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A Low-Cost Approach for Path Programming of Terrestrial Drones on a Construction Site

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Abstract: Robots for construction sites, although not deeply widespread, are finding applications in the duties of project monitoring, material movement, documentation, security, and simple repetitive construction-related tasks. A significant shortcoming in the use of robots is the complexity involved in programming and re-programming an automation routine. Robotic programming is not an expected skill set of the traditional construction industry professional. Therefore, this research seeks to deliver a low-cost approach toward re-programming that does not involve a programmer's skill set. The researchers in this study examined an approach toward programming a terrestrial-based drone so that it follows a taped path. By doing so, if an alternative path is required, programmers would not be needed to re-program any part of the automated routine. Changing the path of the drone simply requires removing the tape and placing a different path – ideally simplifying the process and quickly allowing practitioners to implement a new automated routine. Python programming scripts were used with a DJI Robomaster EP Core drone, and a terrain navigation assessment was conducted. The study examined the pass/fail rates for a series of trial run over different terrains. The analysis of this data along with video recording for each trial run allowed the researchers to conclude that the accuracy of the tape follow technique was predictable on each of the terrain surfaces. The accuracy and predictability inform a non-coding construction practitioner of the optimal placement of the taped path. This paper further presents limitations and suggestions for some possible extended research options for this study.

Key words: Drones, Automation, Project Monitoring, Construction Technology

1. INTRODUCTION

The construction industry is known to suffer from problems with productivity [1] and is largely averse to the consideration of technology and innovation for solving some of these issues [2]. Given the size, complexity, and fragmentation of the industry within the US it is broadly accepted that most smaller firms (in terms of revenue) are unable to spend additional time and money to figure out these productivity problems. Taken as a whole, the number of smaller firms make up most of the construction industry [3]. By some accounts [2] smaller companies are unwilling or unable to invest in technology as a way out of the productivity problem – most do not invest in innovative technology solutions and only very few invest more than 2% of their earnings. This attitude, whether practiced or a function of remaining profitable, will perpetuate the productivity dilemma. Simple and low-cost solutions are needed to convince these smaller firms that the authority is theirs if the industry is to change course on productivity. In this paper the researchers outline an approach toward implementing a low-cost terrestrial drone. Furthermore, the researchers reasoned that by limiting the budget and the sophistication required to implement the drone used in this study, they would satisfy the needs of the larger audience of smaller firms within the construction industry. Today, drones, whether aerial or ground based, provide construction managers a variety of benefits ranging from project monitoring, material movement, documentation, security, and simplifying repetitive construction-related tasks. These tasks could be argued to consume valuable practitioner time – time better spent on creative problem solving or attention toward other worthwhile efforts that are commonly ignored in construction (e.g., innovation, sustainability, waste management, client satisfaction, productivity, etc.).

2. LITERATURE REVIEW

The construction industry is steadily falling behind others in its use of technology and automation to hasten processes and ease the burdens placed on its workforce [4][5]. Moreover, automation technology has matured enough to go beyond the highly controlled environments of laboratories [6]. It has been complicated to develop autonomous machines that can operate effectively for the construction industry because the nature of construction is to actively modify a continually changing environment [7]. Furthermore, the construction industry cannot be considered as a single cohesive unit. The many subindustries that make up the construction industry must each be weighed independently [1]. For instance, factors such as size and technical sophistication can limit how smaller firms embrace technological advancements that are helping their larger counterparts [1][2]. The continually changing environment and the broad scope of services provided by the construction industry are precisely why developing intelligent automation for construction is such a difficult task. Still, these challenges have not stopped the industry from attempting to make technological strides, albeit at a slower pace than other industries [2]. Drones are one way by which the industry is embracing technology with an attention toward improving on the *old* way of doing things [8][9][10]. For instance, tasks that are commonly assigned to junior-level practitioners involve photographic capture and Light Detection and Ranging (LIDAR) scanning. The data gathered from these tasks usually takes a considerable amount of time and diligence to acquire – the process is very repetitive. In instances such as these, the tasks are appropriate for automation. Presently, there is a significant body of knowledge that addresses the benefits of automation in the construction industry – some of this research is theoretical [4][8][12][13] while other research focuses on practical applications through case studies [6][10][11]. Nevertheless, there is little question about the benefits of gathering digital construction data [14] but the process needs to be offloaded from human administration.

