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A Review of Commercially Available Autonomous Painting Robots in the Construction Industry

Chinedu Okonkwo, and Tulio Sulbaran, Ph.D.,
The University of Texas at San Antonio
San Antonio, TX

Painting in the construction industry is a hazardous activity that presents lots of construction risks for workers like falling from heights, musculoskeletal disorders from awkward positioning, and exposure to toxic substances, especially in confined spaces. Most construction projects include painting activities and the repetitive nature of painting activity has led to the proposal of several painting robots with very few being commercially available presently. These robots, however, in their present state have certain limitations affecting the ultimate productivity of the robots and their implementation at the construction job sites. The problem that this paper addresses is the lack of a study on the necessary elements of an autonomous painting robot (APR) to execute construction painting activities efficiently and safely. This presents a need to assess the current limitations of available painting robots to generate information that could serve as a basis for further research on ways to improve the efficiency of APRs. Therefore, the objective of this study is to identify the properties of an efficient APR and compare them with the properties of commercially available APRs. A comprehensive study was conducted on relevant literature from the Scopus database and Google Scholar library on the major parameters that define the performance of an APR. The study highlights the major properties for evaluating the performance of an APR as well as the present limitations of the available robots. The findings of this study are expected to provide further research areas for researchers interested in the improvement of the productivity of APRs.

Key Words: Painting robot, autonomous mobile robot, construction automation, construction safety

Introduction

Painting in construction presents significant health risks, encompassing falls from heights, slips, and musculoskeletal disorders due to awkward working positions (Park et al., 2016). Confined space painting further increases the exposure of workers to hazardous substances like silica, isocyanates, and epoxy compounds, posing pulmonary risks (Keerthanaa et al., 2013; OSHA, 2022; Park et al., 2016; Schwartz & Baker, 1988). Moreover, traditional painting can result in an uneven paint coating due to the unstable working positions of painters (Asadi et al., 2018). To reduce these hazards and problems associated with painting, some human-operated and autonomous painting robots have been prototyped and commercialized for use in the construction industry.

Task automation with robots is becoming commonplace and has seen its application in different sectors like the manufacturing, health, and construction industries (Jayaraj & Divakar, 2018). The major drivers of automation in the construction industry include the need to improve productivity and safety (Naticchia et al., 2007). The repetitive nature of painting tasks plus the shortage of construction workers in recent years presents an opportunity for painting job optimization through automation (Jayaraj & Divakar, 2018; S. Kim et al., 2020). An autonomous painting robot (APR) in this study refers to wall painting robots capable of executing a painting job in a construction project with very little to no human intervention. These autonomous robots are usually equipped with sensors that gather information about their surrounding and leverage artificial intelligence in processing the information to adapt to their environment while executing their tasks (Naticchia et al., 2007). Although, several APR prototypes have been developed by different researchers and companies (Abdelattif, 2012; Asadi et al., 2018; Megalingam et al., 2020), only a handful of them are presently commercially available with different properties and capabilities. This could be attributed to the unstructured and continually changing nature of construction sites as work progresses. These robots are generally expensive to incorporate (Attalla et al., 2023), presenting the need to justify their cost and safety impact on workers in construction work environments. Also, these robots in their present state have some limitations such as speed, power source, level of mobility, and environmental awareness of the robots, which impact their usability and productivity in a construction project.

This study is concerned with commercially available autonomous painting robots. The problem that this paper addresses is the inefficiency of autonomous painting robots (APR) to execute construction painting activity efficiently and safely due to the limitations of available APRs especially in real-time environmental sensing to ensure the safety of human workers working in the same environment. There is a need to analyze the current limitations of available painting robots to generate information that could serve as a basis for further research on ways to improve the productivity of APRs. Therefore, this study aims to identify the limitations of existing autonomous painting robots (APR) by reviewing different commercially available ones. This study compares the performance of the painting robots based on their properties. The findings of this study are expected to inform researchers of potential research areas that could lead to increased productivity, safety, and efficiency in the use of autonomous painting robots.

