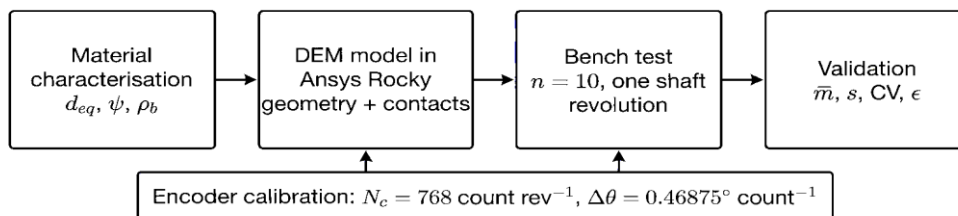


Fig. 3. Calibration and validation workflow for the fluted-roller metering module, linking material characterisation, DEM setup, encoder calibration, bench testing and validation metrics

A three-dimensional DEM model of the fluted roller unit was built in Ansys Rocky. Contact interactions used an elastic frictional law and were calibrated to reproduce discharge mass per revolution and flow stability, following fertiliser spreader DEM validation practice [13]. The model parameter sensitivity was checked against reported findings that discharge predictions can be strongly affected by

uncertain contact parameters and boundary conditions [14].

Bench validation was conducted with ten repeated full output shaft revolutions for each fertiliser. Discharged mass was measured gravimetrically and the mean, standard deviation, and coefficient of variation were computed. The coefficient of variation was used as the main uniformity indicator, which is common in evaluating fertiliser discharge devices and spreader distribution stability [15]. Simulation and experiment agreement was quantified by relative error of mean dose, similar to validation practice used in recent rotary discharge device studies [16].

Mathematical processing was carried out from the individual repetition masses m_i , with $n = 10$ for each fertiliser. The mean, standard deviation, coefficient of variation and DEM relative error were calculated as $m_{mean} = \Sigma m_i / n$, $s = (\Sigma(m_i - m_{mean})^2 / (n - 1))^{1/2}$, $CV = 100 \cdot s / m_{mean}$ and $\varepsilon = 100 \cdot (m_{mean, sim} - m_{mean, exp}) / m_{mean, exp}$, respectively. The dose gain used for plant-level conversion was $k_f = 1000 \cdot m_{mean, exp} / 360$, expressed as $\text{mg} \cdot \text{deg}^{-1}$.

Results and discussion

Table 2 compares the simulated and measured discharge per output shaft revolution for the three fertilisers. In the bench tests, mean dose per revolution ranged from 7.78 g to 10.37 g and the coefficient of variation ranged from 6.38% to 9.60%. These values indicate stable metering for the tested materials under laboratory conditions.

Table 2

Bench-test and DEM-validation metrics for ten one-revolution repetitions per fertiliser

| Fertiliser | Experiment mean \pm SD, $\text{g} \cdot \text{rev}^{-1}$ | Experiment CV, % | Simulation mean \pm SD, $\text{g} \cdot \text{rev}^{-1}$ | Simulation CV, % | Relative error ε , % |
|-----------------|---|---------------------|---|---------------------|-------------------------------------|
| Substral | 10.372 \pm 0.662 | 6.38 | 11.879 \pm 0.950 | 8.00 | + 14.5 |
| Agro NPK | 10.264 \pm 0.985 | 9.60 | 10.881 \pm 1.460 | 13.42 | + 6.0 |
| Agro Organic | 7.776 \pm 0.600 | 7.72 | 7.548 \pm 0.980 | 12.98 | -2.9 |

While DEM predictions accurately reproduced the experimental mean dose (relative error ranging from -2.9% to + 14.5%), the simulation overestimated the flow variability. The DEM-predicted coefficient of variation (CV) was roughly 25% to 68% higher than the experimentally observed CV. This indicates that the current simulation model is highly effective for mean-dose prediction and geometric refinement, but less reliable for modelling exact flow stability and pulsation.