2.1 Contemporary Automation within the Industry

Automation within the construction industry is task specific. For example, applications for task-specific robots include gypsum wallboard sanding, wall painting, bricklaying, façade cleaning/inspection, tying concrete reinforcing bars, focused demolition, and welding [9][10][15][16]. For the most part, the tasks these robots are built for are repetitive and straightforward which is ideal because robots are good at handling tedium, sensing, speed, strength, focus, and routine [15]. Mantha et al. [7] establishes a robot as, “any actuated system capable of performing tasks or actions for people with a certain degree of autonomy”. Hence, this statement supports the assignment of these repetitive tasks to robots. Automation in the construction industry is a developing mindset. Research on construction robotics ranges from supporting broad topics about autonomously unsupervised work [17] to a highly focused determination of path planning for robots (i.e., how the robots navigate a construction project site) [18]. Ultimately, according to de Soto et al. [19] the key motivations for using automation and robotics are for: 1) economic gain, 2) quality improvement, and 3) improvement of working conditions. These three motivations provide a viable framework for relieving construction practitioners of the mundane task that robots are more suited for.

2.2 Cost and the Complexity of Automation

Unmanned aerial vehicles (UAV) along with their counterparts unmanned ground vehicles (UGV) are an important asset for the construction project. UAVs are a wise investment for many tasks, including documenting project progress, often from vantage points that are not easily accessible [10]. Other tasks are also being streamlined through hardware developments from companies such as, Boston Dynamics, Nextera Robotics, Hilti, and Dusty Robotics. These companies are manufacturing better ground-based robots that are capable of crossing terrains that are usually arduous and unsafe. However, UAVs seem to be more widespread than UGVs in the industry. At the moment, many UGVs are sold above the $100,000 USD threshold which is out of the range of most construction company budgets in the US. In other parts of the world, high cost is also a significant impediment for robotic automation [18]. Ownership of a specialized robot requires additional investments in personnel, training, and continual maintenance – further increasing the cost and leaving behind those firms that wish to take part in this degree of automation.

Comparing the difference between navigating the air space around a construction project versus navigating the multitude of obstacles that are on the ground, establishes the difficulties involved when programming and automating UGVs compared to UAVs. Moving across a construction project site involves attention to terrain that is cluttered with reinforcing steel bars, puddles, mud and other combinations of debris and construction materials. Further complicating this, is the fact that these obstacles change continuously on the project site. The programming necessary to precisely avoid these obstacles is daunting – and usually out of the skillset of the conventional construction site practitioner. The industry is at a moment when the technology for robotics and automation is increasingly available but still requires highly skilled practitioners to maintain and operate. An ideal cost-effective solution that is maintainable and simple to operate would be preferred.

2.3 Problem Statement and Research Motivation

The researchers depart from the existing literature acknowledging the benefits and complexities of automation in the construction industry and have identified the following problem statement for this research:

A small construction firm's accessibility to robotic automation equipment is impeded by the cost and complexity of introducing such equipment to the existing practices of the smaller construction firm.

The motivation for this research is served by matching the well-known benefits of automation to the larger population of the industry (i.e., smaller construction firms) with an overwhelming need to address the productivity concerns of the industry at large. The remainder of the paper will discuss a low-cost prototype that is proposed by the researchers that meets the goal of being cost-effective and simple to maintain and reprogram. This research focuses on a hypothetical task of digital data gathering on a project site that could be achieved by using a low-cost prototype UGV.

3. METHODOLOGY

3.1 Equipment

The equipment for this research study included the DJI Robomaster EP Core drone (https://www.dji.com/robomaster-ep-core/specs). This UGV is 17.4 in length X 8.9 in wide X 11.3 in height (44.2 X 22.6 X 28.6 cm). This is a small drone that can carry light equipment such as a 360° camera, therefore, the uses for this drone are somewhat limited to monitoring and photographic archival tasks. However, for this study it is ideal since the goal is to obtain a low-cost drone that would be affordable to a larger population of the construction industry.

