Mobile Additive Manufacturing: A robotic system for cooperative on-site construction*

G. Dielemans, K. Dörfler

Abstract— **As a next step in development of Additive Manufacturing (AM) processes, mobile systems can be introduced for construction on site. Mobile AM systems provide the potential for parallelization of tasks and cooperative processes, where multiple systems work together on single tasks. These mobile systems are complex developments that require expertise of multiple fields combined. This paper aims to outline the findings of the conception and development process of such a mobile system that has been set up as a research platform.**

I. Introduction

Digital systems for Additive Manufacturing (AM) in building construction have seen rapid developments, with transformations from lab experiments to residential and civil structures [1]. At this time, on-site AM for material deposition is dominated by large-scale stationary systems, the most common of which is the gantry system. These stationary facilities provide limited scalability, as they cover a single build volume. Some developments have been made to improve the efficiency of these systems, which includes gains in efficiency through use of multiple nozzles [2]. A possible alternative are mobile systems, these system have large scalability through their unbounded dynamic workspace and provide parallelization of tasks by employing the swarm principle [3], [4]. This results in mobile systems that have the potential to create structures larger than themselves, where cooperative operation could improve process efficiency.

One of the main limitations for mobile systems to perform AM processes on construction sites is due to the rough nature of the environment [5]. AM is highly sensitive to deviations in localization accuracy, where, at minimum, the resolution of the manufactured object could be diminished, or ultimately it could lead to complete inability of fabrication. Through localization of the mobile system and the end-effector, the deviations could be severely diminished.

Current solutions for localization of mobile systems include the use of Simultaneous Localization and Mapping (SLAM) [6] for navigation and localization. Where the accuracy of the system is highly dependent on the fitted wheel encoders and laser scanners. To increase the relative accuracy to the work piece, secondary sensing systems have been included [7]. These systems range from height measurement sensors [8], 3D scanning and point cloud matching [9], to camera-based sensing [10].

II. System Requirements

Our objective of setting up two mobile research platforms is to perform deposition-based AM of concrete on construction sites at building scale, for which we defined four primary categories, each with their specific requirements. These four categories are: A. the robotic manipulator, B. the mobile platform, C. the AM system, and D. the localization system.

A. Robotic Manipulator: For manipulation of the AM end-effector, an anthropomorphic robotic manipulator is required with six degrees of freedom, which allows for interaction with other systems or humans. With anthropomorphic manipulators, other printing configurations can be considered that allow for a better transfer of forces and contact area between layers, one of these techniques is the tangential continuity method [11].

B. Mobile Platform: A mobile robotic platform is required that allows for autonomous localization and navigation, while the mobile platform should be able to carry a medium sized robot and the peripherals required for AM. The system is required to avoid obstacles or other mobile systems, while preventing compromises on the efficiency of the material deposition process by utilizing minimal and effective movements of the platform. To ensure the maneuverability of the system inside buildings, the maximum size is limited to, or should be able to be reduced to, standardized door openings.

C. Additive Manufacturing system: The AM system is twofold, with an off-board material supply system that can be operated using a digital control system to provide a measured flow of material. Dry material is mixed to recipe, and the concrete is conveyed through a hose to the deposition device at the end-effector of the mobile system. A point of consideration regarding the choice of the mobile system is that this type of material supply will form a tethered connection, which impedes the mobility of the system.

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The material deposition system has a main requirement of creating a high resolution extrusion and requires the change of various parameters, these parameters include the extrusion speed, nozzle shape and size and the potential of retractions to allow for non-continuous extrusion and the halting of extrusion in between elements.

D. Localization: To attain an accurate enough localization system for additively manufactured structures and to allow for cooperative operation of multiple mobile systems, the system requires a two tier system. The first tier of the system is the absolute localization of the mobile platform within the context of the construction environment, finding the relation between the platform, work site, collaborators, and other objects. Combined with the second tier, the localization of the end-effector relative to the work piece, the required accuracy of layered concrete deposition will be attained.

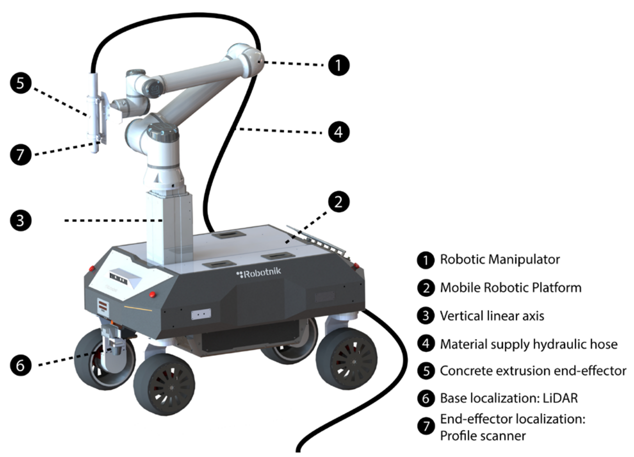

Figure 1. System setup visualization of the mobile additive manufacturing system. Credit original: Robotnik Automation S.L.L, edited.

