Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 106 (2022) 108–113

www.elsevier.com/locate/procedia

9th CIRP Conference on Assembly Technology and Systems

Contour Tracking Control for Mobile Robots applicable to Large-scale Assembly and Additive Manufacturing in Construction

Lukas Lachmayer[a,*], Tobias Recker[a], Annika Raatz[a]

[a] *Institute of Assembly Technology, Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany*

* Corresponding author. Tel.: +49-511-762-18278 ; fax: +49-511-762-18251. *E-mail address:* lachmayer@match.uni-hannover.de

Abstract

In the construction industry, as well as during the assembly of large-scale components, the required workspaces usually cannot be served by a stationary robot. Instead, mobile robots are used to increase the accessible space. Here, the problem arises that the accuracy of such systems is not sufficient to meet the tolerance requirements of the components to be produced. Furthermore, there is an additional difficulty in the trajectory planning process since the exact dimensions of the pre-manufactured parts are unknown. Hence, existing static planning methods cannot be exerted on every application. Recent approaches present dynamic planning algorithms based on specific component characteristics. For example, the latest methods follow the contour by a force-controlled motion or detect features with a camera. However, in several applications such as welding or additive manufacturing in construction, no contact force is generated that could be controlled. Vision-based approaches are generally restricted by varying materials and lighting conditions, often found in large-scale construction. For these reasons, we propose a more robust approach without measuring contact forces, which, for example, applies to large-scale additive manufacturing. We based our algorithm on a high-precision 2D line laser, capable of detecting different feature contours regardless of material or lightning. The laser is mounted to the robot's end-effector and provides a depth profile of the component's surface. From this depth data, we determine the target contour and control the manipulator to follow it. Simultaneously we vary the robot's speed to adjust the feed rate depending on the contour's shape, maintaining a constant material application rate. As a proof of concept, we apply the algorithm to the additive manufacturing of two-layer linear structures made from spray PU foam. When making these structures, each layer must be positioned precisely on the previous layer to obtain a straight wall and prevent elastic buckling or plastic collapse. Initial experiments show improved layer alignment within 10 % of the layer width, as well as better layer height consistency and process reliability.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Consistent automation is considered the most forward-looking development for increasing productivity and sustainability in the construction industry [1]. Thereby, due to the required workspace and the demand for scalability, there is a trend towards developing autonomous mobile systems [2]. These systems are required to be highly flexible, to reduce acquisition costs. So, to perform diverse operations such as large-scale assembly, additive manufacturing, and part processing, the utilized mobile robot systems commonly combine a mobile platform and a manipulator [3, 4, 5, 6].

However, since mobile platforms are primarily designed for transportation duties, such composite systems suffer from inferior positioning accuracy. The reason for the inferior performance is the poor accuracy of the inexpensive and hence widely used internal localization. Especially when operating on uneven or soiled surfaces, localization accuracy will decreases due to slippage. Certainly, such disadvantageous conditions occur constantly in large-scale factory buildings or on construction sites. Thus, since all manufacturing applications require precise positioning, most machining processes are carried out with fixed platform positioning.

In addition to the insufficient positioning of the platform, the wide tolerances of large-scale components pose another problem for machining, assembly, or additive manufacturing with mobile robots.

E-mail address: lachmayer@match.uni-hannover.de (Annika Raatz).

10.1016/j.procir.2022.02.163

Nomenclature

Δd	lateral deviation
$\mathbf{e}$	control error
$\hat{\mathbf{e}}$	control error with velocity offset
$\mathbf{h}$	height profile
$\hat{\mathbf{h}}$	median filtered height profile
$\mathbf{h_d}$	desired height
h_i	height data points
Δh	height deviation
K_i	integral gain
K_p	proportional gain
R_s	scanner resolution
$\mathbf{r}$	reference profile
${}^{i}\mathbf{T}_j$	transformation matrix from i to j
$\hat{\mathbf{x}}_c$	pose offset
$\dot{\mathbf{x}}_c$	velocity control vector

Such operations are usually planned based on a CAD model of the part. Nevertheless, due to the tolerances, the model can significantly differ from the actual part. Therefore, an additional end-effector adjustment is necessary to compensate for inaccuracies of prefabricated components [3, 7]. So, for fully autonomous applications, detection of manufactured parts is needed to ensure relative positioning between the robot and the component [8].

