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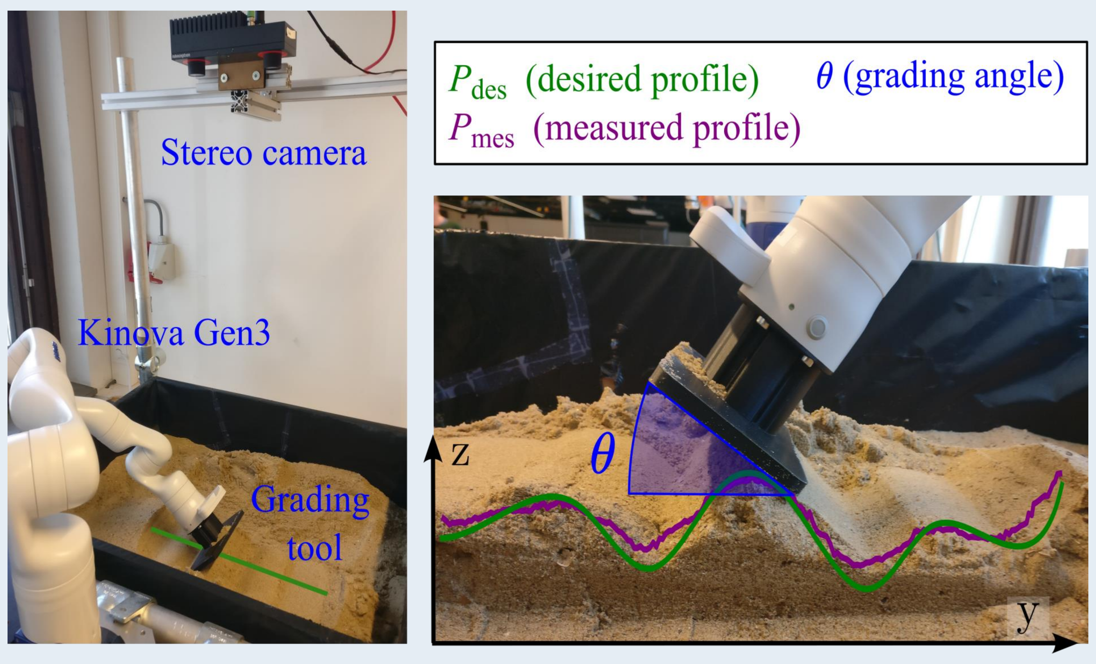
Robotic Framework for Iterative and Adaptive Profile Grading of Sand

Amorphous materials are involved in many **construction applications**: excavation, shotcreting, plastering …

Challenges:
Sand properties, like for other **amorphous materials,** are difficult to estimate and **emergent effects** such as collapses may occur which both influence the manipulation outcome.

→ As humans typically work, we propose an approach where we iterate and adapt the manipulation actions to the observed and desired material states.

We study **sand profile grading**, a task to obtain a desired geometric curve in sand.

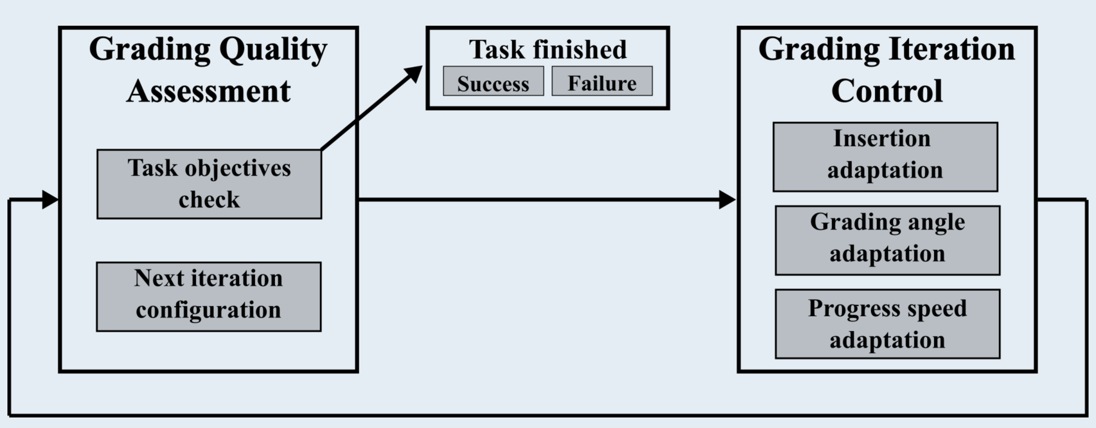


Objectives:
1. Minimize the **profile error** (RMSE between measured and desired profiles).
2. Obtain a smooth **surface finish**.

