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Unmanned Aerial Vehicles: A Survey on Monitoring Advancements for Port Infrastructure Applications

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Abstract: Ports play a significant role in the economic and social activities of the areas they serve. However, the adverse effects of the harsh and highly corrosive environments that ports operate in, along with phenomena related to the climate crisis and insufficient maintenance practices, increase port infrastructure's susceptibility to rapid degradation. This degradation can be aesthetic, functional, or structural and often leads to loss of serviceability at either a component (local and national) level or a global level. Moreover, many port structures have reached the limit of their lifetime, thus introducing the concept of extending their lifespan as a financially attractive alternative to constructing new facilities. Therefore, port operators pursue monitoring the structural integrity of the structures through an inspection plan aiming to reduce their maintenance and rehabilitation costs and ensure the safety of both the port infrastructure itself and human lives. Optimising monitoring approaches to enable damage detection and condition assessment can be achieved through the employment of Non-Destructive Testing (NDT) and Remote Sensing (RS) techniques. The current surge of using Unmanned Aerial Vehicles (UAVs) for both RS and NDT monitoring practices has proved promising since UAVs provide improved accessibility, increased inspection speed, and reduced safety hazards. The present paper is focused on investigating and evaluating the recent advances in UAV-driven port infrastructure monitoring. For this purpose, a comprehensive review of UAVs applications combined with NDT Infrared Thermography (IRT) and Ground Penetrating Radar (GPR) or RS Close Range Photogrammetry (CRP) and Light Detection and Ranging (LiDAR) is carried out to assess the potential and the limitations of the UAV-based monitoring approaches. This research provides valuable information on enhancing management strategies by upgrading port monitoring practices.

Keywords: non-destructive techniques; port infrastructure; remote sensing; structural monitoring; unmanned aerial vehicle

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1. Introduction

Ports are critical energy, industry, circular economy, and employment hubs that facilitate national and international transportation (ESPO, 2021). However, ports are in an extremely harsh environment, affecting their infrastructure's integrity. Corrosion from seawater, high loads from ships and deck cargoes, and alternating wet and dry cycles are some of the causes that lead to structural degradation (Gaythwaite, 2016; 2021 Report Card for America's Infrastructure, 2021). Climate change phenomena (e.g. sea-level rise and extreme storm events) are another pressing issue that needs to be addressed in terms of confronting port deterioration (2021 Report Card for America's Infrastructure, 2021). Furthermore, many marine structures have reached their design life (Heffron et al., 2015). Therefore, targeted measures should be applied to protect structures and public safety against the consequences of failure.

According to Gaythwaite (2016), repair and rehabilitation actions are economically preferable to constructing new marine facilities. To achieve this, port operators are challenged with implementing monitoring strategies to inspect and assess the structural condition of the existing port infrastructure (2021 Report Card for America's Infrastructure, 2021).

Conventional monitoring practices include human visual inspections subject to the investigator's opinion and experience (Jo et al., 2018). Within the context of applying a reliable and efficient approach that is based upon the employment of sophisticated equipment for monitoring port infrastructure, several Non-Destructive Testing (NDT) and Remote Sensing (RS) techniques are currently used for the assessment of structural performance (Rodriguez Millian, 2019). Infrared Thermal Imaging (IRT), Ground Penetrating Radar (GPR), Close Range Photogrammetry (CRP), and Light Detection and Ranging (LiDAR) are among the most common techniques.

Nowadays, the attachment of NDT and remote sensors on Unmanned Aerial Vehicles (UAVs) has gained momentum, given the significant advantages of the UAVs, including hard-reached elements' access, increased inspection speed, and reduced safety risks (Abdelkhalek and Zayed, 2021). Automation in structural monitoring and limitations during inspections, such as time consumption and increased costs due to safety reasons and equipment and personnel costs, have made UAVs an attractive option for infrastructure monitoring (Keaveney and McGetrick, 2020). Nevertheless, in the port industry, a limited number of researches have been focused on UAV-based infrastructure monitoring since UAVs have been chiefly preferred for the security and control of port services and areas (Agatić and Kolanović, 2020).