Background

In the construction industry, like in most industries, robotic technologies are used (or potentially used) to improve productivity achieving cost savings by addressing the inefficiencies of humans, as well as quality improvement (Naticchia et al., 2007; Asadi et al., 2018). Painting robots have been extensively used in controlled and well-defined manufacturing industries like car manufacturing (B. Zhang et al., 2020). However, there is still limited robot technology incorporation in the construction industry which could be attributed to the complex and ever-changing nature of construction projects (Pradhananga et al., 2021). Paint robots' incorporation in construction can improve the management of resources, improve work quality, and lead to higher productivity by combining the benefits of automation and human skills (Asadi et al., 2018). A study by Kahane and Rosenfeld (2004) demonstrated that integrating a robot into a wall-painting task can reduce the task duration by up to 80% and increase profitability, especially in highly autonomous systems. The authors concluded that the level of autonomy of a system and task execution duration affect the profitability of a robotic system. This implies that more continuous autonomous action plus the availability of subtasks that can be carried out by the operator as the robot works increases productivity and profitability.

For a Paint robot to work effectively on a construction site, different parameters, and functionalities are required some of which include a power source (battery-powered or AC), productivity, height reach of robots, weight, and the ability to detect wall openings as well as obstacles along its path (Abdelattif, 2012; Asadi et al., 2018; Megalingam et al., 2020). The construction industry has an infamous reputation as being one of the most hazardous industries (Pinto et al., 2011) with falls from height being the leading cause of fatalities and injury (Tariq et al., 2023). While APRs are being viewed as a viable means of reducing falls from height associated with human painters working at height, measures should be taken not to create a struck-by rolling/sliding object hazard as a result of the movement of the APR. Amongst other properties of an efficient APR identified in this study, real-time environmental sensing is a crucial property of an APR necessary to ensure the safety of workers working alongside robots (Lee & Chien, 2020). This enables an APR to collect, analyze, and make decisions based on the current state of its work environment.

Research Method

To achieve the stated research objectives, two tasks were required (1) Identify the basic properties of an autonomous painting robot (APR) in the peer-reviewed literature, and (2) Compile the properties of the commercially available painting robots. For the first task, relevant journal articles were obtained from Scopus and Web of Science databases. Only articles related to painting in the construction industry were considered in this study. The keywords used to search for relevant articles on the databases listed above include "Autonomous painting robot", "smart painting robot", "painting robot", and "paint robot". Identified articles were screened to exclude articles on manual painting roots, and painting robots in other sectors like manufacturing by first reading the abstract and conclusion to determine the relevance of the materials obtained to the study. Materials initially collected but did not address the research topic were excluded from the study. This was followed by skimming through the full text of the remaining articles to further examine their eligibility. The qualified articles were then reviewed to extract relevant information for this study. For the second task, the Google search engine and LinkedIn were utilized in searching commercially available APRs. Publically available and Practical information from web pages of the different painting robot companies is included in this study. Due to the limited amount of information publicly available on these robots, the authors reached out to the companies for further information as presented in Table 2.

Results

Properties and Performance Measures of an Autonomous Painting Robot (APR)

An autonomous painting robot (APR) comprises a synergy of mechanical and electronic components, complemented by sophisticated software, all meticulously designed to fulfill a specific task. Different APRs have different specifications based on the requirements considered by the manufacturer. An ideal APR should be able to perform a painting task more effectively, faster, and cheaper than a human. First, an energy source is required to power the APR followed by the ability to move around in executing a painting task (Megalingam et al., 2020). Building floors are not always horizontal, therefore, an ideal APR should be able to navigate low-sloped inclined surfaces. Also, construction sites are mostly unstructured, with lots of hazards from flying, falling, rolling, and even stationary objects, environmental sensing, therefore, environmental sensing ability is necessary for a painting robot working autonomously to safely execute its tasks (Niloy et al., 2021). Before commencing a painting job, a scan of the work environment is necessary to map the environment and localize the robot, especially within buildings where GPS is not reliable (Kudriashov et al., 2021). Paints come in different types, colors, and textures, an APR should be able to work with different types of paints and self-clean the sprayer or roller before applying a different color. Finally, an APR should be faster than a human painter and capable of reaching the headroom of the intended structure when used for indoor painting. Figure 1 shows eight properties to be considered in the development of an APR as well as three performance measurement criteria.

