Vision-Guided Adaptive Scooping for Powder Weighing in Autonomous Chemistry Laboratories

Electronic Supplementary Information

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This PDF file includes:

- visualisation of the vision-guided scooping method;
- quantitative evaluation of adaptive scooping efficiency;
- failure mode analysis of the visual feedback for powder scooping.

Visualisation of the Vision-Guided Scooping Method

The following section provides additional insight into the system's perception capabilities by illustrating how the vision-guided framework interprets various scooping outcomes. To provide a clearer understanding of the vision-guided decision process, Figure 1 presents a series of images illustrating the raw camera output (left) alongside corresponding images with Region of Interest (ROI) markers and segmentation masks overlaid (right). These visualisations cover five distinct scenarios where the scooping outcome was correctly classified by the system as failed or successful:

- When a scoop was attempted but no material was retrieved (completely empty) (Figure 1a)
- When the scoop resulted in insufficient material for the dispensing phase (Figure 1b)
- When the scooped quantity is sufficient for dispensing and no clumps are present (successful scoop)(Figure 1c)
- When no clumps are visibly present, but the scooped quantity falls above the comfort zone of the dispensing policy (Figure 1d)
- When the scooped quantity presents clumps (Figure 1e)

As detailed in Section 2.3 of the main manuscript, the vision system does not independently segment or isolate individual clumps within the generated mask. Instead, it utilises the total estimated 2D area as a reliable proxy to detect their presence. Because over-scooping in cohesive materials is predominantly caused by large clumps, the upper threshold (t_{clumps}) is designed specifically to identify this state. By presenting the excessive quantity (without clumps) and the clumped scoop as separate visual cases, these examples effectively demonstrate how the presence of cohesive clumps inherently leads to considerable over-acquisition, triggering the system's threshold without the need for isolated clump segmentation.

Quantitative Evaluation of Adaptive Scooping Efficiency

To highlight the efficiency of the adaptive control loop for scooping, this section provides additional data obtained during the overall system evaluation experiment, showing the number of iterations acquisition took per material. The adaptive scooping mechanism utilises an iterative correction loop (Algorithm 2) to dynamically adjust the pitch angle (θ) and depth (D) based on visual feedback. This loop is a reactive recovery mechanism: it adjusts parameters on a per-trial basis, rather than converging to a static set of optimal parameters. Table 1 presents the average number of iterations required to achieve a successful scoop, alongside the average perceived fill ratio (P_{fill}) upon success for each tested material, during the Overall System Evaluation (Section 3.4 in the manuscript).

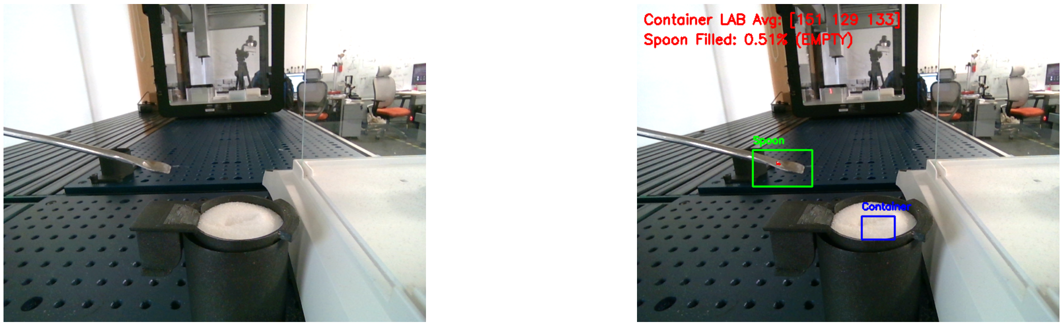
The data shows that highly flowable materials typically require more iterations and result in lower average P_{fill} values. This occurs because P_{fill} is a 2D volume proxy calculated from an elevated side-angle camera perspective, where larger volumes are most easily perceived when powder piles on the spoon. Since highly flowable materials will not easily stack or pile, the system needs to compensate for this. To successfully retrieve enough material to pass t_{empty}, the adaptive loop automatically adjusts, executing shallower scooping angles (θ) and deeper trajectories (D).

Material	Mean number of iterations	Mean final P_{fill}
SiO_2	3.2 ± 1.6	17.96 ± 2.41
Sugar	5.2 ± 0.97	17.41 ± 1.17
$NaCl$	3.6 ± 0.8	17.76 ± 1.21
Semolina	1.2 ± 0.4	23.84 ± 3.26
$NaHCO_3$	1.5 ± 1.2	20.28 ± 2.41
Pectin	1.7 ± 1.26	24.53 ± 2.67
Flour	2.4 ± 1.49	22.77 ± 2.64

Table 1: Average number of attempts needed to obtain a successful scoop, alongside the mean final perceived fill ratio (P_{fill}) at success for each material tested, Overall System Evaluation (Section 3.4 in the manuscript).

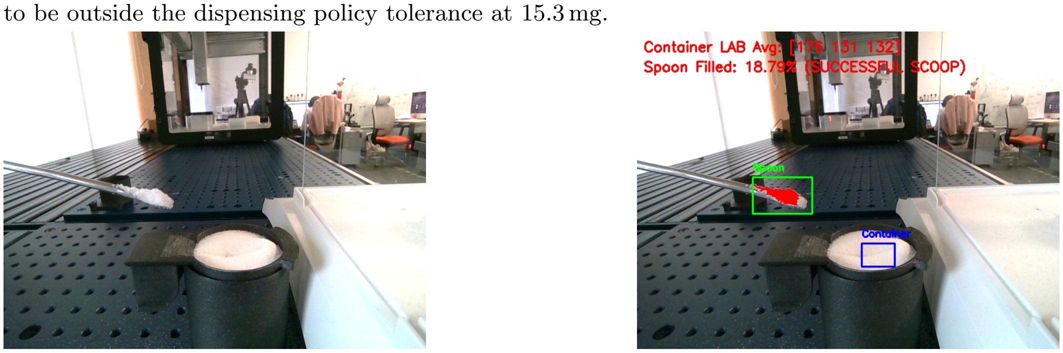
Failure Mode Analysis of the Visual Feedback for Powder Scooping