Considering the above and the recent surges in employing UAVs for NDT and RS practices, the current paper investigates the utility of UAVs as a means of port infrastructure monitoring. For this purpose, four (4) popular techniques integrated into UAV systems, IRT, GPR, CRP, and LiDAR, are further investigated to advance monitoring practices of concrete port infrastructure with UAV approaches. Moreover, a preliminary assessment of the performance of these UAV-enhanced NDT and RS methods is described following the results of similar research.

2. Materials and Methods

2.1. General Framework of UAV Approaches

In recent years, the ever-increasing use of UAVs has been remarkable (Paszotta et al., 2017). UAVs provide applications including the delivery of goods, disaster management, search and rescue for missing persons, security issues, land surveying, construction, and infrastructure inspection (Keaveney and McGetrick, 2020; Gopalakrishnan et al., 2017). UAV applications are up-and-coming, especially in the civil infrastructure (Lattanzi and Miller, 2017; Fan and Ala Saadeghvaziri, 2019). In fact, due to their capability to visually approach vulnerable and inaccessible components of infrastructure, UAVs have been efficiently integrated into infrastructure monitoring practices (Duque et al., 2018). Consequently, inspections become extremely easy, more secure, and cost-effective (Vidyadharan et al., 2017). Therefore, nowadays, many engineers are using UAVs to monitor the integrity of various infrastructures (e.g. bridges, buildings, and dams) and detect possible deterioration (Duque et al., 2018).

As far as ports are concerned, UAVs have a significant role in port security management (Stein, 2019). The threat of a terroristic attack on the port facilities and any disruption of the port operation induces severe consequences to the global supply chains. Using UAVs in conjunction with photogrammetric techniques reduces and controls risks posed to port safety and security (Stein, 2019). Furthermore, UAVs' applications include monitoring the shipping traffic in port waters, loading and unloading operations, and container management (Agatić and Kolanović, 2020). However, limited research has been conducted on integrating UAV approaches into port infrastructure monitoring.

Monitoring of port structures is currently implemented with several NDT and RS techniques as described in the American Society of Civil Engineers' manual on inspecting and assessing waterfront facilities (Heffron et al., 2015). NDT inspections include applying IRT and GPR techniques for locating and mapping delaminations of concrete deck structures. In contrast, RS inspections enclose multi-beam and side-scan sonar techniques for underwater inspections. Integration of UAV-enhanced port monitoring practices has recently attracted research interest and is mainly focused on employing camera-based techniques. Paszotta et al. (2017) have examined the use of UAVs combined with internet photogrammetry techniques for monitoring ports, especially harbours. Moreover, Tsaimou et al. (2021) have proposed a monitoring framework that encloses camera applications integrated into UAVs to record and assess the structural condition of port structures. Govaere et al. (2018) have also used UAV aerial images and photogrammetric techniques to monitor the breakwater at Caldera Port on Costa Rica´s Pacific coast.

Besides photogrammetry-based UAV monitoring approaches, UAV inspection applications can be facilitated by incorporating NDT and other RS techniques. LiDAR (Dorafshan et al., 2019; Fan and Ala Saadeghvaziri, 2019), as well as Radio Detection and Ranging devices (RADAR) and IRT sensors can be attached to UAVs for inspection purposes in civil infrastructures (Fan and Ala Saadeghvaziri, 2019). CRP and LiDAR techniques are mainly connected with UAV applications (Guan et al., 2022), while IRT and GPR have been chiefly applied with compatible means (e.g. use of surface vehicles or human-aided applications) (Harris et al., 2016; Tešić et al., 2021). However, recent studies have examined the application of IRT equipment mounted on UAVs for civil infrastructure inspection purposes (El Masri and Rakha, 2020). Based on the above, the upgrade and optimisation of port infrastructure monitoring approaches can be achieved by investigating the perspective of integrating more techniques into UAV monitoring systems.

2.2. UAV-enhanced Practices with NDT and RS Techniques

As infrastructure monitoring and damage detection automation have been continuously evolving into a sophisticated scientific field, advancements in port infrastructure monitoring should be engaged to facilitate the development of powerful monitoring strategies following recent surges. Towards this, four (4) widely used NDT and RS techniques that can be integrated into UAV-based approaches are described herein in terms of enhancing monitoring practices of port infrastructure.

