THICKNESS SIMULATION WITH KINEMATIC CONSTRAINTS FOR ROBOTIC FIREPROOFING SPRAY

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Abstract

Achieving precise thickness is essential for fireproofing performance. Insufficient thickness fails to secure the required fire resistance, whereas excessive thickness causes material waste and rework. This study proposes a simulation framework that combines a Gaussian accumulation model with a kinematic nozzle motion model. As a result of tests on a fixed raster path, kinematic constraints suppressed excess accumulation, increasing the within range area from 87.55% to 91.16% and reducing the over thickness area from 6.83% to 0%. These results show that spray quality should be evaluated using CV with under/over coverage, within range area to help ensure the required thickness.

Introduction

In fireproofing spray, keeping the thickness within the target range is important for both fireproofing performance and material efficiency. If the thickness is insufficient, the required fire resistance cannot be secured and additional repair or rework may be needed. In contrast, excessive thickness causes unnecessary consumption of spray material.

Recent automated spraying research has focused on trajectory generation and velocity optimization for complex free form surfaces (Verduyn et al., 2023; Nieto Bastida and Lin, 2023). However, unlike thin film paint, heavy construction materials such as wet mix shotcrete and fireproofing form thickness differently, and this process is influenced by spray dynamics (Ning et al., 2024). At corners, robot kinematic constraints such as acceleration and deceleration limits can reduce nozzle speed and increase local thickness, but this effect is not directly addressed in macroscale 3D trajectory planning.

This study presents a simulation framework for robotic fireproofing spray and evaluates how kinematic limit scaling near rounded corners affects thickness maps and the area with thickness within the target range.

Methodology

This study develops a thickness simulation with kinematic constraints for robotic fireproofing spray on a planar target surface. A fixed L shaped raster path with rounded corners is used, and the region of interest is evaluated on a 5 mm grid. A single elliptical Gaussian footprint is used for accumulation. The path is resampled at 1 mm intervals for kinematic profiling and 20 mm for accumulation.

This dual resampling balances motion precision with computational efficiency. According to Eq. (1), local thickness is accumulated along the path, with each accumulation contribution determined by the effective flow rate, the Gaussian footprint, and the inverse of the local travel speed.

$$T(x,y) = \int_S \frac{Q\eta}{v(s)} G(x,y,s)ds \tag{1}$$

Two motion settings are compared. OFF uses the nominal kinematic limits over the full path. ON applies corner speed, acceleration, and deceleration scaling of 1.5 near rounded corners. The predicted thickness map is evaluated using mean thickness, CV, under coverage below 17 mm, within range area for 17 to 19 mm, and over coverage above 19 mm.

Table 1: Baseline simulation settings

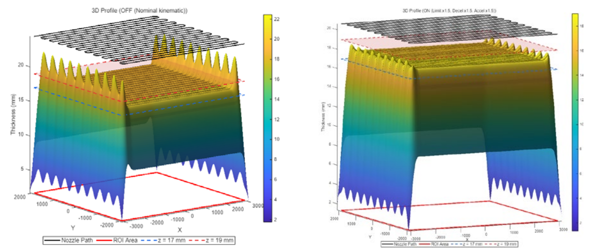
Parameter	Value	Description
Q	36 L/min	Volumetric flow rate
η	0.90	Transfer efficiency
h	300 mm	Standoff distance
α	30°	Nozzle half-angle
k_σ	0.70	Spread factor
Δ	5 mm	Grid resolution
ROI	6000x4000 mm	Spray region
s_{row}	200 mm	Row spacing
r_{turn}	150 mm	Turn radius
v_{min}, v_{max}	100 ~ 150 mm/s	Speed bounds
$a_{tan,max}$	200 mm/s^2	Tangential acceleration limit
$a_{lat,max}$	200 mm/s^2	Lateral acceleration limit
ds_{kin}, ds_{dep}	1 mm, 20 mm	Sampling steps
Footprint	285.51 mm^2	Calculated spray area

OFF	-	Normal limit
ON	1.5	Kinematic limit scaling factor
Mean	18 mm	Target thickness mean

Results

Figure 1 compares OFF and ON at 150 mm/s, the upper bound of the tested speed range reached in both settings. In the OFF case, ridge like peaks appear near the turn side boundary. In the ON case, these local peaks are suppressed and the boundary profile becomes flatter.

Compared with OFF, ON reduced mean thickness from 17.94 mm to 17.60 mm and increased CV from 5.46% to 6.88%, while over coverage decreased from 6.83% to 0.00% and within range area increased from 87.55% to 91.16%.



(a) (b)

Figure 1: 3D Profile OFF(a), ON(b)

Discussion

OFF shows a lower CV than ON, but ON shows lower over coverage and higher within range area. In ON, over coverage decreases from 6.83% to 0.00%, while under coverage increases from 5.62% to 8.84%, which lowers mean thickness and increases CV. Therefore, CV should be interpreted together with under coverage, within range area, and over coverage, especially near rounded corners.

Table 2: Sensitivity Analysis (ON setting)

Parameter	Variation	CV (%)	Target Range Compliance (%)
Baseline	-	6.88	91.16
k_σ	±10%	6.60 ~ 7.31	91.64 ~ 92.25
η	±5%	6.88 ~ 6.91	91.27 ~ 92.18
Kinematic limit	±20%	6.88 ~ 6.89	91.16 ~ 91.16
Δ	1, 10mm	6.74 / 7.06	91.26 / 90.86

Table 2 summarizes the results obtained by varying k_σ, η, kinematic limit scaling factor and Δ around their baseline values. For the tested variations, within range area remained between 90.86% and 92.25%, and CV remained between 6.60% and 7.31%. Notably, within the speed range specified in this study, no significant changes due to variations in the kinematic limits were observed.

Conclusions

This study presented a thickness simulation with kinematic constraints for robotic fireproofing spray on a planar target surface. The main finding is that kinematic limit scaling near rounded corners reduced over coverage and increased within range area, even though CV increased. This shows that CV alone is not sufficient for evaluating spray quality. Instead, it should be interpreted together with under coverage, within range area, and over coverage. These evaluation metrics can be used to contribute to securing the required fireproofing thickness. Future work will extend the present framework beyond the fixed assumptions used in this study by considering additional flow rates, standoff distances, and model and kinematic parameters. Experimental validation of the predicted thickness maps will also be conducted under practical fireproofing conditions.

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