Drywall finishing with collaborative robot arm in off-site construction

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Abstract -

The automation of tasks in construction industries is a solution for countries experiencing a labour shortage in those industries. The task of drywall finishing in an off-site construction environment is particularly interesting for automatization because of the large amount of labour, the strain on the worker's body, the falling risk and the large quantity of dust particles. This article explores assisting workers with drywall finishing using an arm-mounted orbital sander with a collaborative robot arm placed on a mobile platform, combined with a drywall joint compound machine vision detection algorithm. Preliminary results suggest the robot can finish the same depth of material as a human worker, which is typically less than 0.19 mm.

Keywords -

Drywall Finishing; Machine Vision; Construction Robot; Collaborative robot

1 Introduction

Gypsum board, also known as gypsum drywall or plaster board, offers a cost-effective and popular [1] option to build the interior wall of modern-day construction in Canada. Unfortunately, while gypsum boards are easy to install, the seams and screws need to be covered by multiple layers of compound, also known as mud or plaster, to form a uniformly flat surface ready for paint. While drying, this compound shrinks and leave an uneven surface full of bumps and cracks. To finish the drywall, those defects need to be sanded down before applying paint. The general surface is also sanded down to make seams between boards less visible and more aesthetically pleasing.

Unfortunately, drywall finishing is quite laborious and inconvenient for workers [2]. To finish the compound, workers use power tools to remove most of the uneven cracks and bumps. Subsequently, workers use handheld tools like sanding blocks to smooth out the finer details. Sanding the compound produces a lot of irritable dust particles [2], especially when using power tools. To reach elevated walls, workers work with their arms over the shoulders for long hours, which can lead to pain and injuries [3].

Assisting workers with this task represents an opportunity for automation. Fortunately, off-site construction offers a stable environment for automatization and contributes to the reproducibility of the presented results. This paper presents the design of a sanding mobile robot capable of performing the power-assisted part of the drywall finishing task. Our key contributions are : 1) The integration of a 7-DOF collaborative manipulator arm-mounted orbital sander with an autonomous mobile platform; 2) An automatic computer vision pipeline capable of detecting and localizing sections of drywall to sand; and 3) A control scheme to perform the first pass of compound sanding on vertical walls.

This paper is structured as follows. Section 1 presents an overview of the requirements and chosen hardware for the robot. Section 2 presents the machine vision algorithm used to localize the compound joint. Section 3 presents the control strategies used to finish the drywall. Section 4 presents our measurement methodology and discusses the results.

2 Sanding robot hardware

The robot hardware has been designed in accordance with our partners' requirements, which can be summarized as follows: 1) The ability to navigate the construction plant and overcome ground obstacles such as cable covers and ground conveyor chain tracks; 2) A vertical sanding reach of 10 feet to cover the majority of their wall production output; and 3) An orbital sander compatible with vacuum dust control. Figure 1 presents the overall robot and Table 1 the major hardware components, which are described below.

The mobile base is a Clearpath's Husky[1] with the high-torque motorization option for high payload. This mobile platform let us move the robot using a wireless remote control in the off-site construction environment.

For the mobile arm, a collaborative robot is necessary to limit interaction forces, because mobile robots are not constrained to a traditionally fenced robot environment.

[1] https://clearpathrobotics.com/husky-a300-unmanned-ground-vehicle-robot/

The Fanuc CRX-20iA/L[2] has a reach of 1418 mm and a maximum payload of 20kg to manipulate the orbital sander. This arm also features internal force sensors that enables force control. An additional robot axis motor is necessary to reach 10' high walls, and an Igus linear axis of 1050 mm[3] was specified for this task.

The orbital sander mounted on the manipulator arm is a Festool PLANEX LHS-E 225 EQ[4]. The head of the orbital sander was adapted to the robot effector with a custom 3D printed part. Festool P320 ready-to-use abrasive pads for the 225 mm orbital sander are used and is the least abrasive option offered by Festool for this orbital sander.