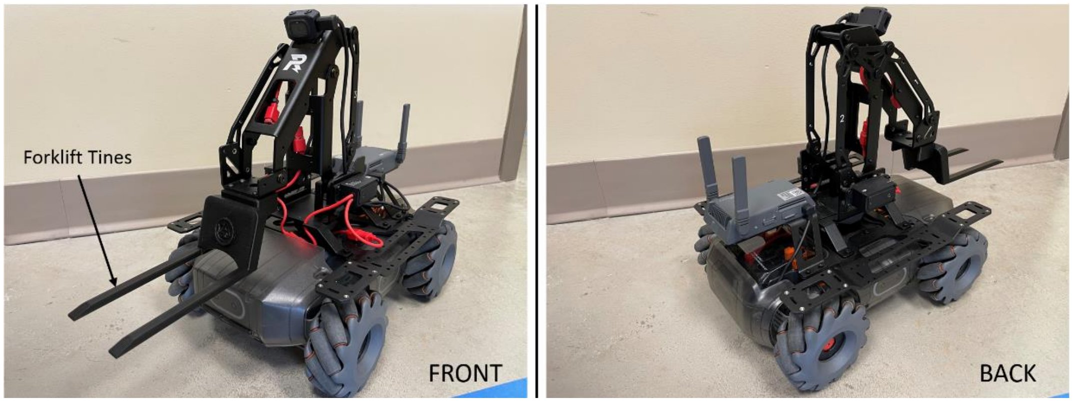


Figure 1. UGV Front and back

This UGV was further selected for its ease in programming. The UGV can receive operations from its Scratch-based visual programming tool or via custom programmed Python scripts. While neither of these programming languages would be considered within the skill set of most construction practitioners, the researchers opted to use the Scratch-based programing since it was primarily designed for secondary school-aged children. Learning to get the UGV to perform basic tasks, such as, taped line following could be accomplished by watching a few short videos on how to use the Scratch programming.

3.2 UGV Cost Comparison

A significant portion of the current literature on automation focuses on semi-industrialized robotic equipment. Consumer-grade robotic equipment (i.e., equipment that is affordable to the general public) is less researched since it may be viewed as less durable and having fewer capabilities. Cost is also a decisive factor when choosing automation equipment. Below is a cost comparison between the UGV used in this research and other more industrialized UGVs that are being research for construction industry applications.

Table 1. UGV Cost Comparison

Cost Factor	**DJI Robomaster EP (UGV proposed in this research)[1]**	**Boston Dynamics (Spot)[2]**	**Nextera Robotics (Oliver)[3]**
Initial asset purchase price	$2,000	$100,000	$75,000
Maintenance cost	No Maintenance Plans Available	$25,000 / year	$12,000 / year
Payload Capacity	2.0 lbs (0.9 kg)	50.0 lbs (23 kg)	50.0 lbs (23 kg)

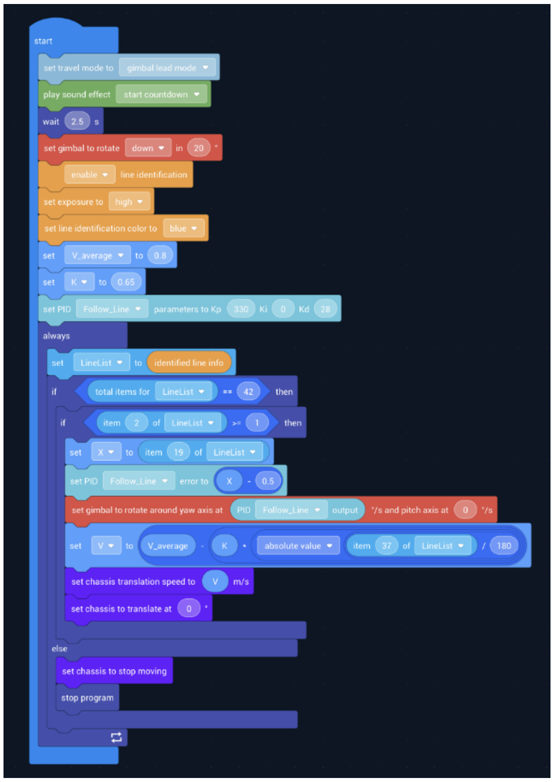
[1] https://www.dji.com/robomaster-ep

[2] https://www.bostondynamics.com/products/spot

[3] https://nexterarobotics.com
All costs in this table are rounded to the nearest $1,000 and represented in USD.

