Toward shotcrete process simulation to support robotic operation

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Abstract -

In this study, we introduce a detailed physics-based particle system for simulation of the shotcrete process. The development of this framework concept is informed by an extensive literature review encompassing diverse modeling and simulation methodologies applied to shotcreting processes, coupled with insights derived from experimental studies on shotcrete. This method can effectively capture key shotcrete characteristics such as adhesion, cohesion, and rebound. Furthermore, simulated shotcrete particles have interaction with different objects, colliding and bouncing off different geometries that represent various construction substrates and conventional reinforcements. The primary objective of the process simulation is to expedite the advancement of robotic systems tailored for executing shotcreting operations, extending beyond mere visualization purposes. Through the integration of shotcrete process simulation into a virtual environment, a simulated representation of a robotic concept can be systematically experimented upon to anticipate and understand its behavior. This approach proves instrumental in refining the design of robotic systems, optimizing robot motion planning, mission planning, and enhancing management and operation practices.

Keywords -

Shotcrete; Process Simulation; Robot; Particle System

1 Introduction

Despite having a pivotal role in the world's economy, construction sector has been one of the last domains to adopt and apply automation technologies. This could be attributed to the irregular and ever-evolving nature of the construction site and the diverse, intricate tasks typically mandated. However, the scarcity of skilled work force, escalating labor costs, accrescent demand for new infrastructure, and the imperative need for maintaining existing ones emphasize the necessity for the integration of automation and robotic technologies in the construction industry [1].

Shotcrete as a concrete compaction method has gained popularity over the past century due to its exceptional economic efficiency. Even though shotcreting is highly mechanized today, the quality of the process is still heavily reliant on the skill of human operators. Conversely, this method poses significant challenges, subjecting workers to strenuous physical exertion, continuous exposure to hazardous dust, and the constant risk of ground instability.

In a standard shotcrete project, understanding the thickness and distribution of the material adhered to the target surface is fundamentally important. Knowledge of the rebounded material is also essential to minimize waste and operational costs. If a robot is to be deployed to autonomously carry out tasks traditionally performed by humans, profound understanding of the intricacies of the process becomes imperative. Without such knowledge, the robot may be at risk of sustaining damage (e.g., from rebounded shotcrete material) or not be able to carry out its task (e.g., without awareness of shotcrete cohesive failure, the robot may become indefinitely stuck in a loop of spraying the same spot repeatedly).

Therefore, we have developed a particle system integrated with a physics engine, with the aim of improving the accuracy and efficacy of shotcrete process simulation. This conceptual framework is considered an essential facilitator for robot-based shotcreting. The paper is structured into two main sections. Firstly, it provides an overview of the current state of robot-based shotcreting and shotcrete process simulation. Secondly, it presents and discusses the simulation's composition and delves into implementation details.

2 Background

Efforts have been made to employ robotic manipulators for shotcreting in underground structures, including tunnels [2, 3, 4]. Cheng et al. [5] simplified the control system of a semi-automated shotcreting manipulator and validated their model through real-time computer simulation. They also utilized a simulation model for calculating the nozzle path in a fully automated shotcreting robot. Girmscheid and Moser [6] introduced a versatile robotic system capable of manual, semi-automatic, and fully automated shotcreting, demonstrating promising results and emphasizing the potential of automation in construction. These methodologies incorporated shotcrete profile measurement and application control, utilizing laser scanning before and after the shotcreting process, resulting in accurate estimations of the thickness of the accumulated shotcrete. However, one might ask, what if the applied layer of shotcrete is not within the specified tolerances, requiring its removal and negating the economic efficiency of shotcrete.

The noticeable differences in nozzle trajectories observed between manual and automatic shotcreting on a shared robotic platform, as emphasized in the study by Nabulsi et al. [7], suggest divergent approaches taken by robots and humans in the application of shotcrete. In contexts such as tunneling and ground support, ensuring uniform coverage is paramount. Equally crucial is a comprehensive understanding of how different nozzle paths can influence the final shape of the shotcrete on the surface, particularly in applications like infrastructure restoration. In conclusion, despite significant advancements in remote-controlled robot-based shotcreting, challenges persist in achieving full autonomy. The question of whether current technology can enable robots to autonomously perform shotcreting remains unanswered.

