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A Review on the Techniques, Challenges and Future Possibilities of Mobile Additive Manufacturing

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Abstract
This research provides a review of the current state of the art of mobile additive manufacturing. It reviews the current capabilities of mobile manufacturing units. This includes aerial and ground-based vehicles i.e. it describes the challenges of mobile manufacturing ranging from path planning, localization, to communication between various units. It also describes the role of Artificial intelligence in flexible and smart manufacturing. Additive manufacturing has revolutionized the manufacturing industry in terms of material wastage and quicker manufacturing. Also, it is portable due to its ability to produce a wide range of parts without big machines and tools. It also discusses the challenges of mobile manufacturing of various materials including materials which require sintering. All the reviews on mobile machines discuss about non-sinterable materials which makes this review novel as it discusses the alternatives of conventional sintering which could save time, energy and could be deployed in a flexible manner, hence, increasing the range of materials manufactured in hard-to-reach environments. This article identifies the potential areas for future research in mobile setups.

Keywords: Mobile additive manufacturing, Sintering, Metals, Swarm manufacturing.

Introduction

A review on mobile manufacturing units have comprehensively outlined the current state of the art of these systems ranging from ground based to aerial systems. It also discusses the concept and significance of swarm manufacturing.

Among the seven additive manufacturing techniques (Rastegarpanah et al., 2024), only material extrusion has so far been implemented in mobile systems. This is primarily due to its low weight and simple design, which facilitate integration into mobile systems. Furthermore, it has only been implemented for the fabrication of materials that do not require sintering, since sintering demands heavy equipment and extensive shielding. However, factory-in-a-box setup is available currently which extrudes, debinds and sinters in a container (Oghbaei & Mirzaee, 2010). The idea of discussing sintering options in comparison to traditional ones is the possibility of incorporating them in mobile systems both aerial and ground, to take the current mobile manufacturing a step further through the manufacturing of sinter able materials using mobile setups. Mobile manufacturing can be a game changer in remote environments, disaster relief and space missions and these small devices are a step towards it in the near future.

Moreover, it discusses the current challenges of ground based and aerial systems in terms of localization, path planning, material delivery and the coordination of mutirobot systems. It also presents Artificial intelligence as a possible solution to these problems. The paper first summarizes the systems in terms of solo, swarm aerial and ground based systems, it then presents the advanced sintering techniques and the role of machine learning in AM, which is followed by a discussion.

Methods

This section provides a review of the current state of mobile vehicles in terms of ground-based, aerial, solo or collaborative systems. The researches reviewed are in the time window (2017-2025). It also provides a review of advanced sintering technologies which could be integrated with mobile systems to manufacture materials like metals, ceramics which require sintering. Lastly, it provides a short review on the importance of machine learning in additive manufacturing i.e. how could it be used to make it better. This review can be categorized as a scoping review as it reviews and analyzes the current research and finds the future research areas in mobile additive manufacturing.

Mobile Manufacturing

Ground-based Solo Systems

Various ground-based systems have been developed which deposits and builds concrete while moving (Zhang, 2019; Sustarevas et al., 2018). Both of them discuss about path planning and localization of the nozzle during printing. Both of them use structured lab environments and sensors to achieve the purpose. However, the latter is termed agile as it synchronizes extruder motion with base and eliminates error in extruder´s path when base is given disturbance. Koala 3d prints PLA while climbing using additive manufacturing. The machine combines a climbing robot with a 3d printer (V´elez et al., 2020). It is again for structured lab environements. Table 1 below summarizes the technologies.

Table 1: Ground-based solo systems

Name	Technique	Material	Coordination with other robots
Printing-while-moving: a new paradigm for large-scale robotic 3D Printing (Zhang, 2019)	Ground	Concrete	No
A mobile agile printer robot for on-site construction (Sustarevas et al., 2018)	Ground	Building material	No
Koala 3D (V´elez et al., 2020)	Ground	PLA plastic	No

Ground-based Swarm Systems

Fiberbots work in collaboration and each constructs a composite tube by winding fiber and resin around it in outdoor environment. The robots can climb the composite tube, extend it and can build structures upto tens of times larger than themselves from raw and homogeneous materials (Kayser et al., 2018).

Mobile systems are used to print additively by depositing material used for construction purposes (Sustarevas et al., 2019). Similar mobile systems are used to print plastic filaments using fused deposition modelling approach (Marques et al., 2017). A group of researchers have developed multiple mobile robots to construct a large single piece concrete structure (Zhang et al., 2018). Just one system is tested outdoors (Kayser et al., 2018), rest all of them are in structured environments. Table 2 below summarizes the technologies.