This paper aims to increase the position accuracy relative to an existing contour and improved material deposition of a mobile robot to enable large-scale manufacturing. The content is divided into the following sections: First, we briefly overview available methods and current research approaches. We then present our experimental setup and explain the algorithm developed. Based on the experimental results and the evaluation, statements on applicability and functionality are made. Finally, additional enhancements are discussed.

2. Related Work

Two basic approaches exist for increasing the positioning accuracy of mobile robots. On the one hand, referencing via external measuring systems such as total stations is applied to improve absolute localization. First experiments utilizing such additional measurement systems for manufacturing while moving are carried out in [9]. Aruco markers were placed within the workspace and captured by a stereo camera system mounted on the platform to ensure good positioning accuracy. However, the precise alignment of the markers and optimal marker vision must be ensured throughout the whole process.

On the other hand, existing environmental objects are recognized and combined with onboard localization sensors to achieve enhanced relative accuracy. In favor of higher positioning accuracy, [10] relies on the fusion of LiDAR scanners, a visual detection system, an IMU, and the platform's initial odometry data. However, examining the improved system via external measuring reveals that the self-localization could only be narrowed to 5 *cm* in a 10 by 10 *m* workspace. While this is a significant improvement compared to stand-alone odometry, the precision is still not sufficient for manufacturing tasks.

Contour following is a common challenge when tasks include components subject to manufacturing tolerances [11] or require operating in an unknown environment. By implication, part tolerances and variable surroundings lead to inaccurate robot positioning when solely relying on predefined robot path planning. To compensate for such undefined boundaries, an additional end-effector alignment relative to an existing contour can be used. The available approaches can generally be divided into tactile and non-tactile methods.

In [12], for example, a tactile sensor is used to explore and follow the outer 2D contour of an unknown object. While this reduces the relative positioning error to 5 *mm*, the force-based tapping approach is unsuitable for performing continuous tasks. An advanced online force-controlled method is described by [13]. While moving along a given 2D trajectory, the z-coordinate of the end-effector is adjusted according to force values measured by a 6-DOF force/torque sensor. Thus moving across an unknown surface is possible while maintaining contact. However, it should be noted that in some cases contacting the surface may not be allowed, or contact forces cannot be measured constantly during all tasks. Thereby non-tactile methods are more advantageous.

Non-tactile contour-following is mainly applied in autonomous mobile robotics and is often referred to as wall-following. Toibero et al. [14] propose an approach based on a laser radar sensor for wall contour recognition and following. Besides implementing multiple control modes to handle contour interruptions and obstacles, the main focus is on averaging and filtering the sensor data to provide stable controller input values. This also seems necessary when transferring contour-following algorithms to end-effector correction values. An example for such a correction algorithm is proposed by [15]. Within their paper, the authors install a camera to a manipulator and use an image processing algorithm to calculate the x and y tool position error within the image frame. Nevertheless, room lighting, as well as the surface condition of the machined com-

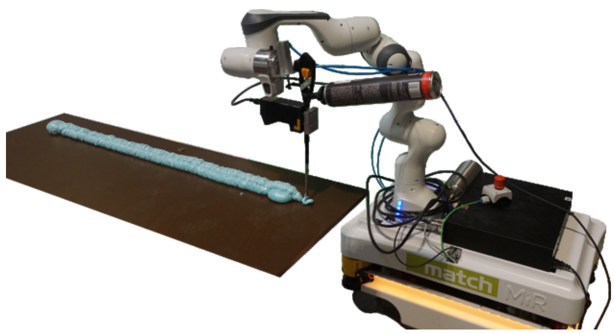

Fig. 1. PU foam printing with mobile robot requires contour following for multiple layers

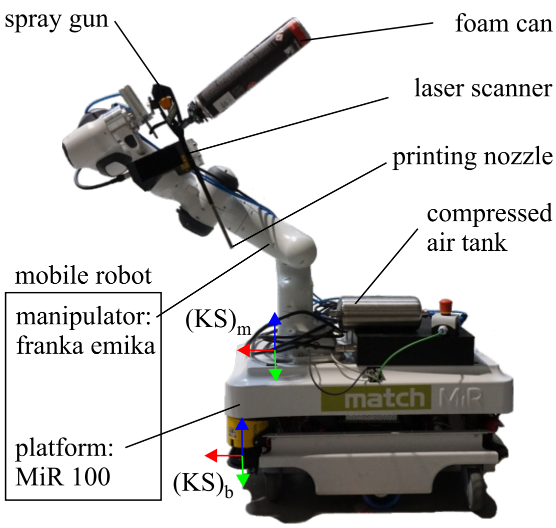

Fig. 2. mobile robot with manipulator $(KS)_m$ and base coordinate system $(KS)_b$