3.3 Taped Line Following

Programming the UGV for the taped line follow routine was the primary objective for this study. By having the UGV execute this routine, it was reasoned that a UGV would follow a taped line that could be laid out by a construction practitioner on their project site. Once the UGV executed the taped line follow routine, no further intervention would be required of the practitioner. Furthermore, if the practitioner needed to redirect the UGV's path, they would remove the existing taped line and tape a new line. From there, the UGV would execute a taped line follow on a new path route. Below is the Scratch programming code used for this study.



```
start
  set travel mode to gimbal lead mode
  play sound effect start countdown
  wait 2.5 s
  set gimbal to rotate down in 20 °
  enable line identification
  set exposure to high
  set line identification color to blue
  set V_average to 0.8
  set K to 0.65
  set PID Follow_Line parameters to Kp 330 Ki 0 Kd 28
  always
    set LineList to identified line info
    if total items for LineList == 42 then
      if item 2 of LineList >= 1 then
        set X to item 19 of LineList
        set PID Follow_Line error to X - 0.5
        set gimbal to rotate around yaw axis at PID Follow_Line output °/s and pitch axis at 0 °/s
        set V to V_average - K * absolute value item 37 of LineList / 180
        set chassis translation speed to V m/s
        set chassis to translate at 0 °
    else
      set chassis to stop moving
      stop program
```

Figure 2. Taped line follow Scratch code

3.4 Terrain Tests

The researchers tested the UGV on various terrains that are representative of the types of terrains on most construction project sites. The goal here was to determine how reliable the UGV was at crossing each of these terrains and to inform a practitioner of what to expect if the taped line was to cross one of these terrains. The terrains used in this study included a smooth concrete surface (CONCRETE), a semi compacted aggregate surface (COMPACTED), and a loose aggregate surface (LOOSE). Figure 3 illustrates the three surfaces used in this research study.

CONCRETE COMPACTED LOOSE

Figure 3. Terrain types

Research on benchmark testing of robotic navigation and comparison of the empirical data gathered from successive trial runs is documented in the existing literature [20][21]. This literature serves as a basis for the measurement methods designed in this research.

The UGV was trialed on each of the terrain types ten times. Each trial was video recorded and scored based on accomplishing ten objectives. If the UGV successfully completed all the objectives on the trial run a perfect score of 10 points was assessed. Below is an enumeration of the ten points that were measured and scored in each of the trial runs.

A. (+1 point) the drone successfully finds the taped line to initiate the trial run
B. (+1 point) the UGV begins to execute the taped line follow Scratch programming
C. (+1 point) the UGV successfully follows the entire taped line
D. (+1 point) the UGV remains within a 15.24 cm (6 inch) tolerance distance (left-to-right) from center of the taped line on straight runs
E. (+1 point) the UGV completes the trial at or less than 30 seconds
F. (+1 point) the UGV successfully executes turn 1 – left turn
G. (+1 point) the UGV successfully executes turn 2 – right turn
H. (+1 point) the UGV stops at the end location
I. (+1 point) the UGV stops at the end location within a 15.24 cm (6 inch) tolerance
J. (+1 point) the UGV completes the trial run without unexpected movements along its path

4. RESULTS

At the conclusion of the trial runs described in section 3.4 of this paper an accuracy score was calculated for each terrain type by using the mean of all ten of the trial runs for each point noted in section 3.4 of this paper. The scores for each point for each terrain type are enumerated in Table 2. A score of 100% indicates that the UGV perfectly executed all parts of the trial run for all ten trials.