Photogrammetry is a technique that creates 3D point clouds and a photorealistic structure model by analysing 2D images collected with UAVs (Perry et al., 2020). To perform CRP techniques remotely, the required equipment system refers to an optical sensor mounted on a UAV. CRP applications enable damage detection in concrete structures by generating photorealistic models using Structure-from-Motion (SfM) algorithms (Perry et al., 2020) and, consequently, assessing their performance (Harris et al., 2016). Within the context of port monitoring, Paszotta et al. (2017) have suggested the solution of internet photogrammetry as a means of port infrastructure inspections, transport safety, and cargo control.

LiDAR technique uses light or laser beams to measure the distance between the structure and the light source to produce 3D point clouds (Perry et al., 2020). After processing the 3D obtained data, a 3D triangulated model is generated (Bobkowska et al., 2017). Similar to CRP inspections, LiDAR applications have been used for recording the in-situ condition of various concrete structures such as bridges (Harris et al., 2016). In recent years, LiDAR equipment has also been mounted on a UAV to detect defects during bridge inspections (Bolourian and Hammad, 2020). Regarding port infrastructure analysis, data acquired with airborne and terrestrial LiDAR measurements allows for assessing stability and degradation level (Bobkowska et al., 2017).

IRT has been characterised as a very effective technique for condition monitoring since it enables the recognition of possible defects by detecting heat signatures with an infrared camera (Lauritzen et al., 2019). Indeed IRT technique is one of the most common techniques for structural monitoring in the marine industry and the most suited for docks, jetties, caissons, and piers inspections. Besides port infrastructure, the IRT technique has been widely used in building (El Masri and Rakha, 2020) and bridge (Omar and Nehdi, 2017) inspections. Similar to LiDAR, IRT practices can be enhanced with UAV approaches, as indicated in the research of Omar and Nehdi (2017), where an IRT system mounted on a UAV has been used for recording the in-situ condition of bridge infrastructure. Hiasa et al. (2017) also referred to bridge inspections and presented the capabilities and limitations of a UAV system equipped with IRT sensors.

GPR is considered one of the most popular NDT techniques in civil engineering. GPR application is based on sending electromagnetic waves through a structure and receiving a reflected signal depending on the electric properties of the host material (Tosti and Ferrante, 2020). Ibrahim (2016) mentioned that GPR could be used to inspect composite structures such as port infrastructure and concrete structures like bridge decks or pylons. GPR applications have been expanded for monitoring transport infrastructure, including bridges, retaining walls, and tunnels (Dinh and Gucunski, 2021). Nevertheless, GPR mounted onboard a UAV for infrastructure inspection is not often encountered. In most cases, GPR combined with UAVs is used for buried objects on land surveying (Garcia-Fernandez et al., 2018).

3. UAV-based Performance of NDT and RS Techniques

3.1. Existing Framework for Assessing NDT and RS Techniques

Many researchers have been focused on assessing and ranking infrastructure monitoring techniques by estimating their performance based on various significant criteria (Yehia et al., 2007; Vaghefi et al., 2012; Oh et al., 2013; Gucunski et al., 2014; Lee and Kalos, 2015; Omar and Nehdi, 2016; Hesse et al., 2017; Kušar et al., 2018; Abdelkhalek and Zayed, 2021). Regarding concrete infrastructure, IRT, GPR, CRP, and LiDAR techniques have been compared to identify the optimal alternative for an effective monitoring program. Table 1 includes previous studies that have compared NDT and RS techniques while simultaneously indicating the ones that have performed a further assessment, scoring, and ranking of the techniques. It is noticed that only one research encloses all four considered techniques (i.e. Vaghefi et al. 2012).

In particular, Yehia et al. (2007) scored IRT and GPR, among others, for their performance in bridge inspection based on test speed, test results, nature of the method, detection depth, lane closure, surface crack detection, depth calculation accuracy, surface preparation, and equipment cost. Vaghefi et al. (2012) ranked among twelve techniques, IRT, GPR, LiDAR, and Photogrammetry, according to their performance in eight critical criteria regarding bridge inspections. The eight criteria refer to the requirement accomplishment, the availability of the equipment, the cost of the measurements, the need for precollection preparation, the complexity of analysis, the ease of data collection, the stand-off distance rating, and the traffic disruption. The overall evaluation was based on previous research conducted by Ahlborn et al. (2010), where a comprehensive table with the scores of each technique for the majority of the potential surface and subsurface defects was derived.