Table 2: Ground-based swarm systems

Name	Technique	Material	Coordination with other robots
Fiberbots (Kayser et al., 2018)	Ground	Fiberglass composite	Yes
YouWasps (Sustarevas et al., 2019)	Ground	Construction material	Yes
3D printer for cooperative 3d printing (Marques et al., 2017)	Ground	PLA	Yes
Large scale 3d printing by a team of mobile robots (Zhang et al., 2018)	Ground	Concrete	Yes

Solo Aerial Systems

Much research has been done in aerial drones for 3d printing. The multirotor unmanned aerial vehicles have better stability at hovering than the fixed unmanned aerial vehicles (Boon et al., 2017), hence, they are utilized in printing during flight. Jacob L., etal., have developed a drone for 3d printing in multidirection during flight. They have used polyurethane foam as the extrusion material (Jacob et al., 2024). A hexacopter which detects cracks in road during flight then gets down and repairs it by 3d printing asphalt over it (Doychinov et al., 2019). Nettekoven A., Topco U., have developed a drone which prints a single layer of PLA while in flight (Nettekoven & Topcu, 2021). However, there are significant improvements required as ground contact is present which is necessary to remove in order to print more layers. They have used ground contact to minimize the wobble of the drone during printing but this is not the ideal solution. Table 3 below summarizes the technologies.

Table 3: Solo Aerial systems

Name	Technique	Material	Coordination with other robots	Deposition mechanism
Multi-Directional Aerial 3D Printer (Jacob et al., 2024)	Aerial	Expanding foam	No	Rotating manipulator
Infrastructure Robotics Research (Doychinov et al., 2019)	Aerial	Asphalt	No	Delta manipulator
A 3D Printing Hexacopter (Nettekoven & Topcu, 2021)	Aerial	PLA	No	None

In order to maintain stable nozzle-bed distance, a deposition mechanism is selected so as to control the placement of the nozzle while minimizing the wobble of the drone. Maintaining a nozzle-bed distance is crucial in 3d printing (Wang et al., 2019) as it largely affects the print quality.

A rotating manipulator is used so as to print on curved surfaces (Jacob et al., 2024). A delta manipulator is used in (Doychinov et al., 2019) so as to minimize wobble of the drone.

Another major concern of printing during hovering is ``Downwashing``. To generate lift against gravity, the rotors generate massive airflow on the wings. As a reaction, the turbulent airflow present downwards lifts the vehicle in turn. This can interfere with the printing mechanism and it needs to be catered for successful prints either by using these manipulators or using the ground racks of the drone.

Swarm Aerial Vehicles

A group of researchers have developed multiple mobile robots to construct a large single piece concrete structure (Zhang et al., 2022). It comprises of two drones namely BuilDrone which deposits the material and the other is called ScanDrone which detects the quality of the print in realtime and communicates to the BuilDrone. The BuilDrone has the nozzle which deposits using the end effector of a delta manipulator so that it compensates for any errors which arise in printing during flight. Ghaziani M., has developed a gimbal for precise printing of PLA from the quadcopter. He has also simulated the concept of swarm UAVs in his thesis (Ghaziani, 2023). He has made significant improvement in printing PLA as compared to Nettekoven´s work (Nettekoven & Topcu, 2021). However, Ghaziani´s results are not tested on the actual drone but only on the test bed and in simulations. Table 4 below summarizes the technologies.

Table 4: Swarm Aerial Systems

Name	Technique	Material	Coordination with other robots	Deposition mechanism
Aerial additive manufacturing with multiple autonomous robots (Zhang et al., 2022)	Aerial	cementitious-polymeric composite mixtures	Yes	Delta manipulator
Fused filament fabrication via multi quadcopter collaboration (Ghaziani, 2023)	Aerial	PLA	Yes	Gimbal

The deposition mechanism in Zhang et al. (2022) is a delta manipulator which is used to stabilize the nozzle during flight. In Ghaziani (2023) although the experiments are conducted on a test bench but vibrations are induced on it to simulate drone movements, hence, a gimbal is used to stabilize the nozzle.

Advanced Sintering

As opposed to conventional sintering, various other sintering technologies like microwave, laser diode and IR sintering have been shown to be effective. These techniques are effective as well as less heavy than the conventional sintering apparatus. Also, the techniques discussed have the capability of sintering in few seconds or minutes rather tahn long hours required in conventional sintering.

This study describes advantages of microwave sintering over conventional sintering; microwave sintering requires much less energy in less time and better mechanical and physical properties are achieved (Oghbaei & Mirzaee, 2010). Another study has concluded that an IR/red diode laser with a wavelength of 808 nm and a laser power ratio of 1.0 is feasible for sintering 3D printlets (Lekurwale et al., 2022). Students from Aerospace engineering at the California State University presented their proposal to deal with lunar dust during landing. Their design features a rover equipped with a microwave sintering apparatus that would traverse the lunar surface, heating and fusing the top layer of regolith to form a solid path for landers. This method is energy-efficient and sustainable, relying on solar power and utilizing materials readily available on the Moon (Tao et al., 2024). This is still a proposal and needs to be developed. If it develops, it will be a breakthrough as it will be so much easier for humans to land on Moon. The idea of discussing here is the incorporation of microwave sintering apparatus in a rover.