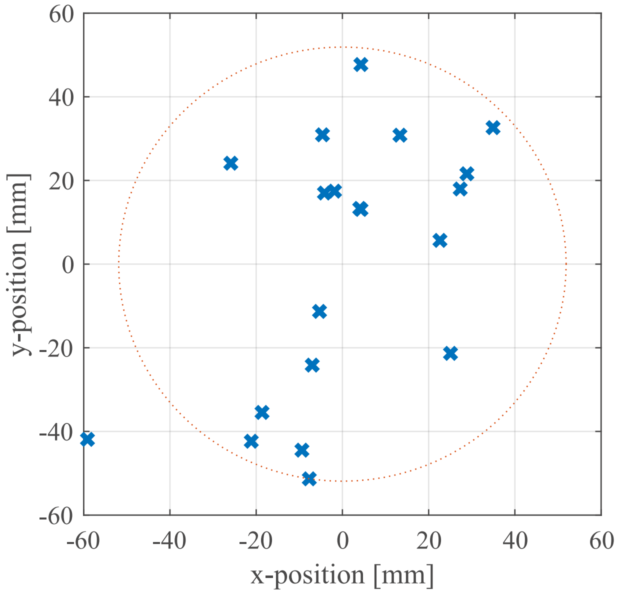

Fig. 3. repeatability results for Mir 100 end-effector position

ponent, had to be taken into account. In this context, [16] further enhances the contour tracking capabilities by adding a 2D line sensor to the end-effector of a 6-DOF manipulator. By running the scanner ahead of the tool and calculating the path from the recorded contour points, the manipulator automatically follows an unknown component feature. A similar industrial approach from Volk Welding, sold as ARC-EYE CSS, seems to calculate correction values for welding applications based on a circular sensor. Nonetheless, no mobile application was tested.

Previous research has shown that contour tracking algorithms are capable of accurately guiding robotic end-effectors on existing objects. Therefore we assume, that by further development of former approaches for mobile robotic systems we will be able to compensate for the low positioning accuracy.

Since the initially mentioned manufacturing tasks are generally carried out on existing geometries, e.g., printing one layer on top of each other or assembling pre-produced components, we chose to enhance the accuracy of our mobile manipulator by referencing directly to the processing component. Specifically, our method can correct the platform and robot position relative to a given 2D contour of the workpiece. We record the necessary data with a high-precision 2D laser scanner attached to the end-effector of the manipulator. Based on real-time 2D profile recognition, correction values for the position of the tool are determined. These position offsets are converted into velocity feedforward values and transferred to the manipulator and the mobile platform using a PI-controller. The algorithm was tested on a mobile 3D printer by layer-wise application of PU foam (see Fig. 1). We aimed for a final accuracy and average layer depositions error below 10 % of the layer width, which is equal to 0.7 *cm*, to ensure build-up stability. Additionally, we strive for an increased consistency of the layer height through mobile platform feed rate adjustment. Based on the proposed contour following procedure, the system can perform manufacturing processes on components with unknown dimensions and during movement, without limitations to the workspace.

3. Experimental Setup

The experimental setup for investigating our contour following control algorithm is based on a non-holonomic Mobile Industrial Robot 100 (MiR 100) platform controlling its movement speed based on wheel odometry. The platform is extended by a 7-axis Franka Emika manipulator with a payload of 3 *kg*. In the following, this mobile manipulator is referred to as ”the robot”. We attached a PU foam gun to the manipulator of our robot (see Fig. 2), which supplies the material. The can is opened and closed using a valve actuated by pressurized air. For control purposes, we installed a 2D line sensor (Keyenece LJ-V 7080). A central computer controls all components by using the *Robot Operating System* (ROS).

The positioning of the platform within our test environment is based on a predefined 2D map. The robot position within this map is determined by an adaptive Monte Carlo localization approach (AMCL[1]) combining wheel odometry and the two laser scanners at the opposite corners of the platform. To evaluate the accuracy of our localization, we attached a spherically mounted retroreflector (SMR) to the robot's tool and tracked its position with a high precision Faro Vantage S laser tracker. With a measurement deviation of about 16 μm , the tracker can be considered ground truth compared to AMCL. We then approached the same point 20 times using the MiR platform and recorded the error pattern (see Fig. 3). The experiment showed a repeatability of 51.9 *mm*, which coincides with the manufacturer's specification of 50 *mm*.