Oh et al. (2013) analysed IRT behaviour, among others, in detecting delamination in bridge decks. The criteria used were: cost, time, relative sensitivity to ambient noise and environmental conditions, operator skills, weight and size, lane closure, surface preparation, delamination detection accuracy, objectivity, and repeatability. Gucunski et al. (2014) graded IRT and GPR based on five criteria: accuracy, speed, repeatability, ease of use, and cost. Apart from these techniques, six additional techniques were evaluated in this study. Similarly, Lee and Kalos (2015) compared the degree of application difficulty, effectiveness, and efficiency of standard NDT techniques. Moreover, Omar and Nehdi (2016) rated IRT and GPR among the five NDT techniques based on their performance in the capability of subsurface defect detection, speed of data collection, simplicity of analysis and interpretation, and the accuracy of results, and the cost of measurement. The above-mentioned research achieved NDT ranking by integrating decision-making methodologies, including the Fuzzy Analytical Hierarchy Process (FAHP).

Hesse et al. (2017) evaluated numerous inspection techniques for bridge infrastructure, including IRT. The complete evaluation was carried out according to bias, accuracy, precision, reliability, and cost criteria. Kušar et al. (2018) have included IRT and GPR techniques in scoring various monitoring techniques for bridge inspections based on results' reliability, test duration, interpretation reliability, cost, usability, and standardisation. Kušar et al. (2018) have also attributed weights to the selected criteria through the Analytic Hierarchy Process (AHP) decision-making method.

Table 1. Summary of research assessing monitoring techniques.

	Literature	IRT	LiDAR	GPR	CRP	Short description
Scoring	Yehia et al. (2007)	✓		✓		No ranking of techniques. Questionnaire for scoring (targeted at departments of transportation-DOTs in the United States). Distributed to and scored by 50 experts.
Scoring	Vaghefi et al. (2012)	✓	✓	✓	✓	No ranking of techniques. Existing literature and experts' judgment for scoring. Based on Ahlborn et al. (2010) research.
Scoring	Oh et al. (2013)	✓				No ranking of techniques. Laboratory tests and in-situ NDT measurements.
Scoring	Gucunski et al. (2014)	✓		✓		No ranking of techniques. Laboratory tests by ten academia, industry, and government teams.
Scoring	Lee and Kalos (2015)	✓		✓		No ranking of techniques. Questionnaire for scoring (targeted at bridge inspection unit managers or a similar high-level role within a state's bridge inspection program). It was distributed to 52 states and territories. Competed by 40 responders.
Scoring	Omar and Nehdi (2016)	✓		✓		No ranking of techniques. Questionnaire for scoring (targeted at NDT experts and bridge inspectors). Distributed to 35 experts. Completed by 27 experts.
Scoring	Hesse et al. (2017)	✓				No ranking of techniques. Questionnaire for scoring (targeted at employees in departments of transportation-DOTs who are involved in bridge evaluation and private companies in the United States that work in the NDT domain. Distributed to 36 DOTs and 27 contractors. Completed by 11 DOTs and three contractors.
Scoring	Kušar et al. (2018)	✓		✓		No ranking of techniques. Existing literature and laboratory tests for scoring.
Scoring	Abdelkhalek and Zayed (2021)	✓		✓		Ranking of techniques. Questionnaire for scoring (targeted at government agencies, consultancy agencies, research centres, universities. Distributed to 65 experts. Completed by 24 experts.
No Scoring	Chiu et al. (2017)		✓		✓	No ranking of techniques. Theoretical comparison of techniques.