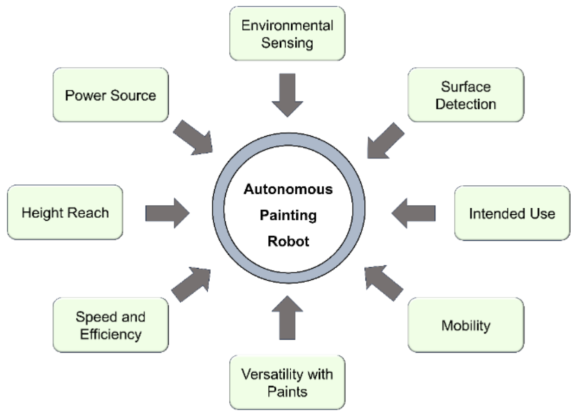

Fig 1: Elements of an Autonomous Painting Robot

Environment sensing

The construction environment is characterized by its dynamic nature, with loud noises, airborne particles, and rapid temperature changes. An Autonomous Painting Robot (APR) operating in such conditions necessitates advanced sensors that can function accurately amid these challenges, minimizing distractions. Various sensors play crucial roles in enhancing the APR's operational efficiency, including ultrasonic, contact, sound, vision, tilt, gyroscope, and Global Positioning System (GPS) sensors. Ultrasonic sensors, for instance, facilitate distance measurement by transmitting ultrasonic waves and gauging the time taken to receive the echo (Zhmud et al., 2018). Meanwhile, gyroscope and tilt sensors become instrumental in determining the angle of inclination with reference to the horizontal plane, a critical aspect for maintaining balance when operating on inclined surfaces (Lee & Jung, 2012). Contact sensors act as safety mechanisms, detecting any interaction with objects or humans in a human-robot collaborative environment (Tsuji & Kohama, 2020). Additionally, the integration of sound sensors with vision sensors, such as cameras, enhances the APR's environmental awareness and overall effectiveness (Kooijmans et al., 2007).

Accurate localization, the ability of the APR to identify its position within the work environment, is crucial. Achieving this involves a combination of GPS technology and/or a comprehensive environmental map generated using sensors like LiDAR and cameras as reference points (Panigrahi & Bisoy, 2022). In GPS-denied scenarios, a combination of LiDAR and Inertial Measurement Units (IMU) can be deployed (Niedzwiedzki et al., 2020). Furthermore, the diverse nature of building structures, with varying shapes and sizes, featuring openings like windows and doors, underscores the importance of the APR's capability to detect and navigate such architectural elements without interfering with them, particularly in painting applications.

Power source

In general, most APRs are powered either by a direct current (DC) or alternating current (AC) (Megalingam et al., 2020). The power source of an APR affects its mobility and productivity (Farooq et al., 2023). For instance, a battery-powered (DC) APR is less susceptible to tripping from power cables but can be limited in work output based on the capacity of the battery. On the other hand, an AC-powered APR can work longer periods as it is not limited to the battery capacity, however, it could be limited by the availability of a power source nearby. However, this AC availability limitation could be overcome with commonly available portable power generators.

Height reach

Based on the intended purpose of the APR, it should be able to move and reach the needed heights. A height reach of 3 to 3.5 meters may suffice for the interior painting of buildings (Chou & Ngo, 2016; Rajapaksha, 2020) and 9 to 10 meters for warehouses (Asadi et al., 2018). For exterior walls of high-rise buildings, wall-climbing robots may be more effective.

Speed and Efficiency

Perceived safety and higher productivity are among the major drivers of automation (Motamedi et al., 2020). Therefore, an efficient APR should not just be able to replace a human painter but should also be able to perform a painting task faster than an average human painter. An average painter has a painting speed of 0.15 sqm/min (Abdelattif, 2012). An ideal APR should have a balance between execution speed and quality of paintwork.