[1] http://wiki.ros.org/amcl

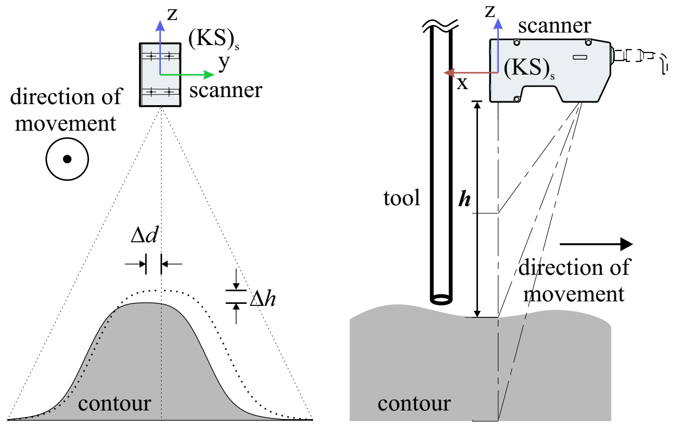

Fig. 4. frontal view with recognized deviations Δh, Δd and lateral view with sensor position ahead of the printing nozzle

4. Algorithm

Our contour tracking algorithm consists of two parts. In the first part, the respective contour is detected. In the second part, we control the robot to follow the contour while correcting height deviations in the previous layers.

4.1. Contour tracking

We first use the 2D laser-scanner for contour tracking to get a contour profile close to the tool. The scanner is oriented in the machining direction of the tool so that the contour can be seen in front of the tool. While moving the robot, we create 200 laser profiles per second. From each profile, we calculate basic geometric features like height, width, or volume to estimate the contour's deviation from a target contour. This deviation is transformed into the robot's coordinate system and added to the velocity control loop as an offset. In this paper, we measure the height profile $\mathbf{h}$ of a printed PU foam layer (see Fig. 4).

Given a reference contour, we can calculate the height deviation Δh and lateral deviation Δd as:

$$\Delta h = h_d - \max(\hat{\mathbf{h}}) \qquad \Delta d = \max_i(\hat{h}_i) \cdot R_s \tag{1}$$

with $\hat{\mathbf{h}}$ being the median filtered (n=5) height:

$$\hat{\mathbf{h}} = \mathrm{med}(\mathbf{h}) = \mathrm{med}(h_1, h_2, \ldots, h_i) \tag{2}$$

where h_i denotes the individual data points from a given profile, h_d the desired height and R_s denotes the scanner resolution. A median filter is used to minimize the effects of sensor noise. From Δh and Δd we can calculate a correction term for the robot to adapt its path planning.

4.2. Mobile robot control

To control our mobile robot, we define a target trajectory for the platform and the manipulator. The Cartesian target trajectory is calculated offline and maintains the range and velocity limits of the manipulator as well as a constant tool center point

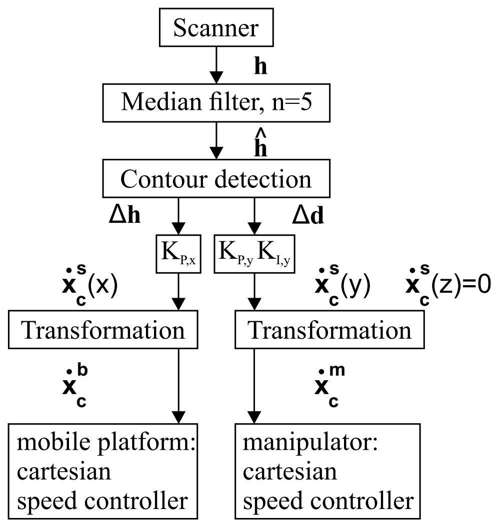

Fig. 5. integration of the scanner evaluation into the robot control, height error are added to the platform speed, position errors are integrated to the manipulator speed