A patent describes a machine which debinds and sinters filament extruded metal or ceramic parts. The debinding heater is a low intensity laser or an infrared lamp. Preferably, the low intensity laser is a 1W, continuous wave diode laser for debinding, with a wavelength of ~850 nm. the sintering heater is a CO_2 Laser or a Nd:YAG Laser, a microwave heater or an induction heater (EP 4 137 254 A1, European Patent application, 2023/08, 21192364.4). This could lead to a key contribution to the flexible manufacturing as it has consolidated the material extrusion process in a single machine as opposed to previous practices.

Vilchez et al. (2023) have designed a novel induction heater for sintering powdered extruded material (Vilchez et al., 2023). All of the techniques discussed above are lighter and compact which makes them suitable for integration with mobile manufacturing devices. However, shielding remains an important aspect to take care of during the process. Table 5 below summarizes the key technologies:

Table 5: Advanced Sintering techniques

Technique	Mobility	Heating Method	Materials Used
SLS (laser sintering) (Lekurwale et al., 2022)	Aerial	IR / Red diode laser	Pharmaceutical tablet
Microwave sintering (Tao et al., 2024)	Aerial	Microwave radiation	Lunar regolith
Debinding and Sintering Unit (EP 4 137 254 A1, European Patent application, 2023/08, 21192364.4)	Stationary	Laser, induction or thermal	Metal or ceramic powder mixed with polymeric mass as a binder
Induction Heater (Vilchez et al., 2023)	Stationary	Induction	Metals

Role of Machine learning in Additive Manufacturing

Since Mobile AM does not have guided rails, printing without them especially in air is tricky due to vibrations and air quality, hence, Machine learning can help in adjusting nozzle based on prior trajectories and image data. Also, it can help in optimizing process parameters for printing.

A study has performed a review on deep learning across seven major AM categories - binderjetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photo polymerization (Islam et al., 2024). Another study has performed a review on how machine learning can help improve additive manufacturing by identifying defects, quality assurance and process efficiency (Inayathullah & Buddala, 2025). It also describes whether supervised, unsupervised, semi-supervised or reinforcement learning to be applied based on the AM data available. These techniques can help in making accuracies realtime during printing. Another study has developed a GUI for optimizing process parameters of extrusion based 3d printing which can speed up the time to manufacture with less material waste and more cost efficiency (Rahmani et al., 2022).

Discussion

This above review has outlined the state of the art of ground and aerial mobile manufacturing. The ground based techniques reviewed focus on path planning and feedback control. The two ground robots namely Fiberbots (Swarm ground robot (Kayser et al., 2018)) and Koala (Solo Ground robot (V´elez et al., 2020)) climb on the structure they have printed to print objects larger than themselves. These are the only two which use this approach of climbing the own structure they have printed in order to print structures larger than themselves. However, both of them are still not robust enough in terms of dynamic environments, structural and localization issues.

On the other hand, aerial vehicles facilitate manufacturing in dynamic environments but raise new challenges of flight path planning, vehicle stability and localization. Drones are used as their hovering capability is better than airplanes. However, downwashing poses significant risk in the quality of print as the turbulent airflow can disperse the extruded material way too quickly and unevenly. Hence, the systems described either use extended nozzles or ground racks to mitigate the risk associated with the downwash mechanism.

Collaboration of unmanned aerial vehicles or ground vehicles is also being investigated to build a more robust system. However, these systems still lack robustness in terms of localization, communication and material delivery. Algorithms of machine learning like regenerative and deep learning could be used to produce a more reliable network of mobile robots especially for accuracy from aerial devices as achieving sub millimeter accuracy with the drone in flight during printing is a challenge and an area of further research.

The above review discusses alternative options like laser diode, microwave and induction heaters which may be employed in a mobile setup due to their compactness, efficiency and light weight. This will revolutionize what materials could be printed. Still, the advanced methods need more work before they are able to being deployed in a mobile setup.

Conclusion

The above review tells about the current research in mobile manufacturing machines. Most of the ground and aerial work has been done to extrude cement or polyurethane foam. Ground based mobile systems have so far manufactured plastic, concrete, clay, fiber composites and polyurethane foam. And most of them work in coordination with other robots to flexibly manufacture. Future research could focus on more efficient systems in terms of path planning, coordination, obstacle avoidance and more varied materials using different AM techniques. Since the systems rely on laboratory conditions for localization especially the aerial ones, hence, future work could address integrating various sensors like vision, LiDAR for multirobot localization in dynamic environments. Machine learning could be integrated further to allow robots to detect and correct defects in real time. Besides, standards for mobile AM machines are not built yet in terms of optimal size, energy efficiency and precision. This is a crucial step in accelerating development in mobile manufacturing as it would unite researchers at one point which would serve as a building block towards novelty in this area.

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