For the vision system, the RGB-D (color + depth) Intel D435i[5] camera is common and easy to use for the design of the first prototype. After comparing multiple segmentation approaches based on other sensors, such as a Time-of-Flight camera, the combination of near-UV lights with the RGB-D camera was found to be the most efficient in maximizing the visual differences between the compound and the board's paper layer [4].

Commercially-available solutions, such as the CANVAS 1200CX[6], use similar hardware configuration. However, they usually used a sprayed compound, and our study focuses on performance with manually applied compound.

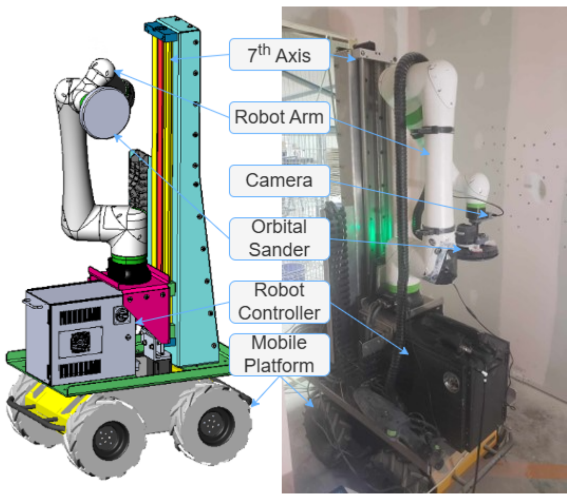

Figure 1. Left: CAD model. Right: Robot

[2]https://crx.fanuc.eu/wp-content/uploads/2022/06/MDS-04849-FR.20220329130728332.pdf
[3]https://www.igus.eu/product/20917?artNr=SLW-25120-xxx
[4]https://www.festoolcanada.com/produits/sableuses-lectriques/sableuses-autoportes--rallonges/571935---planex-lhs-e-225-eq-usa
[5]https://www.intelrealsense.com/depth-camera-d435i/
[6]https://www.canvas.build/products/canvas1200cx/

Table 1. Hardware Overview

Robot Arm	CRX-20iA/L
Robot Controller	R-30iB Mini Plus
Additional Axis Motor	βiS 4/4000-B
Linear axis	Igus SLW-25120
Camera	Intel RealSense D435i
UV Light	Everbeam 100W IP66
Orbital Sander	PLANEX LHS-E 225 EQ
Sander's abrasive	Festool GRANAT P320
Mobile Platform	Clearpath Husky

3 Perception pipeline

The perception pipeline is used to find the 3D position coordinate of the compound surface to finish in the 3D frame of the camera. The combination of a stereo depth camera with an RGB component creates a point cloud in the camera's frame with corresponding colour values for each point.

Every point in the cloud is segmented depending on whether they originate from the paper layer of the gypsum board or from the compound covering the seam of the boards and the screws head. First, near-ultraviolet spotlight helps differentiate the board and the compound because the fine layer of paper on the boards is fluorescent and emits blue light when exposed to near-UV light [4]. While the joint compound simply reflects the near UV light [4] as shown in figure 2.

To maximize this colour difference, empirical tests revealed that the red colour channel is best to differentiate the blue fluorescence from the paper layer and near-UV reflection from the compound. Thus, the compound surface corresponds to the highest value in the red channel. Then the image is equalized with a Contrast Limited Adaptive Histogram Equalization (CLAHE) and filtered with Otsu's threshold [4]. Then, a median filter is used with a kernel of 21 and a binary threshold of 250, both empirically determined. A segmentation example is shown in figure 2. Finally, the open-source computer vision algorithm minimal area rectangle from OpenCV[7] generates an oriented bounding box around the highlighted compound in the image [4].