A more comprehensive study for prioritising monitoring techniques refers to the research of Abdelkhalek and Zayed (2021), who assessed, among others, the IRT, GPR, and UAV-camera techniques aiming to compare them in terms of inspection of concrete bridge decks. The assessment was based on experts' opinions. It was performed using weighting techniques (Analytic Network Process – ANP) and multicriteria decision aid methods (Technique for Order Preference by

Similarity to Ideal Solution – TOPSIS). The techniques were evaluated against five criteria, thirteen sub-criteria, and forty parameters. The five essential criteria used refer to capability, performance under different environments, ease of use, cost, and speed. Based on their research, the IRT technique indicated the near-best performance for most criteria, thus being ranked first in preference. More, in particular, IRT took third place under the standard of capability and second one in the requirements of ease of use, speed, and cost. Furthermore, the GPR technique followed the IRT one indicating a slight difference in the ranking results. Although GPR had the best score on the criterion of performance under different environments, this result was inadequate to lead the GPR dominance above the other techniques. Its performance to the remaining criteria was also satisfactory since it ranked second in the standard of capability and third in the ease of use and speed requirements. The UAV-camera technique was ranked in the sixth position in the total evaluation.

Finally, monitoring techniques have also been assessed on a theoretical basis. Chiu et al. (2017) compared the methods of LiDAR and Photogrammetry according to the way of use on the field, the 3D construction of the inspecting infrastructure, the cost, and the ability to capture textures.

Fig. 1 illustrates the criteria selected for assessment analyses of monitoring techniques based on the existing literature presented above. The numbers in parentheses refer to the studies that include each criterion for assessment purposes. As expected, several criteria are common for most of the included studies such as cost, speed duration, ease of use, and accuracy.

3.2. Considerations for UAV-based NDT and RS Assessment

All the criteria mentioned so far are crucial for assessing the IRT, GPR, CRP, and LiDAR monitoring techniques. However, the ranking of these techniques was performed following the conventional way they are most commonly applied. The combination of NDT and RS techniques with UAVs may modify the performance of these techniques on several criteria, mainly when such an integrated system is used for port infrastructure monitoring. This section aims to analyse how the implementation of IRT, GPR, CRP, and LiDAR techniques varies when UAV approaches are included for port infrastructure inspections.