Versatility

Versatility in this study refers to the ability of an APR to work with different types of paints. Most of the commercially available APRs use the spray painting system (Myro, 2022; Okibo, 2021; Vertidrive, 2023; Asadi et al., 2018). A spray painting system consists of a spray gun, compressed air, a paint container under pressure, and connecting tubes and it works by using air to break down paint into smaller particles and launching them on the surface to be coated (Rudzuan et al., 2019). The pressure required to achieve this is affected by the viscosity of the paint, the more viscous the paint is, the higher the pressure required (Mueller & Kleinebudde, 2007). Commercial paint products vary in viscosity, therefore, the spray system should be able to provide enough pressure capable of working with different varieties of paints.

Mobility

Mobility is an essential part of an APR necessary to function effectively. An APR should be able to move instantaneously in all directions to work in congested environments (Megalingam et al., 2020). An ideal APR should be capable of moving on both flat and low slope surfaces like a ramp way while working. Presently most APRs move using rolling wheels that can turn at different angles for easy maneuvering of the work environment (Myro, 2022; Okibo, 2021; Vertidrive, 2023; Asadi et al., 2018). This rolling system is usually a three-wheel or four-wheel arrangement system for faster lateral feed motion and higher load-bearing capacity of the APR (Abdelattif, 2012).

Intended use

APRs are designed for indoor and outdoor use. The nature of the environment of the intended use affects the design of the APR. Outdoor environments are generally more random and difficult to navigate compared to indoor environments. In the design of an outdoor APR, the safety of the APR itself should be taken into consideration as it can be adversely affected by factors like weather and other construction equipment. The sensors of an outdoor APR should be able to adapt to the changing outdoor environment with vision recognition capable of identifying a wider range of objects (Zhang et al., 2022), sensors capable of working in poor weather like vision sensors in foggy weather (Kim & Sumi, 2020), and water resistant to avoid water damage.

Surface Detection

The goal of surface detection is to enable the robot to understand the environment and identify various surfaces and objects. 3D scanning is a method of analyzing an object or an environment by converting a physical object into a 3-dimensional image (Javaid et al., 2021). The surface to be painted is scanned and processed on-site to make adjustments for the uncertainties of a construction site. A popular method of 3D scanning is the use of a time-of-flight (TOF) camera because of its ability to pick up intensity images and depth at the same time (Asadi et al., 2018). TOF cameras are relatively simple and cost-effective technology for 3D scanning with their operation similar to a video camera (Cui et al., 2010).

Commercially Available Autonomous Painting Robots

Amongst the few commercially available autonomous painting robots are Myro, PictoBot, Okibo, DF061, OutoBot, Finishbot, Robosurf Robot Painter, and Vertidrive M9 painting robot. These APRs are in their early stages and are produced by relatively young and small companies of 11 to 50 employees. Table 1 summarizes the profile of these companies.

Table 1: *Profile of commercially available APR companies*

ID	Company / PaintBots	Company Web Site	LinkedIn	Industries	Company size	Foun-ded	Country
1	MYRO	https://www.myro.bot/	https://in.linkedin.com/showcase/myro.bot	Machinery Manufacturing	11-50 employees	2019	Singapore
2	Okibo	https://okibo.com/	https://il.linkedin.com/company/okibo-ltd	Construction	11-50 employees	2018	Israel
3	Dafang DF061	http://dafangai.cn/en/					China
4	Vertidrive/ M9 painting robot	https://www.vertidrive.com/	https://nl.linkedin.com/company/vertidrive	Machinery Manufacturing	11-50 employees	2008	Netherlands
5	Transforma / PictoBot-PBA 300	https://www.transformarobotics.com/pictobot	https://bh.linkedin.com/company/transformarobotics	Construction	11-50 employees	2017	Singapore
6	Robosurf Robot Painter	https://robo.surf/	https://www.linkedin.com/company/robosurf	Industrial Machinery Manufacturing	11-50 employees	2018	Italy
7	Finish Robotics/ Finishbot	https://www.finishbot.com/	https://www.linkedin.com/company/finishbot	Automation Machinery Manufacturing	2-10 employees	2021	USA