(TCP) velocity. Using Δd we adjust this pre-planned manipulator trajectory to account for lateral deviations (y-direction) from the target path (see Fig. 5). The adjustments are made using a PI-controller with a linear gain $K_{P,y}$ and an integral gain $K_{I,y}$. The height (z-direction) of the trajectory is not modified, as this would result in an uneven layer height. Instead, we increase or decrease the material application volume to even out height deviations from the previous layer. To change the material application speed, we either have to adjust the flow of PU foam or change the feed rate of the mobile platform. As we are using ready-to-use foam cans (see Fig. 2), which offer no simple way for flow control, it is much easier to adjust the feed rate by slowing down or speeding up the platform along the contour (x-direction). The resulting control term $\dot{\mathbf{x}}_c^s$ is:

$$\dot{\mathbf{x}}_c^s = \begin{pmatrix} \dot{v}_x \\ \dot{v}_y \\ \dot{v}_z \end{pmatrix} = \begin{pmatrix} K_{P,x} \cdot \Delta h \\ K_{P,y} \cdot \Delta d + K_{I,y} \cdot \int \Delta d \, dt \\ 0 \end{pmatrix} \tag{3}$$

All adjustments to the trajectory are done in the Cartesian space. The inverse kinematics are calculated using *MoveIt* for *ROS Melodic*. *MoveIt* also avoids singularities and collisions for the manipulator.

In 3 we use the superscript "s" to indicate that the velocity $\dot{\mathbf{x}}_c^s$ is defined in the scanner's coordinate system $(KS)_s$ (see Fig. 4) and first has to be transformed into the manipulator $(KS)_m$ and platform coordinate system $(KS)_b$ (see Fig. 2) to control the robot. This transformation is done in (4).

$$\dot{\mathbf{x}}_c^b =^b \mathbf{T}_s \cdot \dot{\mathbf{x}}_c^s \quad \text{, with} \quad ^b\mathbf{T}_s =^b \mathbf{T}_m \cdot^m \mathbf{T}_{TCP} \cdot^{TCP} \mathbf{T}_s \tag{4}$$

Here, $^b\mathbf{T}_s$ denotes the transformation from the platform's base to the scanner, which consists of the static transformation between the platform's base and the manipulator's base $^b\mathbf{T}_m$, the

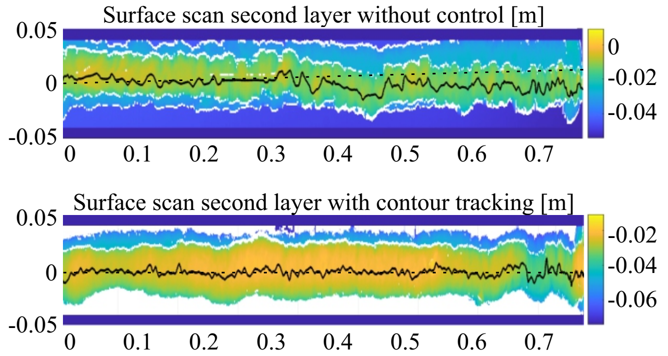

Fig. 6. scanned height profiles of uncontrolled and controlled PU foam printing

transformation from the manipulator's base to the TCP ${}^{m}\mathbf{T}_{TCP}$ (direct kinematics), and the static transformation from the TCP to the scanner frame ${}^{TCP}\mathbf{T}_{s}$. The transformed velocity offset $\dot{\mathbf{x}}_c^b$ is then added to velocity error $\mathbf{e}$ resulting in the adjusted velocity error $\hat{\mathbf{e}}$. In this way, we are effectively altering the reference velocity $\mathbf{r}$ to account for the inaccuracy of our robot.

5. Evaluation

To evaluate the functionality of our algorithm, we have done two experiments. In both experiments, a mobile robot is supposed to dispense two layers of PU foam on top of each other. First, the robot applies an 0.7 m long initial layer of foam. Then, the robot raises the nozzle by one layer height and extrudes a second layer moving in the opposite direction. In the second experiment, however, the nozzle position is controlled by our algorithm. The results of the two experiments are evaluated by 3D surface scans (see. Fig. 6) and visual inspection (see Fig. 7).

At the beginning of the second layer, the nozzle is exactly above the previous layer since the robot only moved in the z-direction. However, due to the low repeatability of the mobile robot ($\pm 52\,mm$), the previous trajectory cannot be repeated exactly. After 0.7 m the nozzle has drifted about 20 mm from the first layer. The surface scan also reflects this clearly when comparing the centerline of the first layer (dashed line) with that of the second layer (see Fig. 6). The lateral deviation results in the second layer sliding off the first layer when printing without the control algorithm (see Fig. 7).