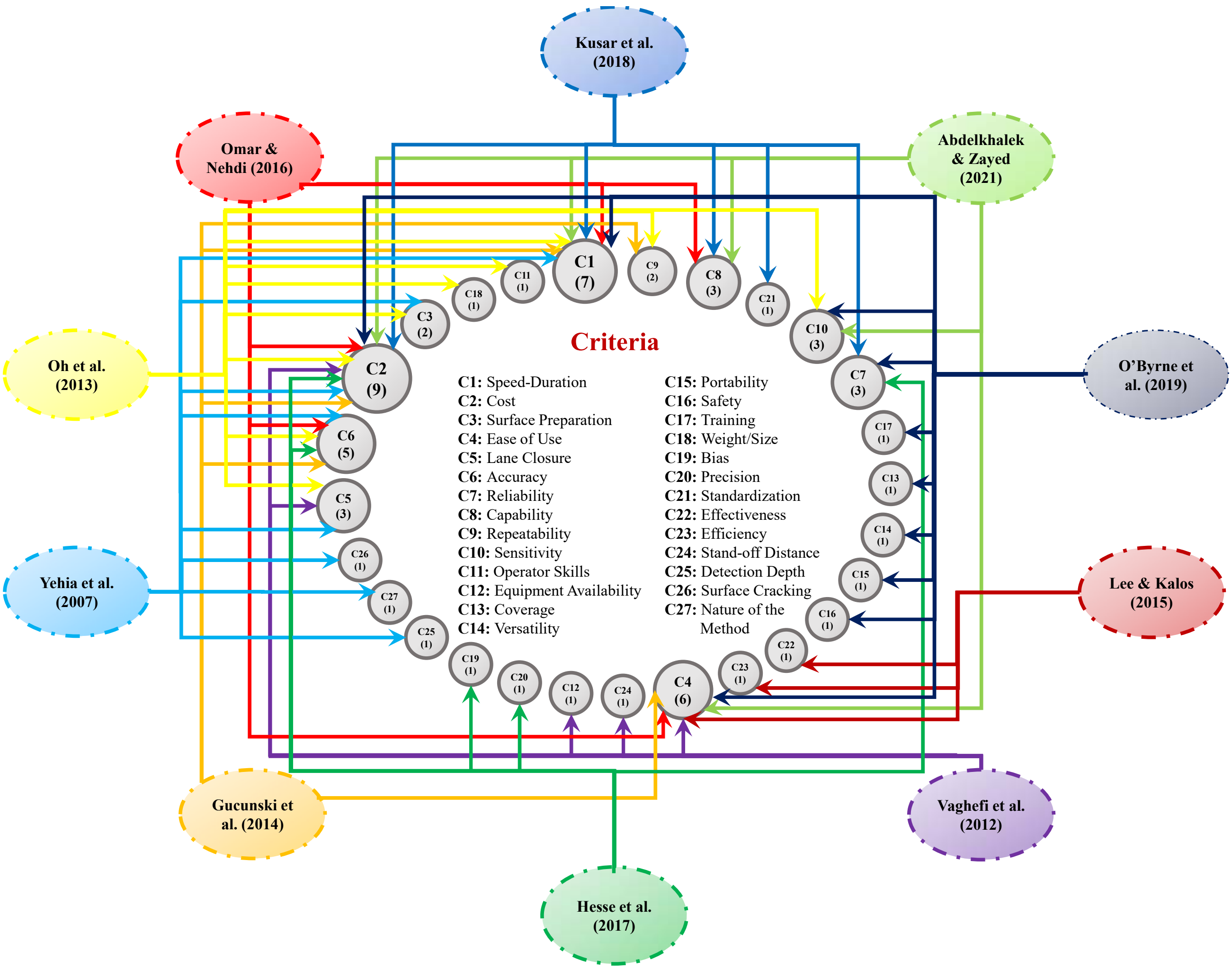

Fig. 1. Criteria for performance assessment of NDT and RS monitoring techniques.

It is noted that in most cases, the CRP technique is applied in combination with UAVs. Thus, no difference in its performance will be noticed. However, depending on the assessment of the other techniques, the prioritizing results can be altered. The most significant criteria that will be discussed are cost, speed, ease of use, capability, accuracy, and reliability, deduced through data themes noted in Fig. 1.

Cost is the most significant criterion for assessing and ranking the monitoring techniques. This criterion can be divided into sub-criteria including equipment cost, data collection, and data analysis cost. Regarding the equipment cost of each technique, UAV integration into monitoring practices can affect the required budget. Typically, IRT, GPR, and LiDAR applications involve a vehicle to be mounted on. The use of UAVs as the required vehicle will increase the equipment cost since usually, the vehicle that is employed during infrastructure inspections is the same as the one used for equipment and operators' transport (i.e. a wheeled vehicle such as a van). As far as the other two sub-criteria are concerned, no difference will be noticed with the integration of UAVs, given that the way of data collection and analysis remains the same.

The criterion of speed refers to three sub-criteria, i.e. the time needed for the pre-collection preparation of the investigated surface, the time for the collection, and the analysis of data. Given that none of the techniques require special preparation applied for the considered surface, no change will be induced by the use of a UAV. Furthermore, the employment of a UAV in the monitoring process doesn't have an impact on data analysis speed, because UAV is a means of collecting data and not analyzing them. However, as for the data collection speed, the use of UAVs reduces the time on the field for the IRT and LiDAR techniques since larger areas can be inspected without further disruption. Regarding the GPR technique, since limited research has been conducted in terms of the relationship between the height of the antennas and their performance, it can be suggested that data collection speed remains the same considering a low flight altitude.

The ease of use or simplicity is another criterion that can alter the performance of the considered techniques when inspection equipment is mounted on a UAV. This criterion depends on the expertise of the operators for the inspection or the analysis of data, the environmental conditions, and the traffic interruption. Since 2016 considerable restrictions by the Federal Aviation Administration (FAA) on the commercial operation of a UAV have been alleviated (Duque et al., 2018). However, additional knowledge of UAV applications is always a prerequisite. Moreover, in Europe, EASA regulations provide the framework for employing UAVs and obtaining the relevant certificate that enables the user to conduct flights (https://www.easa.europa.eu/domains/civil-drones#group-easa-downloads). Therefore, although the inspectors can have easy access to the operation of UAVs for monitoring purposes, the required expertise is increased. On the other hand, the weight of a UAV-inspection tool (IRT, GPR, or LiDAR) system, and the hard environmental conditions in a port (e.g. wind), as well as the operation of the port raise challenging issues to be addressed. Port operators are tasked to handle these limitations, and consequently, IRT, GPR, and LiDAR techniques take lower scores to the criterion of ease of use when mounted on UAVs.