Shotcrete is a complex process of spraying concrete mixture onto a designated surface with high-impact velocity. This involves shooting a multi-phase blend of cementitious material, water, aggregates, and admixtures through a hose. Besides air, an additive, a quick-setting agent, is often introduced at the nozzle. In application, a majority of the sprayed concrete adheres to the target substrate. However, a fraction of the material may exhibit rebound, impinging upon objects and adjacent surfaces or returning to the ground. The efficacy of the shotcrete operation significantly hinges on the proficiency of the operator, who plays a pivotal role in minimizing rebound and preventing the detachment of previously applied shotcrete.

It is common to apply sprayed concrete over steel reinforcements. These structures are affixed to the surface with a specific distance, partially obstructing it. Spraying with the nozzle perpendicular to the surface can lead to the creation of large air pockets or sand lenses behind these elements. A skilled operator directs the nozzle to fill the space between the reinforcement and the wall, ensuring complete encapsulation with concrete. A basic illustration of the shotcrete process is shown in Figure 1.

A realistic simulation ought to incorporate shotcrete sprayability parameters. According to Trussell and Jacobsen [8], the term sprayability is frequently used to describe properties such as:

- `Adhesion` which is the ability of sprayed concrete to attach to the substrate and avoid falling. It is mostly affected by the nature and status of the substrate and the composition of the mix.
- `Cohesion` which is the ability of fresh sprayed concrete to stick to itself and avoid falling and slumping under its own weight. It can be measured in terms of the thickness that can be applied before the build-up material starts to fall under self-weight.
- `Rebound` which is an unwanted yet unavoidable by-product of the shotcrete process and occurs when the shotcrete particles fail to adhere to the substrate and instead bounce back from the surface. Armelin and Banthia [9] put an effort to derive a constitutive model of the rebound phenomenon.

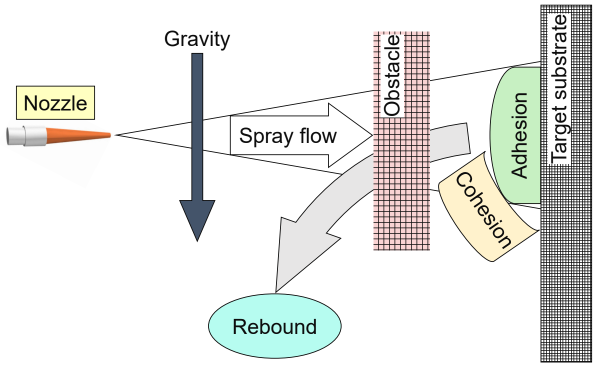

Figure 1. Simplified shotcrete process model

There are additional properties associated with the sprayability of shotcrete. Some researchers found strength gained with time to be an intriguing aspect [10, 11]. In a study by Han et al. [12], Artificial Intelligence (AI) was employed to rapidly determine the mix proportion of wet-mix shotcrete. Others, such as [13], focused on examining the impact of process parameters and model-based process control.

The absence of any need to prepare concrete forms renders shotcreting an extremely competitive technology. Nevertheless, the skills of the nozzle operator play a vital role in minimizing material waste during application, thus impacting the economic efficiency of the construction process [14]. Therefore, construction companies invest significantly in training their shotcrete personnel. They require workers to undergo repetitive shotcreting drills as part of their training until their skills are fully developed. While this method is not sustainable and not always applicable, researchers have addressed the issue by focusing on the development of real-time simulators for shotcrete training.

Presumably, Börjesson and Thell [15] were the first researchers to experiment with various rendering techniques in developing a virtual environment for shotcrete training. They implemented a particle system and put forward the idea of addition of gravity and dynamic forces to the shotcrete particle, albeit in their implementation they utilized ray casting for their adhesion model. They deliberately limited the particle system to rendering of the spraying effect with no impact on the surfaces. Moreover, their work lacked realistic sprayability parameters of shotcrete. Nevertheless, they managed to commercialize the findings of their research into a real-time training simulator [16].

In their study, Velez et al. [17] developed a real-time shotcrete simulation that introduced gravity to affect rebound and detached concrete. They also employed ray tracing for the adhesion model and introduced a shadow mapping technique to account for cells on the target surface that were shadowed by the steel mesh from the nozzle's perspective. While their approach was commendable, it leans toward oversimplification, especially in the aspect of particle collision with other objects—a complexity that may not be fully captured by their model.