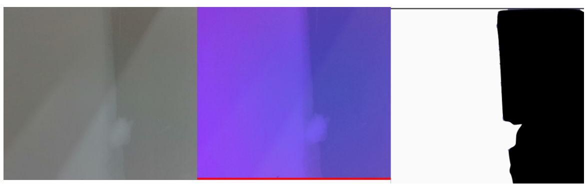

Figure 2. Left: RGB vision. Middle: RGB vision with near-UV spotlight. Right: Segmentation result

[7]https://opencv.org/

4 Control Law

Depending on the orbital sander diameter, the 2D bounding box in the RGB image frame is segmented into smaller rectangles corresponding to the sanding passes necessary to cover the full compound surface to finish. Empirically, 2 or 3 passes are needed to cover most seams. The sequence of rectangles, from top-left to bottom-right, form a path for the orbital sender to follow. This 2D path is converted to 3D in the reference frame of the stationary robot by finding the corresponding points in the depth channel of the RGB-D camera.

The 3D path points are converted into robot's joint position with KDL inverse kinematics available with ROS's moveIT package[8] and sent to the robot with a modified version of ROS indsutrial's KAREL drivers[9]. The Fanuc's force control schedule is adjusted with a closed-loop force control of 1.1N (empirically determined) and with the parameters tuned to reduce vibration [5]. This make sure the arm applies a constant contact with a varying environment.

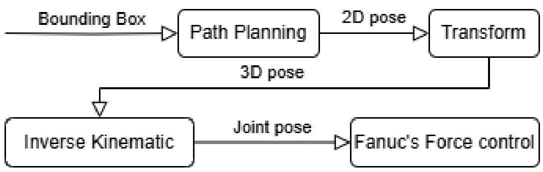

Figure 3. Block diagram of the control law

To make a good assisting robot for drywall finishing, the robot should at least remove the rougher bumps and cracks that workers would remove with similar power tools, without removing too much material so that workers may remove the finer details with handheld sanders. Also, removing too much material would leave visible traces under the paint. To leave the workers with enough material for the sanding block finish, the robot should remove slightly less material than the workers.

Three parameters determine the depth of material removed [6]: the grit of the sanding paper (Preston coefficient), the relative velocity between the compound and the orbital sander, and the pressure applied by the robot arm. Using the right equipment is key to control the first two parameters. Although the specific Preston coefficient between the compound and the sander abrasive was not examined in this study, using the finest grit abrasive reduces Preston coefficient, thus also the amount of material removed. In the same way, using the lowest orbital sander speed also reduces the amount of material removed. Reducing the commanded force in the Fanuc contouring controller would reduce the pressure, but it also reduce the performance of the algorithm to maintain contact on the compound surface.

[8]https://moveit.ai/
[9]https://wiki.ros.org/fanuc/

Although not all the sanding would be done automatically, this robot would reduce most of the workers' inconvenience with dust exposure and strain on the body, but also reduce human labour time while maintaining workers control over quality.

5 Experimental setup and results

The HandyScan 300 handheld external precision laser scanner, also known as the HandyScan SILVER[10] is used to measure the results of the finish. The difference between the scan before and the scan after the finish determines the depth of compound removed. To do so, scans are realigned using an Iterative Closest Point (ICP) algorithm with HandyScan's positioning targets to obtain the transformation between both frames of reference. Differences between point cloud positions in the Z axis serve as a basis for comparison.

The average depth in the Z-axis across the joint before and after the finishing, as shown in bottom figure 4, can help visualize the orientation of the two gypsum boards and the shape of the compound on the seam.