In contrast, the experiment with contour tracking shows no deviation from the centerline. The reason for this can be seen in the feed rate and lateral correction values. They show that, like in the first experiment, the mobile platform deviated from its previous path. However, this time the contour tracking algorithm adjusted the manipulator to compensate for this deviation (see Fig. 8). It should be noted that although the scale of our experiment is limited due to material supply constraints (foam can), the experiments show no degradation of contour quality after 0.7 m, especially compared to the uncontrolled application. The last increase in the velocity correction was generated by a build-up of material within the sight of the scanner. This is due to the early expansion of the foam after the valve is closed and the printing process is stopped.

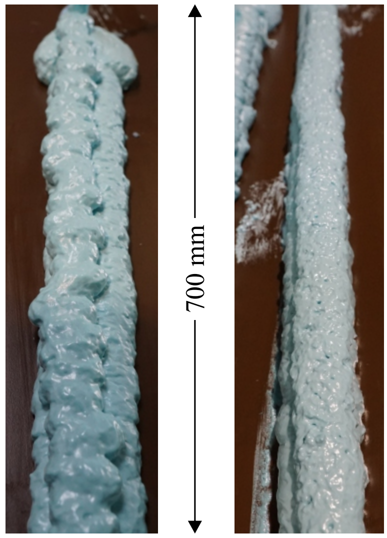

Fig. 7. uncontrolled and controlled PU-foam printing

6. Conclusion

The low positioning accuracy of mobile robots currently limits their suitability for autonomous machining of large-scale components. In applications such as additive manufacturing, the inaccuracy means that the individual layers cannot be stacked properly on top of each other. We have presented an algorithm to align a mobile robot with an existing contour / layer to allow the precise printing of new layers on top of an existing layer. This means the workpiece tolerances are almost exclusively limited by the accuracy of the first layer. The contour detection is performed by evaluating 2D-laser scanner data recorded directly at the end effector. Thus, the setup requires

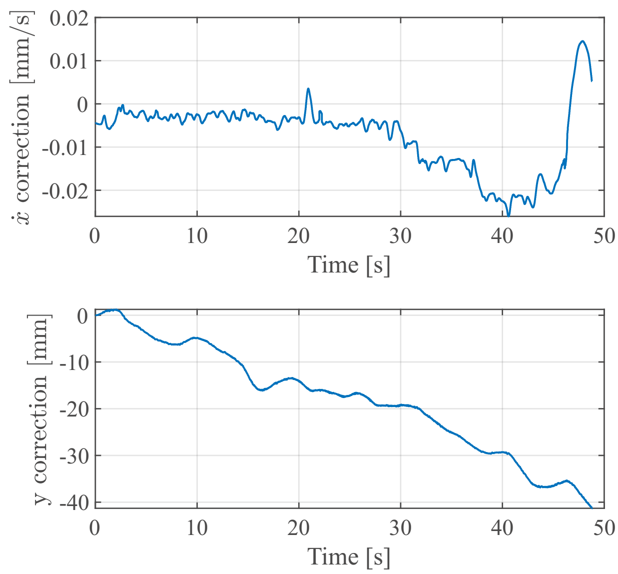

Fig. 8. feed rate correction and lateral correction values

no external measurements. First experimental results from additive manufacturing with PU foam show a major improvement of the TCP positioning in relation to the material deposition location. Based on the outcome (see Fig. 7), this correction results in a higher overlap of the individual layers and an improved dimensional accuracy. Furthermore, control of the feed rate has been implemented to realize a constant layer height. However, due to the low predictability of the foam's expansion, the final layer height of the expanded material is subject to considerable fluctuations between the individual tests. Therefore, adjusting the feed rate produces a locally increased or reduced material application, but the final layer height after unpredictable foam expansion cannot be set precisely. Thus given, the controller reacts by reducing the feed rate (see Fig. 8), but the resulting layer height still shows some irregularities (see Fig. 6).

7. Outlook

The experiments presented in this paper demonstrate the viability of a contour tracking controller for enabling a mobile robot to perform production tasks while moving. Although the algorithm performed well during the challenging process of 3D printing with PU foam, two main topics arise for further development.