3 Shotcrete process simulation

In this chapter, a novel shotcrete process simulation is introduced to address the limitations identified in previous research. The proposed method enhances critical aspects of the process, addressing adhesion, cohesion, rebound, and simulation of the shotcrete application over additional supporting elements. This contributes to a more thorough and realistic depiction of the process.

The simulation involves parameters that can be categorized into two main groups: those related to the performance of the particle system, such as the number of active particles and simulation time step, and those related to the shotcreting process, such as nozzle spread angle and rebound rate. The latter parameters are adopted and adapted from the current state of the art (i.e., scientific articles and technical reports).

This section is divided into three subsections. The first part explains the functioning of the particle system, including the initialization of particles, and their emission. The next part delves into the implementation of the sprayability parameters of shotcrete—detailing what happens when particles hit an object. Finally, the output of the simulation is described and discussed.

3.1 Particle system

Ballou [18] drew an analogy between shotcrete and the action of throwing balls dipped in paste at a surface. He highlighted that the transfer of paste to the surface occurs upon the ball rebounding, emphasizing the importance of a certain degree of rebound as the primary method for transferring cementitious material to the target surface. Subsequently, each successive ball hitting the surface contributes to and compacts the already deposited concrete into the voids and porosity of the surface. It is not an exaggeration to assert that shotcreting is similar to shooting out particles. Similarly, aggregates, acting as particles, transfer mortar to the target surface, filling cracks and voids, contributing to excellent in-place compaction due to their high kinetic energy.

The foundation of this model is rooted in the intricate functioning of a particle system, which serves as the primary mechanism for simulating and visualizing various aspects of the shotcrete process. The particle system is designed to emulate the behavior of individual particles, representing shotcrete particles, as they interact with surfaces, undergo collisions, and contribute to the build up of material on the target substrate. This sophisticated approach allows for a detailed and dynamic simulation, enabling a closer approximation to real-world shotcrete scenarios.

Firstly, particles are initialized with a randomized direction. Illustrated in Figure 2, the parameter *Spread* denotes the angle of the spray cone, and its value can be adjusted within the simulation environment. In practical scenarios, the spray cone angle depends on factors such as the type of mix (wet or dry), material composition, and air pressure. The data for *Spread* have been sourced from [19]. All particles originate from a circle with a variable diameter, simulating the nozzle aperture, and each is assigned a direction vector. The magnitude of the velocity vector is randomly chosen from a range between a minimum and maximum value, with velocity data derived from experimental studies conducted by Ginouse et al. [20].

To account for the effect of gravity on the particle, a vector expressed as $(0, 0, -9.8)$ $^{m}/_{s}$ is added to the defined velocity vector in each second of the simulation. Without gravity, the particle would have followed a straight path along the velocity vector toward the point (x, y, z), as illustrated in Figure 2. However, due to gravity, the particle deviates toward the negative z direction in each time step, eventually hitting a point (x, y, z') slightly lower. Substantial evidence from the work of Ginouse and Jolin

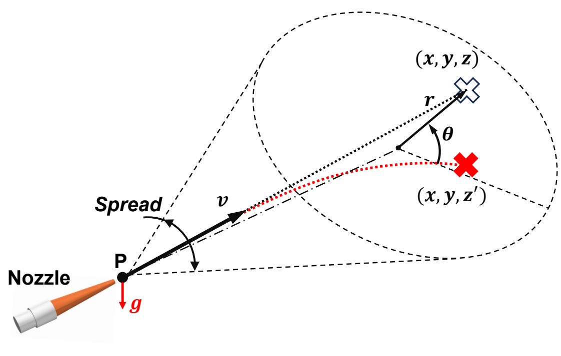

Figure 2. Particle initialization and emission

[19] supports this observation. In their study, high-speed cameras captured images of shotcrete spray, revealing that the shotcrete particles are influenced by gravity even over short distances.

The particle engine handles creating and updating particles throughout the simulation. Essentially, the number of particles to be emitted is determined by the value of this parameter, which is set in the simulation. Each particle is randomly initialized and is updated at each time step during its active lifespan. When a particle hits a surface and adheres to it, it is deactivated and returned to the pool of total number of particles.

The total number of particles and particles emitted per second are two essential parameters in the simulation. Increasing the value of these parameters would enhance the realism of the simulation, but it comes at the cost of computational efficiency. Nonetheless, this provides flexibility to run the simulation on machines with varying computational power.