The capability criterion refers to the identification of existing structural condition regarding the type, the variety and the number of potential distresses. Both the type and the variety of the defects recorded with IRT, GPR, and LiDAR techniques are not affected by the use of a UAV since each technique detects specific surface and subsurface anomalies regardless of their incorporation into a UAV. Nevertheless, the number of defects that can be identified may change because UAVs enable approaching remote parts of a structure. Therefore, difficult-to-approach elements of the port facilities (e.g. cranes set up in wharves, stacked containers on the pavements, etc) can be inspected by monitoring tools mounted on a UAV, thus increasing the number of recorded distresses. Considering this, the capability of IRT, GPR, and LiDAR could be improved if they are combined with a UAV.

Furthermore, regarding the criterion of accuracy, three approaches are considered for assessing monitoring techniques. The first approach refers to the capability of identifying the exact location of the distress, the second one to the accuracy of detecting the exact depth of the defect, and the third approach corresponds to the potential of determining its severity. Even though inspection tools mounted on a UAV are applied at a longer distance than the same equipment mounted on a vehicle, the results are not affected to a large extent. Therefore, IRT, GPR, and LiDAR sensors define the location, depth, and severity of a defect irrespective of their combination with a UAV.

Reliability refers to the potential of collecting the same data when you repeat the whole inspection process in the field. Bearing in mind that there is always a pre-defined flight plan for the UAV, the collected data won't crucially differ. Similar circumstances occur in the application of these techniques without a UAV. The only possibility of receiving different results during the repeatability of an inspection would be if the process took place exclusively by inspectors. The subjectivity of the inspectors would possibly alter the collected data.

The above-mentioned criteria, the examined monitoring techniques, as well as the way that the performance of the latter is modified when they are applied with a UAV system are presented in Fig. 2. The central bar represents the classification of the techniques' performance in three categories. The green area includes the techniques that are positively affected by the specific criteria when they are used in combination with a UAV. The red area consists of the techniques that are negatively affected when applying a UAV-based inspection, while the grey area encloses those that remain stable after the addition of a UAV to the inspection process. The shapes and the colors show the monitoring techniques and the criteria, respectively. On the right side of the bar, the RS techniques (CRP, LiDAR) are depicted, while on the left side, the NDT techniques (IRT, GPR) are shown. This chart aims to illustrate indicatively the variation of the performance for the four techniques under six important criteria. It is mentioned that it is out of the scope of the present research to estimate the degree of differential.

Based on Fig. 2 it is noticed that the techniques of IRT and LiDAR indicate a better performance regarding the criteria of speed and capability when applied with a UAV system. As for the GPR, the criterion of capability is positively affected when this technique is combined with UAVs, in contrast with the criterion of speed which is not affected at all. Moreover, cost and ease of use are negatively affected for the two NDT techniques, i.e. the IRT and GPR, as well as for the LiDAR technique. Finally, the performance assessment for the CRP technique does not differentiate when UAV-based approaches are implemented.

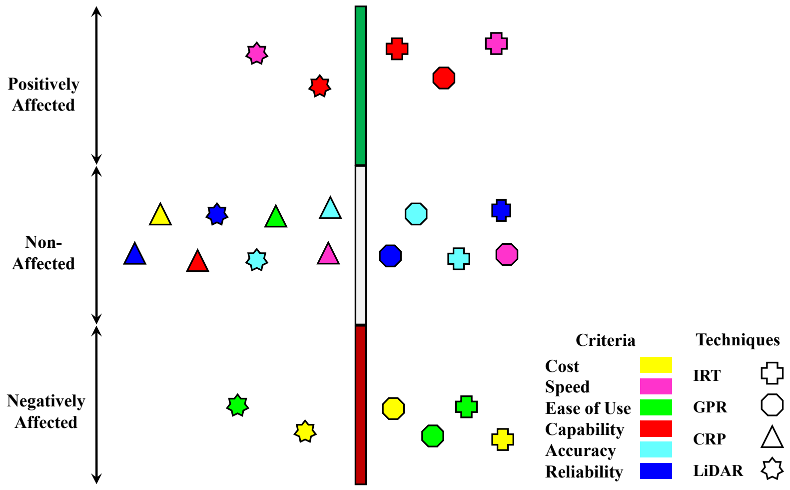

Fig. 2. Assessment variation of IRT, GPR, CRP, and LiDAR monitoring techniques considering a combination with a UAV system.