One focus is in particular on the extension to more complex shapes. While the first experiments concentrated on straight wall elements, the main advantage of additive manufacturing is its freedom of form, and other aspired tasks also require advanced tool paths. Therefore upcoming research will investigate the performance of our algorithm during curves and three-dimensional trajectories. In specific we need to consider the offset between the printing nozzle and the recorded data, to account for the possible inclination between the scanner and contour.

The second concern relates to a validation based on varying manufacturing processes. While it has been proven that a simple controller parameterization and a straightforward controller design is sufficient for 3D printing, assembly or machining processes may require a stiffer control method. In this regard, a generally practical approach to define the controller parameters and an advanced control algorithm for multiple tasks might be required.

Acknowledgements

The authors gratefully acknowledge the funding by the Deutsche Forschungsgemeinschaft (DFG – German Research Foundation) – Project no. 414265976. The authors would like to thank the DFG for the support within the SFB/Transregio 277 – Additive manufacturing in construction. (Subproject B04)

References

[1] T. Bock, The future of construction automation: Technological disruption and the upcoming ubiquity of robotics, Automation in Construction 59 (2015) 113–121.
[2] R. Bogue, What are the prospects for robots in the construction industry?, Industrial Robot: An International Journal (2018).
[3] X. Zhang, M. Li, J. H. Lim, Y. Weng, Y. W. D. Tay, H. Pham, Q.-C. Pham, Large-scale 3d printing by a team of mobile robots, Automation in Construction 95 (2018) 98–106.
[4] A. Gawel, H. Blum, J. Pankert, K. Krämer, L. Bartolomei, S. Ercan, F. Farshidian, M. Chli, F. Gramazio, R. Siegwart, et al., A fully-integrated sensing and control system for high-accuracy mobile robotic building construction, in: 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, 2019, pp. 2300–2307.
[5] V. Helm, S. Ercan, F. Gramazio, M. Kohler, Mobile robotic fabrication on construction sites: Dimrob, in: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, 2012, pp. 4335–4341.
[6] B. G. de Soto, I. Agustí-Juan, J. Hunhevicz, S. Joss, K. Graser, G. Habert, B. T. Adey, Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall, Automation in Construction 92 (2018) 297–311.
[7] K. Subrin, T. Bressac, S. Garnier, A. Ambiehl, E. Paquet, B. Furet, Improvement of the mobile robot location dedicated for habitable house construction by 3d printing, IFAC-PapersOnLine 51 (11) (2018) 716–721.
[8] H. Ardiny, S. Witwicki, F. Mondada, Construction automation with autonomous mobile robots: A review, in: 2015 3rd RSI International Conference on Robotics and Mechatronics (ICROM), IEEE, 2015, pp. 418–424.
[9] M. E. Tiryaki, X. Zhang, Q.-C. Pham, Printing-while-moving: a new paradigm for large-scale robotic 3d printing, in: 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, 2019, pp. 2286–2291.
[10] H. Blum, J. Stiefel, C. Cadena, R. Siegwart, A. Gawel, Precise robot localization in architectural 3d plans, arXiv preprint arXiv:2006.05137 (2020).
[11] A. S. Prabuwono, R. Sulaiman, E. Sundararajan, Contour following task with dual sensor logic algorithm for adept selective compliant assembly robot arm robot 1 (2009).
[12] U. Martinez-Hernandez, G. Metta, T. J. Dodd, T. J. Prescott, L. Natale, N. F. Lepora, Active contour following to explore object shape with robot touch, in: 2013 World Haptics Conference (WHC), IEEE, 2013, pp. 341–346.
[13] A. Winkler, J. Suchỳ, Force controlled contour following on unknown objects with an industrial robot, in: 2013 IEEE international symposium on robotic and sensors environments (ROSE), IEEE, 2013, pp. 208–213.
[14] J. M. Toibero, F. Roberti, R. Carelli, Stable contour-following control of wheeled mobile robots, Robotica 27 (1) (2009) 1–12.
[15] H. Zhang, H. Chen, N. Xi, G. Zhang, J. He, On-line path generation for robotic deburring of cast aluminum wheels, in: 2006 IEEE/RSJ international conference on intelligent robots and systems, IEEE, 2006, pp. 2400–2405.
[16] H. Koch, A. König, A. Weigl-Seitz, K. Kleinmann, J. Suchỳ, Force, acceleration and vision sensor fusion for contour following tasks with an industrial robot, in: 2011 IEEE International Symposium on Robotic and Sensors Environments (ROSE), IEEE, 2011, pp. 1–6.