3.2 Shotcrete sprayability parameters

It is assumed that during a small time-step, each particle travels in a straight line. Hence, the collision problem is simplified to finding the intersection between a line segment and other basic geometries [21]. For instance, when simulating the adhesion of material on a wall, the target surface is treated as a finite plane. The algorithm then seeks the intersection between a line segment and a finite plane. If collision is detected, the intersection point is calculated. A similar approach is applied to handle intersections between a line segment and a cylinder, making it suitable for simulating shotcreting in tunnels and objects along the spray path (i.e., reinforcements).

When an intersection point is found, the algorithm determines whether the particle adheres to the surface or rebounds. This is achieved by calculating the rebound percentage rate of that particle, referencing Melbye curves. In his technical handbook, Melbye [22] identified and categorized the factors affecting rebound, declaring the nozzle angle to the substrate as the decisive one. Therefore, the angle between particle's velocity vector and the surface normal vector at intersection point is calculated. Based on this angle, rebound percentage rate is determined. If the particle adheres to the surface, a value based on the deposition model is added to the corresponding height-field. Subsequently, the particle is deactivated, and the visualization is updated in the simulation. If the particle rebounds, the collision response involves assigning a new direction, which is the reflection of the velocity vector with respect to the surface normal vector. The magnitude of the reflected velocity is multiplied by the coefficient of restitution of shotcrete (e) derived from [23]. The particle continues to be updated until it adheres to any surface

Table 1. Proposed algorithm for particle collision with surface, and subsequent adhesion or rebound

Pseudo-code:
nowPos = *shotcreteParticle −> position*;
velocity = *shotcreteParticle −> velocity*;
nextPos = *nowPos* + (*velocity* ∗ *diffTime*);
point = compileIntersection(*lineSegment, surface*);
if (!contactOnSurface(*point*))
return;
chance = generateRandomNumber();
normal = compileSurfaceNormal(*point*);
rebound = calculateReboundRate(*velocity, normal*);
if (*chance* <= *rebound*)
deactivate(*shotcreteParticle*);
updateHeightField();
updateVisualization();
else
velocity = *e*∗ compileReflection(*velocity, normal*);

(the target surface, reinforcements, or the ground). The pseudo-code for this algorithm is presented in Table 1.

In the simulation of cohesive failure, the algorithm simplifies the process using a modified seed fill algorithm, akin to the approach in [17], to identify the detachment area. A detachment occurs when the difference between neighboring values exceeds h_{max}, as specified in [24]. The detachment volume is then calculated based on the disparity between the number of adhered particles in the detachment zone and those in neighboring cells. Consequently, an equivalent number of particles detach from the target surface and fall to the ground. This may result in more material being detached, creating a hole-like effect characteristic of shotcrete cohesive failures. For a more in-depth illustration of the proposed simulation process and the interrelationships among its various components, please refer to Figure 3.

3.3 Output of the simulation

The most critical outcome of the process simulation is the amount of concrete deposited at each point on the target substrate. To capture and analyze this information, a data structure capable of storing accumulated material values is essential. A height-field, representing a two-dimensional array of integers, emerges as a valuable tool for presenting the simulation results. During the simulation, the height-field is visualized as heat-maps, providing a dynamic representation of the concrete deposition. Subsequently, this data is stored and shared with other software in image file formats, facilitating in-depth analysis or rendering within an environment visualization engine. While realistic rendering of the height-field could enhance the