A. Robotic Manipulator: For manipulation of the end-effector, a Universal Robots UR10e collaborative robot was chosen, which has a range of 1.3m and a maximum end-effector weight of 10kg [13]. The benefit of these anthropomorphic manipulators is that these systems allow for close collaboration with humans due to the included force sensors that detect interference [12].

B. Mobile Platform: In terms of movement types, there are many different systems available. Main categories include: differential steering, Ackermann steering, and holonomic movement. Where the former two categories consider rotation angles and friction based steering, holonomic movement allows for rotation in-place and movement in any direction. Holonomic movement can be achieved through either of two technologies. The first option is the use of a special wheel type, commonly used types are Omni wheels or Mecanum wheels, where the individual direction and speed of rotation determine the movement of the system. A second approach to omnidirectional systems is achieved through independent wheel axis rotation, similar to the first approach, all wheels are controlled individually for speed, direction, and additionally rotation.

With the aim of using an omnidirectional movement system that would also be able to be used in an on-site environment, both special wheel types are excluded as these perform optimally in clean, smooth environments. An alternative was found in the Robotnik RB-VOGUI+ system [14], which is suitable in both in and outdoor environments due to the option of fitting either hard rubber tires or air-filled profile tires. The omnidirectional movement of the system allows for simplified maneuverability over the building site, as it is able to avoid obstacles in various configurations and supports smooth transitions [15].

To ensure building scale, an extension is required for the end-effector to reach ceiling height. Opted is for an extension of the static work range through integration of a vertical axis [16], which allows the robotic manipulator to achieve a total deposition height of approximately 2.7m. This results in a mobile platform with three degrees of freedom, which combined with the robotic manipulator results in a total of nine degrees of freedom.

C. Additive Manufacturing system: The AM system consists of two parts, 1) the material supply system and 2) a material deposition system.

1) Material supply system

A continuous mixing and pumping system M-Tec Duo-Mix Connect [17] was chosen for the material supply, which consists of a mixing system, a material conveying system and provides the connection between both subsystems and the material deposition system. The mixing system provides a consistent material with the right viscosity. This material is then fed to the conveying system, where the material is pressurized and transported through a hose towards the material deposition system at the end-effector of the robotic manipulator. The material flow is controlled through a digital control system.

2) Material deposition system

Deposition of material in the form of extrusion is governed by the end-effector design, where continuous flow of the concrete mixture is desired with limited obstruction. In addition to minimizing obstruction of the concrete flow, the end effector is aimed to be lightweight and to apply minimal strain to the robotic manipulator. Strain on the robotic manipulator has been reduced by the integration of a rotation-free hose connection, while the use of fine threads allowed for thinner wall thicknesses of the extruder housing. The extruder is actuated to precisely control the extruded volume through the use of a screw conveyor, which additionally allows for halting of the printing process. This increases design freedom by allowing relocation of the end effector in between objects or the creation of non-continuous print paths.

D. Localization: The localization of the mobile AM system is separated in two tiers, where the first tier is the mobile platform localization in the global coordinate system of the work site. With on-board systems, including a laser range finder, autonomous navigation and obstacle avoidance is enabled through the use of SLAM. The mobile platform is thus equipped with a RoboSense Bpearl LiDAR, which sports a hemispherical field of view with an absolute accuracy of up to ±3cm [18].

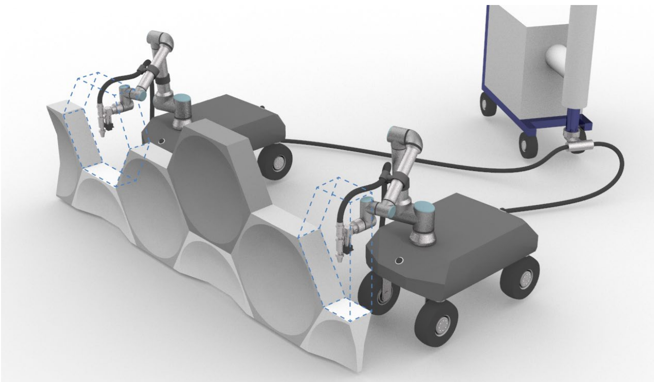

Figure 2. Scenario for cooperative operation of two mobile AM systems performing a 3D printing of discrete parts in a print-drive-print approach.