Constraints:
1. Respect the dynamical limits of the robot.
2. Avoid undercuts (i.e. grading deeper than desired profile).

Simplification assumptions:
1. P_{init} is higher than P_{des} everywhere
→ **Subtractive grading.**
2. Material is graded along a 1D straight line trajectory.

Our **layered framework** separates the manipulation problem into different abstraction levels..



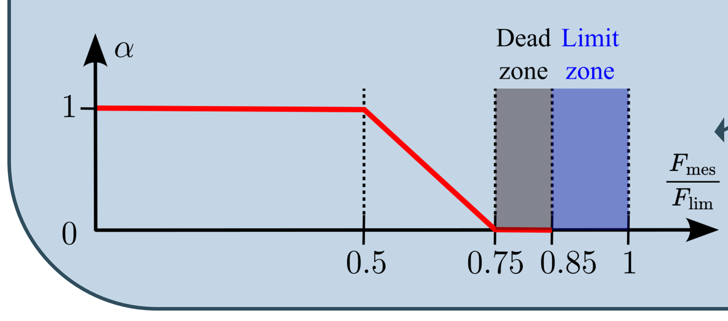
The **iterative** grading process uses two control levels:

- The **Grading Iteration Control:** adapts the robot's motion during one grading iteration to account for material properties and achieve the task objectives while respecting constraints.
- The **Grading Quality Assessment** evaluates the task objectives in between iterations to determine whether the task is finished, or another iteration is necessary.

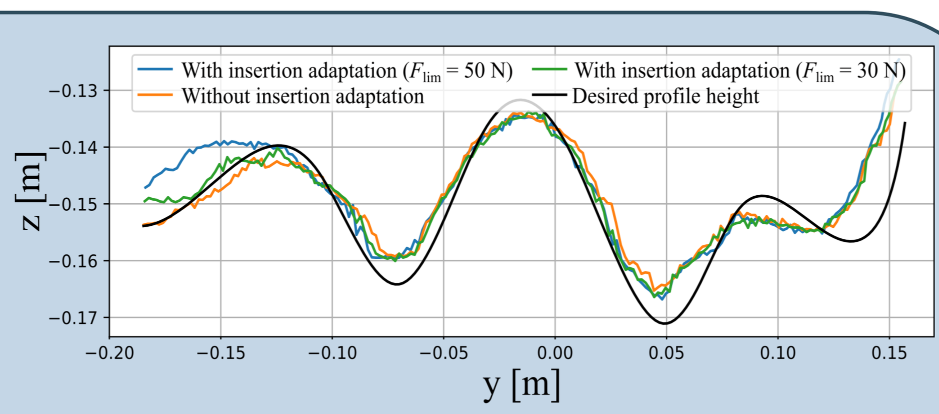
Tool insertion adaptation reduces force violations during tool-material interactions.

Interaction forces may vary significantly during contact and even exceed the robot's limits.
→ Tool insertion is regulated based on interaction force, allowing **deviations from the desired profile** if necessary.

$$v_z = k\,(z_{\text{setpoint}} - z_{\text{mes}})$$
$$z_{\text{setpoint}} = z_{\text{mes}} + \alpha\,(z_{\text{des}} - z_{\text{mes}})$$



Insertion via a simple proportional velocity controller in which z_{setpoint} is adjusted through α based on measured force.



Results: The obtained profiles are geometrically similar.