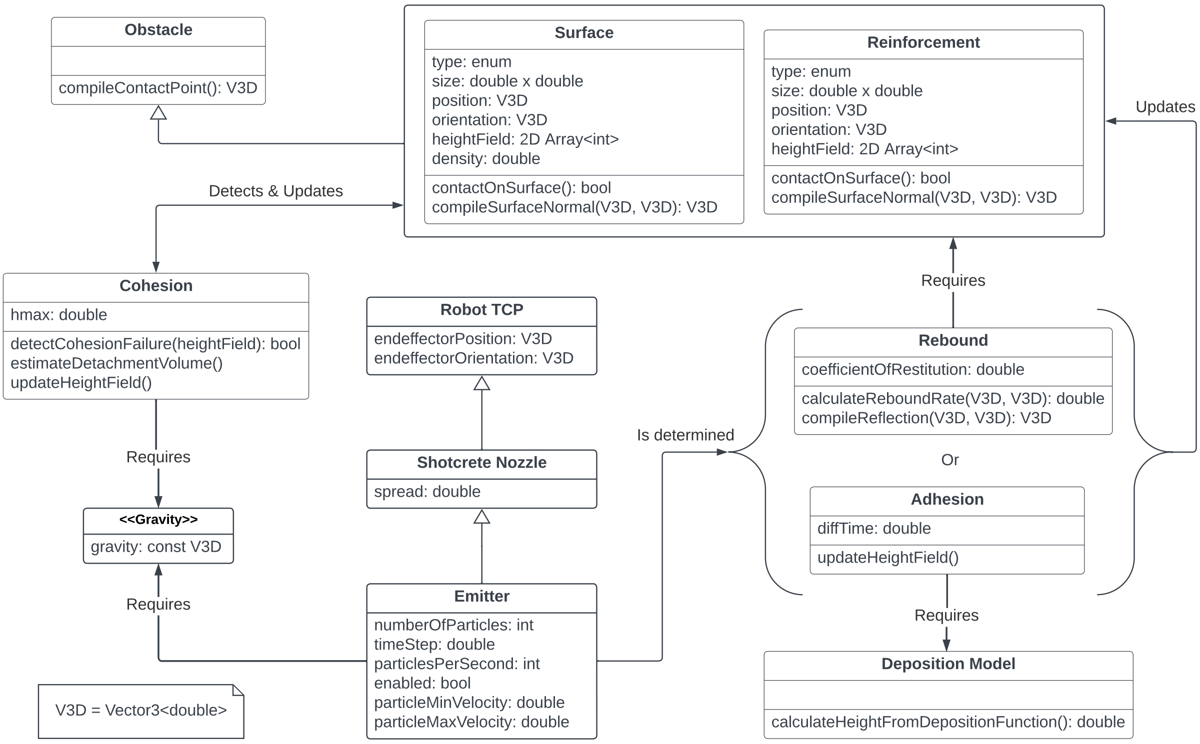

Figure 3. Proposed system component diagram of the shotcrete process simulation

simulation's visual realism, it is important to note that this research is not primarily focused on training human operators. Therefore, realistic rendering for human perception is not a priority; instead, the emphasis lies in ensuring that the output is well-defined for machine interpretability.

This methodology enables the execution of simulations involving 10 million particles, with 0.1 million particles emitted per second, and a simulation time step of 0.001 second, close to real time. These simulations were conducted on a system equipped with an AMD Ryzen 7 3700X CPU and 16 GB of RAM, using VEROSIM®, a software solution for virtual reality and simulation.

Figures 4 and 5 display the robot shotcreting within the virtual environment, offering insight into particle interaction. Within this scene, two planar obstacles are introduced: one simulating the accumulation of concrete on a hypothetical wall and another positioned on the ground to capture rebounded material. At the nozzle's tip, an emitter releases particles in a cone-shaped spray pattern. The varying colors on each surface represent heat-maps, correlating accumulated material thickness with color. Analogous to topographic maps, this visualization method aids in identifying unevenness, crucial for assessing material deposition uniformity. Furthermore, as extensively discussed in this section, the height-field is concurrently generated behind this layer.

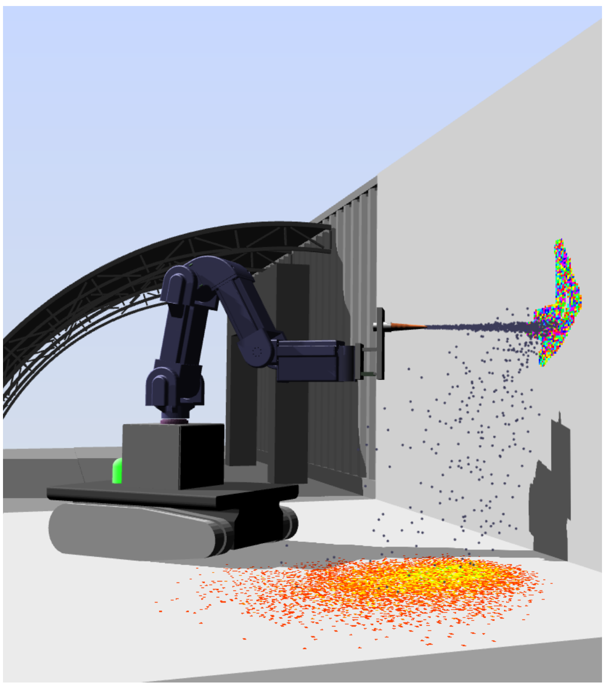

Figure 4. Screenshot of a conceptual robot performing shotcreting in the virtual environment