The influence of particle diameter and sphericity was assessed by comparing the physical properties in Table 1 with the discharge metrics in Table 2. The largest equivalent diameter was observed for Agro NPK (4.08 mm), and this material also had the highest experimental CV (9.60%), suggesting that particles close to the flute depth are more sensitive to orientation, bridging and occasional retention. Agro Organic had the lowest sphericity (0.71) and the lowest dose gain, indicating that elongated organic particles produced a lower effective fill factor than the more spherical mineral granules.

The observed variability is comparable with recent efforts to improve distribution uniformity in variable rate granular fertiliser application systems, where reported coefficients of variation often remain in the same order of magnitude after parameter optimisation [17]. For applications requiring simultaneous dosing of multiple fertiliser types, mixing and transport effects can further increase variability, as shown in multi fertiliser uniformity studies [18].

DEM predictions reproduced the experimental mean dose with relative errors of minus 2.9% for Agro Organic and plus 6.0% to plus 14.5% for the mineral fertilisers. Such fertiliser dependent bias is consistent with reports that rotary discharge devices can exhibit strong sensitivity to particle friction, restitution, and boundary details that are difficult to measure directly [19]. Recent DEM based structural optimisation studies for centrifugal spreading components also report that small geometric changes can shift discharge patterns, indicating that tight tolerance manufacturing and model geometry fidelity are important for reducing prediction errors [20]. Using the experimentally measured calibration, plant level target doses can be implemented by commanding a rotation angle proportional to the desired mass. For

the dose targets considered in the robot concept, required angles ranged from 466° to 1852°, corresponding to approximately 995 to 3951 encoder counts (Table 3).

The implementation of the pulsed dynamic braking algorithm successfully mitigated the motor overshoot. Experimental position verification demonstrated that this active control strategy reduced the stopping error to just 0.2° per full revolution. This confirmed that the theoretical 0.47° encoder resolution translates into highly repeatable physical actuation, validating the mechatronic reliability of the targeted plant-level dosing. In practice, such plant specific control should be coupled with decision algorithms that generate spatially varying nitrogen recommendations, including machine learning based prescriptions [21]. Combining reliable metering with data driven prescriptions can improve both profitability and environmental performance by reducing unnecessary nitrogen inputs [1].

Table 3

Dose-calibration and encoder-conversion constants derived from the experimental mean dose

| Fertiliser | Dose gain k_f mg·deg ⁻¹ | Target dose, g | Required revolutions | Required rotation, deg | Required counts, count |
|-----------------|---|-------------------|-------------------------|---------------------------|---------------------------|
| Substral | 28.811 | 32.0 | 3.086 | 1111 | 2369 |
| Agro NPK | 28.511 | 13.3 | 1.294 | 466 | 995 |
| Agro Organic | 21.600 | 40.0 | 5.144 | 1852 | 3951 |

Future work will focus on expanding the validation envelope beyond bench-scale testing. Further refinement of the DEM model is planned to improve the prediction of flow variability and pulsation, which will require a more rigorous calibration of particle-boundary contact parameters. Finally, the metering module will be integrated into the autonomous field platform for in-field trials. In response to the particle-property limitations observed here, future DEM work should include multi-bin particle-size distributions, direct measurement of particle-boundary friction and restitution, and validation with additional fertiliser batches.

Conclusions

The study developed a compact fluted roller dosing module suitable for plant specific fertilisation by an autonomous blueberry field robot. Bench experiments demonstrated mean discharge of 7.78 g to 10.37 g per output shaft revolution with coefficients of variation below 10% for three granular fertilisers. The discrete element method model reproduced the mean dose within minus 2.9% to plus 14.5%, providing a useful tool for iterative geometric refinement. Encoder based rotation control with 0.47° resolution enables scalable per plant dosing and supports precision fertilisation strategies.

Author contributions:

Conceptualization, G.R. and Y.I.; methodology, T.L. and Y.I.; software G.R.; validation, G.R. and T.L.; formal analysis, G.R.; writing - original draft preparation, G.R.; writing - review and editing, T.L, Y.I and J.O.; funding J.O.

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