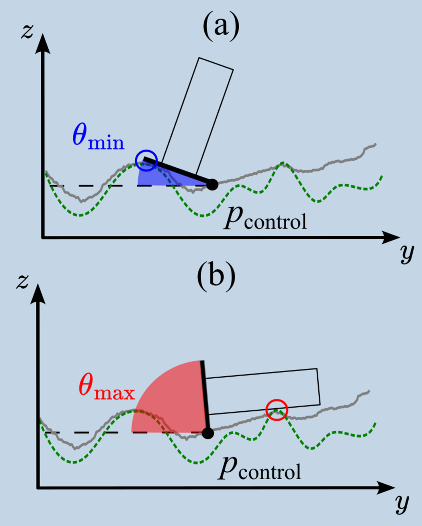
Configuration	F_{lim} = 30 N		F_{lim} = 50 N	
Insertion Adaptation	On	Off	On	Off
Sand level S2	8.09	18.28	4.96	9.88
Sand level S3	6.86	21.25	4.68	11.29

However, adaptation reduces at least 50% of force violations.

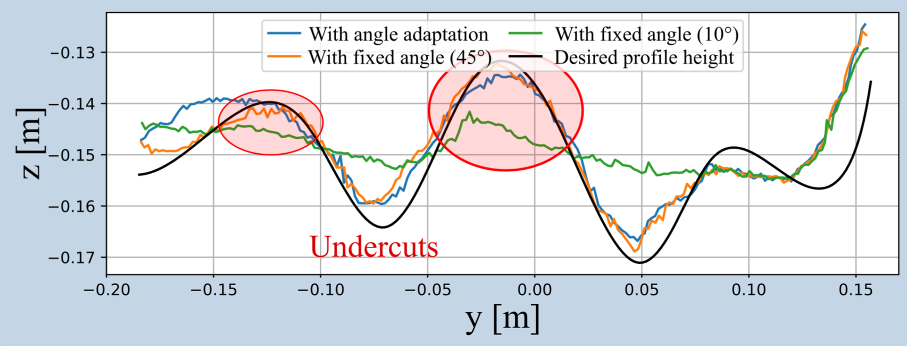
Why are force violations still observed?
They occur at profile summits when tool angle changes rapidly (angle adaptation does not consider material accumulation).

Grading angle adaptation switches between cutting and smoothing behaviors, while avoiding undercuts and collisions.

- Constraints to avoid **undercutting** and robot-material collisions.
- **Skill**-based functions defining cutting and smoothing angles depending on task progress.



Results:
- A fixed low angle (see green curve) leads to undercutting.



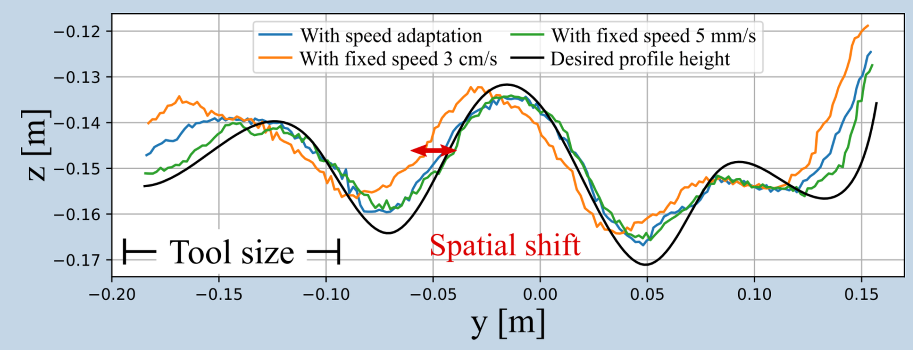
Speed adaptation provides a balance between grading precision and execution time.