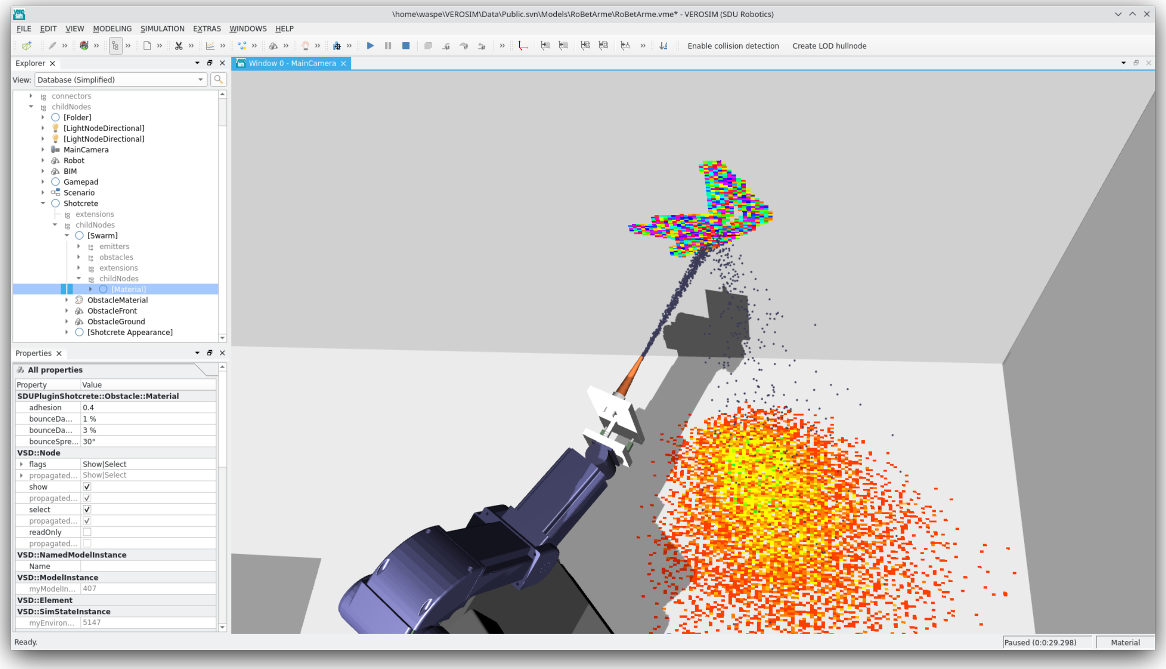

Figure 5. Detailed screenshot of robot-based shotcrete process within the simulation software

4 Conclusions and future work

This article introduces a concept of a framework for realistic shotcrete process simulation. In contrast to previous methods that relied on ray tracing, our approach utilizes a particle system to track particles from emission until collision with surfaces. These collisions can result in either adhesion to the surfaces or rebound. The incorporation of a physics engine allows particles to be influenced by gravity, air drag, and interactions with obstacles. The algorithm evaluates collisions and estimates rebound at each time step. When a particle adheres to a surface, the simulation increments the corresponding value in the height-field. The output of this simulation is a height-field representing the accumulated shotcrete on the surface, visualized through heat-maps in the simulation. This data can be saved as an image for further analysis or rendering.

Integrating the process simulation with a robot's kinematic simulation establishes a platform for offline optimization for achieving objectives, including optimal surface coverage, uniform material distribution, and effective filling of irregular voids. Furthermore, enhances shotcrete application efficiency and contributes to the versatility of robotic operations across diverse construction scenarios.

Opportunities for refinement persist in enhancing the realism of the process simulation. Continued efforts could be directed toward improving the model's fidelity, with a focus on incorporating nuanced aspects such as the spread of shotcrete material post-particle impact. This may be achieved through the integration of a cellular automata simulation, allowing for a more accurate representation of shotcrete sprayability parameters, including adhesion, compaction, and shrinkage over time. Furthermore, the integration of the process simulation into a Digital Twin of a robot holds promise for conducting high-fidelity, experimentable simulations. Such simulations can contribute significantly to the design, evaluation, and deployment of efficient robots tailored for shotcreting tasks.

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