Table 2. Accuracy Score for UGV Trial Runs

Terrain	A	B	C	D	E	F	G	H	I	J	Accuracy Score (AVG)
CONCRETE	100%	100%	100%	100%	100%	100%	100%	100%	80%	100%	98.0%
COMPACT	90%	90%	40%	60%	40%	60%	60%	40%	40%	10%	53.0%

LOOSE	40%	40%	0%	40%	0%	30%	0%	0%	0%	0%	15.0%

Note: The letters in the heading row (e.g., A, B, C, etc.) above correspond to the score points defined in section 3.4.

5. DISCUSSION

From the trial data, it is obvious that when the UGV travels across the smooth concrete surface, the results are predictable that it will find the end point of the route. This is evident from the highest accuracy score calculated for that terrain type. While this was to be expected, it is informative to realize how much more reliable it was on the smooth concrete surface when compared to the other two surface types. The UGV has omnidirectional (Mecanum) wheels which responds erratically when the terrain become roughened. Several of the trial runs across both the compact and loose aggregate surfaces exhibited bouncing of the UGV that caused it to veer off the path. This presents a mobility challenge for the UGV if it needs to move across non-finished surface types – such as those found outside the building enclosure or as the project is in its early stages of earthworks. Perhaps larger wheels (found on Nextera Robotics) or a legged mobility (Boston Dynamics) would be more suitable for the roughened environments. This finding certainly limits the places that the UGV can go and successfully complete its route. If a practitioner needs the UGV under more controlled conditions where the floor surface is smooth, such as when the project is structurally topped out or during interior construction, then this UGV type is highly reliable – and cost effective.

5.1 Limitation & Future Work

The researchers conducted the trial runs in open daylight on a cloudless day. It is reasoned that this amount of sunlight washed out the image that was viewed by the UGV's visual sensors while trying to recognize the blue taped line. The accuracy results were affected by this with the more roughened terrain types. It is presumed that the tape was not highly contrasted when the background surface contained reflected light and shadows that is present with the looser aggregate surface. In future iterations of this experiment some consideration needs to be made for adjusting contrast or the UGV's camera sensitivity.

While addressing the limitation would be the first consideration in a future study, there is also a desire to assess the prototype in a live construction setting. It is reasoned that other obstacles and limitations could be addressed, such as, limited lighting, standing water, noise, worker safety, speed, battery life, and digital documentation quality.

6. CONCLUSION

The goal at the outset of this research project was to identify if a cost-effective prototype drone could be used on a construction project site to replace some of the less desirable (and less profitable) tasks that are being done by human practitioners. The results of this study determined that the drone could reliably navigate a solid smooth surface (i.e., smooth concrete). This result provides information to practitioners about the limits of this low-cost drone. However, it is supposed that practitioners may be willing to forgo a small investment (around $2,000 USD, see Table 1) so that tasks that often get ignored, such as digital documentation, can be accomplished with less effort, less cost, and more reliably than when it is assigned to a human practitioner. Lastly, when practitioners are freed of tasks such as these, they can begin focusing on more creative problem solving and addressing issues such as productivity, sustainability, and quality control.

Reducing the cost and complexity of automation, as exhibited in this research study brings the benefits of automation to a larger segment of the construction industry – the smaller firms. These firms have been unwilling to implement technological solutions for economic reasons [2].

Furthermore, a lacking skill set in maintenance and programming of some of the more robust terrestrial drones unintentionally turns away the smaller firms. This research engages this challenge by addressing *cost* and *simplicity* when designing the methodology and the case study for this paper.

Concluding this research study also enlightened the researchers on an outer objective that could be assigned to this research. The benefits to productivity with more automation in the construction industry is an acknowledged fact [16]. However, due to the industry's fragmentation the larger subset of smaller firms often gets ignored, yet their potential to drive change within the industry is significant. In time, the economics of automation will level out, making UGVs and other important technologies more available to a broader range of firm sizes. The researchers contend that these smaller firms must also be a part of the learning curve that will get us there, but they must first be a part of that process and research that focuses on this subset is the best place to start.

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