This section provides examples of specific conditions and material properties that lead to misclassification in the acquisition phase of the system. While the vision-guided scooping system is highly robust, certain edge cases can result in misclassifications. Figures 2 and 3 illustrate *false negative* cases, observed primarily with highly flowable powders, such as sugar and $Si0_2$. In these scenarios, the acquired powder quantity was physically within the acceptable lower tolerances of the dispensing system, yet the vision system classified the scoop as empty ($P_{fill} < t_{empty}$). However, rather than causing a system failure, the false negative triggered the robot to discard the current material and attempt a subsequent scoop using a shallower pitch angle and higher depth parameter. This automated recovery results in an increase of the acquired material volume. Crucially, experiments demonstrated that this compensatory increase remained within the optimal operational bounds of the downstream DRL dispensing policy, preventing target overshoots despite the initial vision failure.



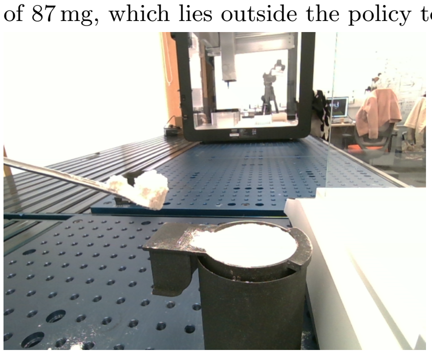
(a) Failed sugar scoop attempt that resulted in no material being retrieved.

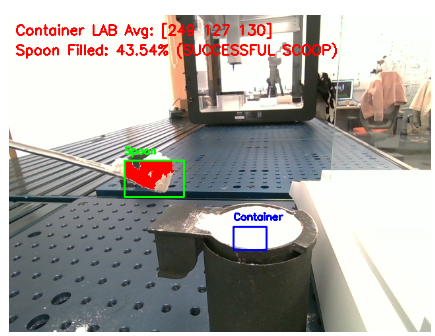
(b) Failed SiO_2 scoop attempt that resulted in material being scooped, but the material was found to be outside the dispensing policy tolerance at 15.3 mg.



(c) Successful sugar scoop attempt.

(d) Failed $NaHCO_3$ scoop attempt, with no visible clumps, that resulted in a retrieved quantity of 87 mg, which lies outside the policy tolerance.





(e) Failed flour scoop attempt, with a visible clump at the front of the spoon.

Figure 1: Scooping outcome visualisations.

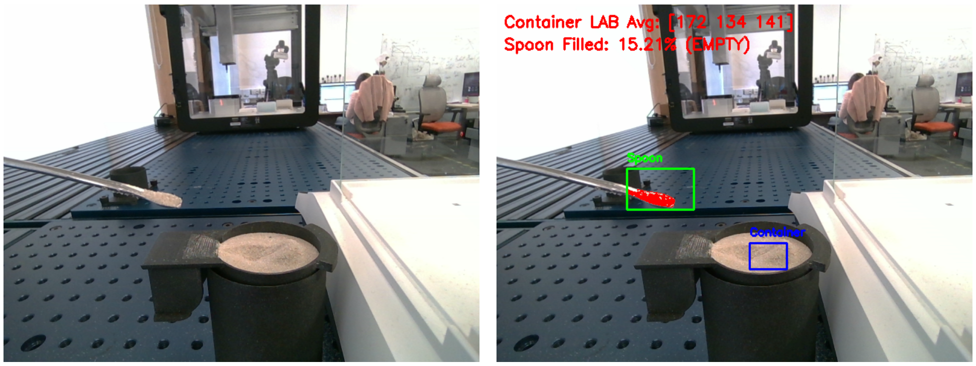


Figure 2: False negative classification of scooped SiO_2: the scoop was flagged by the vision system as having insufficient material with $P_{fill} = 15.21$, below the required threshold $t_{empty} = 16$. The measured quantity however was 25.2 mg.

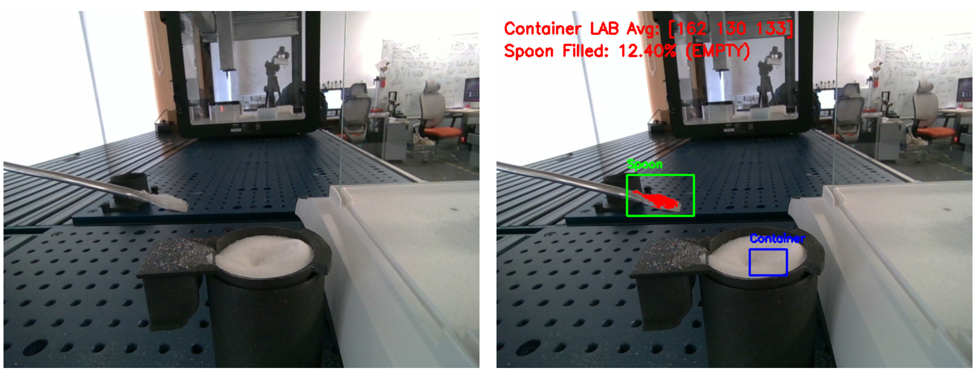


Figure 3: False negative classification of scooped Sugar: the scoop was flagged by the vision system as having insufficient material with $P_{fill} = 12.4$, bellow the required threshold $t_{empty} = 16$. the measured quantity however was 22.3 mg.