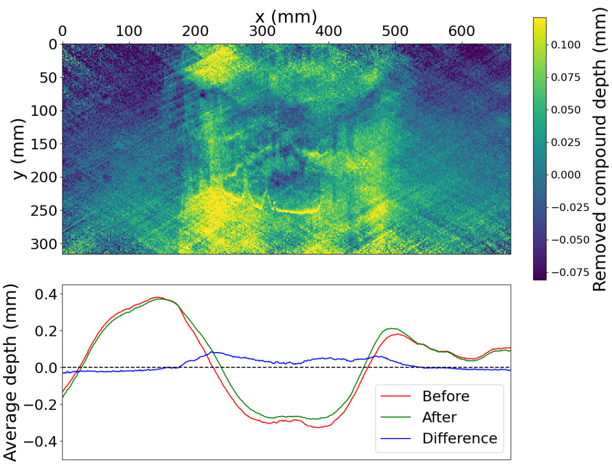

Figure 4. Top: Position difference in the camera Z axis before and after finishing. Bottom: Means position in the camera Z axis across the joint

5.1 Worker baseline

To investigate how much material is removed during workers' drywall finishing, 7 sample scans from different seams were taken before and after the complete finishing process (power tool-assisted and hand-finished). The baseline of what a typical drywall finish is the average of all depth removed plus twice the average standard deviation

[10]https://www.creaform3d.com/en/handyscan-3d-silver-series-professional-3d/technical-specifications

Table 2. Worker and robot depth removed (mm)

	Worker		Robot	
	Means	σ	Means	σ
1	0.10	0.04	0.08	0.03
2	0.11	0.07	0.09	0.06
3	0.04	0.04	0.10	0.03
4	0.04	0.04	0.14	0.05
5	0.08	0.05	0.09	0.03
6	0.13	0.08		
7	0.04	0.03		
8	0.16	0.04		
Means	0.09	0.05	0.10	0.04
Upper bound	0.19		0.18	

for each joint in Table 2. With a normal distribution, two standard deviations over the mean represent 95% of all measurements. This gives an approximate upper bound of how much material is removed from the general surface without measuring the max depth measured, which is where the large bump would skew the result.

On average, the upper bound of the worker's measured depth is 0.19 mm (average mean of 0.09 plus twice the average standard deviation of 0.05). Large bumps caused by uneven drying will have more material removed and larger cracks will have relatively less material removed.

5.2 Robot finishing

With adjusted orbital speed and commanded force, preliminary results presented in Table 2 show that the robot sanded an average amount of 0.10 mm with an average standard deviation of 0.04 mm. Thus, 95% of the robot's finish is expected to be below approximately 0.18 mm. With the upper bound of the workers estimated at 0.19 mm, it leaves enough material for the workers' finer handheld tool finish. The workers' upper bound is a useful benchmark for the robot's adjustment, but it is not a hard limit because many of the workers' and robot's individual scans had a mean and standard deviation higher than the expected workers' upper bound and they still did not damage the gypsum board. Furthermore, individual seams with a larger amount of irregular compound features, such as bumps, necessarily lead to a larger amount of material removed, even if the applied finish is the same. Thus, the proposed system performs as expected regardless of the amount of irregular compound features.

6 Conclusion

A construction robot has been tested to assist the finishing of drywall. The robot is composed of a machine vision algorithm to plan the trajectory of the robot arm, the integrated Fanuc force controller to regulate the pressure of the orbital sander on the wall, and a mobile platform to navigate autonomously inside the off-site construction environment. Preliminary results show that the robot can detect compound on gypsum boards and use the orbital sander mounted on the robot arm to do most of the drywall finishing. Compared to the workers, the robot sanded out a similar quantity of compound and left enough material to adjust the finish if necessary, without removing too much material as to irreparably damage the surface.

Future work includes confirming the repeatability of the preliminary test, introducing the robot to a production line for an assessment by the workers and investigating the automation of the mobile platform, enabling the whole system to navigate autonomously between drywall joint. We will also investigate the applicability of the approach to on-site construction settings.

Acknowledgements

The design of the system has been done in partnership with R.C.M. Solutions Modulaires Inc. and this work was supported by Mitacs Business Strategy Internship (BSI) grant IT34280 and the NSERC-CREATE program on collaborative robotics in manufacturing (CoRoM).

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