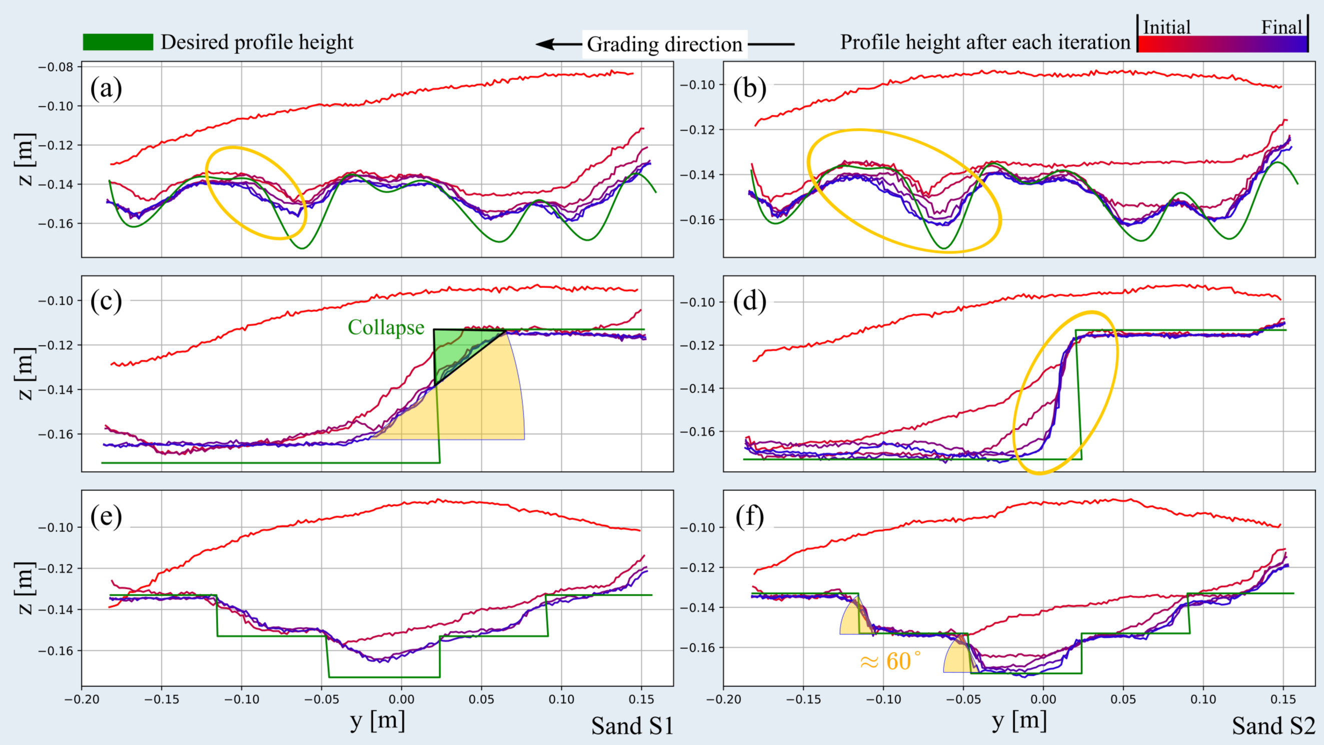
→ We take advantage of the task progress to **switch between rapid grading** when the objective is still far **and then work with more precision** for the finishing steps (like humans typically work).

$(z_{mes} - z_{des})$ [mm]	<2	]2;5]	]5;10]	>10
$v_{progress}$ [mm/s]	5	10	20	30

Velocity [mm/s]	5	30	Adaptive
Obtained PE [mm]	5.03	9.19	5.66
Execution time [s]	254.63	89.93	200.8

Higher velocities (e.g., fixed at 3 cm/s) cause a spatial shift between the obtained and desired profiles.





Grading quality is limited by **material constraints** and **emergences**.

- The material itself imposes constraints, such as the **repose angle** (material stability). Wetter sand can be graded steeper than dry sand.
- **Emergent effects** such as Collapses or Accumulation Shifts (Fig. (a) and (b)) occur when grading complex profiles. Those effects **can not be resolved**, resulting in significant deviations from the desired profile. → Future work: emergence handling mechanisms or monitors to adapt world model and robot capabilities for next executions.

In short, we present a framework for **iterative** sand profile grading that employs **simple adaptation rules** relying on limited knowledge of the material behavior.

By extending this work with advanced **high-level decision making**, we envision the potential for **generalizing** to 2D surface grading and other amorphous materials manipulation tasks, automating a broader range of construction tasks.

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