Myro International PTE Limited developed an intelligent interior painting robot that is about ten times faster than a human painter and can reach heights of up to 3.1 m. It is capable of detecting the presence of objects, corners, and humans along its part as a safety feature for human-robot collaboration (Myro, 2022). Unlike Myro which is powered by an alternating current, Okibo Construction developed a battery-operated finishing robot that is capable of real-time 3D scanning and modeling. Although not as fast as Myro, Okibo finishing bot offers more cost reduction (about 50%) compared to Myro (30%) (Okibo, 2021; Myro 2022). The DF061 by Defang is also an intelligent paint robot with a maximum working height of 6 meters and equipped with panoramic imaging and remote construction ability for both exterior and interior wall finishing (Defangai, 2022). Vertidrive also developed the wall-crawling M9 painting robot that is capable of painting both indoors and outdoors and can complete a painting job six times faster than a human painter (Vertidrive, 2023). Transformarobotics developed the PictoBot, a surface-finishing robot four times faster than a human painter, equipped with a battery, and can reach up to 10 meters (Asadi et al., 2018). The RoboSurf painter robot from RoboSurf is another autonomous painting robot with a working height of up to 20 meters, equipped with industry 4.0 enabling technologies, and capable of other surface finishing activities grinding, milling, and spray filler (RoboSSurf, 2023). Table 2 below summarizes available information on the elements of the APRs.

Table 2: Commercially available APRs

APRs	**Elements of an Autonomous Painting Robot**							
	Environment sensing	Power source	Height reach (m)	Speed (m^2/min)	Versatility	Mobility	Intended use	Real-time 3D scanning
MYRO	✓	Outlet	3.1	3.7		F	ID	
Okibo		Battery	3.7	1.7 to 3.3	ALL	F	ID	✓
Dafang DF041/ DF061/ DF201/ DFH11		Battery	6	3.1	EP	F	ID	✓
Vertidrive/ M9 painting robot						F	ID & OD	
Transforma/ PictoBot-PBA 300		Battery	10 (3m indoor)			F	ID & OD	✓
Robosurf Robot Painter		Outlet & Battery	20	7	ALL	F	ID	✓
Finish Robotics/ Finishbot						F		✓

<u>Legend</u>

OF = flat surface
I = inclined surface
ID = indoor painting
OD = outdoor painting
AC = Alternating current
OP = Oil paint
EP = Enamel paint
EMP = Emulsion paint
CP = Cement paint
BP = Bituminous paint
AP = Aluminum paint
ALL = All paints above

Performance Measures of an Autonomous Painting Robot Economy (ROI)

The economy is a major factor in the acceptance and evaluation of the performance of technology incorporation in the construction industry (Pan et al., 2020). The initial cost and the long-term cost-benefit tradeoff are crucial in justifying the effectiveness of an APR. The total cost of an APR for a project should be lower than the cost of using a human painter. The total cost includes capital cost, setup, operation, and maintenance, while the benefits include better quality painting and reduced human involvement in hazardous tasks in an unhealthful work environment (Warszawski, 1985). This may be difficult to achieve in smaller construction projects with tight budgets.

Quality

Uniform coating refers to the quality of a painting task done by an APR. With the use of proximity sensors such as ultrasonic sensors, APRs can maintain a uniform distance from a vertical surface to be painted (Megalingam et al., 2020). However, surfaces are not always uniform as there may be indentations and protrusions on the surfaces which could affect the uniformity of the paint coating. This can be addressed by performing real-time 3D scanning that will enable the APR to adjust the paint sprayer or brush to ensure a uniform coating.

Conclusion

Painting is a repetitive construction activity that is associated with lots of hazards ranging from falling from heights and ergonomic problems to chemical hazards due to the content of the paint. Several APRs have been developed to reduce these hazards to construction workers by incorporating robots in painting. This study provides a review of the elements of an automated painting robot required to work efficiently in a construction work environment. The construction environment is very dynamic, presenting the need for an intelligent robot that can work autonomously and collaborate with humans. Eight major elements required for an APR to work efficiently were identified in this study as well as the performance indicators of an APR. These elements include environment sensing, surface detection, the intended use of the APR (indoor or outdoor), mobility, versatility in working with different paint products, speed of task execution, height reach of the APR, and the source of power. The performance of the APR can be evaluated through its productivity, economy, and the quality of the paint job. Commercially available APRs were reviewed based on the elements of an APR identified in this study.

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