IV. Conclusion

With this designed mobile AM system, we aim to perform research on extrusion-based AM of concrete, where opted is for a two-tier localization and positioning strategy with a tethered material supply system. The system has an extended range as a result of the integrated vertical linear axis, increasing the maximum deposition height to 2.7m. With two identical systems, planned is to perform experiments with both a print-drive-print and a print-while-drive approach, with the aim of creating building-scale elements using coordination of tasks and cooperative behavior with both machines and humans. Through building component discretization and use of all nine degrees of freedom of the system, aimed will be to create building components with considerations of fabrication constraints, among which the open time of concrete, contact area, and overhang angle.

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References

[1] F. Bos, R. Wolfs, Z. Ahmed, and T. Salet, "Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing," Virtual Phys. Prototyp., vol. 11, no. 3, pp. 209–225, Jul. 2016, doi: 10.1080/17452759.2016.1209867.

[2] "Autodesk Project Escher Finds First Commercial Release in Cronus | Engineering.com." https://www.engineering.com/story/autodesk-project-escher-finds-first-commercial-release-in-cronus (accessed Aug. 19, 2021).

[3] J. Sustarevas, K. X. Benjamin Tan, D. Gerber, R. Stuart-Smith, and V. M. Pawar, "YouWasps: Towards Autonomous Multi-Robot Mobile Deposition for Construction," IEEE Int. Conf. Intell. Robot. Syst., pp. 2320–2327, Nov. 2019, doi: 10.1109/IROS40897.2019.8967766.

[4] J. McPherson and W. Zhou, "A chunk-based slicer for cooperative 3D printing," Rapid Prototyp. J., vol. 24, no. 9, pp. 1436–1446, 2018, doi: 10.1108/RPJ-07-2017-0150.

[5] X. Zhang et al., "Large-scale 3D printing by a team of mobile robots," Autom. Constr., vol. 95, no. August, pp. 98–106, 2018, doi: 10.1016/j.autcon.2018.08.004.

[6] C. Cadena et al., "Past, present, and future of simultaneous localization and mapping: Toward the robust-perception age," IEEE Trans. Robot., vol. 32, no. 6, pp. 1309–1332, Dec. 2016, doi: 10.1109/TRO.2016.2624754.

[7] V. Helm, S. Ercan, F. Gramazio, and M. Kohler, "Mobile robotic fabrication on construction sites: DimRob," in IEEE International Conference on Intelligent Robots and Systems, 2012, pp. 4335–4341, doi: 10.1109/IROS.2012.6385617.

[8] R. J. M. Wolfs, F. P. Bos, E. C. F. Van Strien, and T. A. M. Salet, "A real-time height measurement and feedback system for 3D concrete printing," in High Tech Concrete: Where Technology and Engineering Meet - Proceedings of the 2017 fib Symposium, 2017, pp. 2474–2483, doi: 10.1007/978-3-319-59471-2_282.

[9] K. Dörfler, T. Sandy, M. Giftthaler, F. Gramazio, M. Kohler, and J. Buchli, "Mobile Robotic Brickwork," in Robotic Fabrication in Architecture, Art and Design 2016, Cham: Springer International Publishing, 2016, pp. 204–217.

[10] M. Lussi et al., "Accurate and Adaptive in Situ Fabrication of an Undulated Wall Using an on-Board Visual Sensing System," in Proceedings - IEEE International Conference on Robotics and Automation, Sep. 2018, pp. 3532–3539, doi: 10.1109/ICRA.2018.8460480.

[11] C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger, and P. Morel, "Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders," Mater. Des., vol. 100, pp. 102–109, Jun. 2016, doi: 10.1016/J.MATDES.2016.03.097.

[12] J. E. Colgate and M. A. Peshkin, "Cobots," U.S: Patent No. 5,952,796, Oct. 28, 1997.

[13] "Universal Robots e-Series User Manual UR10e Original instructions (en) UR10e User Manual," 2009.

[14] "RB-VOGUI Mobile Robot - Outdoor Mobile Robot | Robotnik®." https://robotnik.eu/products/mobile-robots/rb-vogui-en/ (accessed Aug. 20, 2021).

[15] M. Udengaard and K. Iagnemma, "Analysis, Design, and Control of an Omnidirectional Mobile Robot in Rough Terrain," J. Mech. Des., vol. 131, no. 12, pp. 1210021–12100211, Dec. 2009, doi: 10.1115/1.4000214.

[16] "LIFTKIT-UR Lifting Columns for Collaborative Robots | Ewellix." https://www.ewellix.com/en/global/products/7th-axis-for-robot/liftkit/liftkit-ur (accessed Aug. 20, 2021).

[17] "duo-mix-connect - m-tec." https://m-tec.com/construction-site-equipment/machines/mixing-pumps/duo-mix-connect/ (accessed Aug. 20, 2021).

[18] "RS-Bpearl - RoboSense LiDAR - Autonomous Driving, Robots, V2R." https://www.robosense.ai/en/rslidar/RS-Bpearl (accessed Aug. 20, 2021).