Within the context of a holistic assessment of the monitoring techniques combined with UAVs considering the total number of criteria (Fig. 1), further research is required. Expert judgment is a tool that could be used, especially in terms of the application of these techniques at port infrastructure, where adverse and corrosive conditions are prevailing. Data collected from the targeted interviews or the questionnaires can be analysed with Multi-Criteria Decision Analysis (MCDA). MCDA can contribute to the evaluation of the monitoring techniques following a UAV-based approach, as well as to their ranking aiming at determining the most and the least preferable ones. It is noted that this further investigation is out of the scope of the present research.

4. Discussion

The application of UAVs equipped with NDT and RS sensors is a modern practice for port infrastructure monitoring. The present study aims to introduce a first approach towards assessing the performance of four common monitoring techniques, i.e. IRT, GPR, CRP, and LiDAR, combined with a UAV under essential criteria. For this purpose, several previous studies that evaluated these techniques, with or without UAV applications, were considered. Based on the literature review, it is concluded that the most important criteria are cost, speed, ease of use, capability, accuracy, and reliability. Considering these criteria, a new assessment of the performance of IRT, GPR, CRP, and LiDAR techniques combined with a UAV was performed. The goal of this assessment was to detect the potential improvement or decrease in the performance of these techniques (Fig. 2).

As far as the NDT techniques are concerned, IRT sensors mounted on a UAV indicate significant performance enhancement compared to the typical monitoring practice applied with surface vehicles. The implementation of a UAV-IRT system accomplishes faster inspections while maintaining the same level of accuracy and reliability. Additionally, the ease of hovering and maneuvering a UAV leads to the reduction of data collection time. Therefore, the speed of the total in-situ inspection process is increased. UAVs also contribute to the detection of a large number of surface and subsurface defects since their employment enables inspecting remote components of infrastructure, thus identifying hidden defects in inaccessible areas. Moreover, the accuracy and reliability of the collected data are equivalent to those of the conventional IRT application. However, the simplicity of a UAV-IRT application is decreased, by the prevailing environmental conditions in ports and the nature of the method itself. Specialized operators are required for the successful accomplishment of monitoring. As far as the cost criterion is concerned, a UAV-IRT system adds expense regarding both equipment acquisition and operation costs.

The performance of the GPR mounted on a UAV system doesn't differ significantly from the conventional practice applied with surface vehicles. Only the criterion of capability seems to be improved, while the reliability, accuracy, and speed of the inspection remain the same. Similar to UAVs equipped with IRT sensors, the UAV-GPR system increases the cost and the difficulty of use. GPR technique is quite an expensive inspection method that needs experienced and well-trained operators and analysts to identify the subsurface defects. Therefore, the employment of a UAV-GRP system does not improve significantly the performance of the GRP technique considering also the limited research performed for infrastructure monitoring based on this combination.

With regard to the RS techniques combined with a UAV system, for the CRP technique, it is obvious that no difference in the performance results is noticed. As mentioned before, the CRP technique is inherently linked with UAV applications and consequently, its performance assessment has been already based on UAV employment. On the other hand, the performance of the LiDAR technique indicates significant differences when mounted on a UAV similar to the IRT technique. The performance for speed and capability is enhanced, for cost and ease of use is reduced, while for reliability and accuracy of the measurements and results is not affected.

The overall research is based on a theoretical approach for assessing the performance of the four monitoring techniques, i.e. IRT, GPR, CRP, and LiDAR, combined with a UAV without considering potential limitations posed by UAVs' flight requirements. UAV restrictions, such as flight time, sensor weight, and permitted distance from the surface under investigation may affect the applicability of the considered monitoring techniques and, consequently, the criteria scoring.

5. Conclusions and Future Recommendations

The present paper is focused on investigating UAV-enhanced NDT and RS applications for inspection purposes of port infrastructure aiming at optimizing monitoring practices. Two (2) NDT techniques, i.e. IRT and GPR, and two (2) RS techniques, i.e. CRP and LiDAR, are further examined to qualitatively assess their performance when combined with UAV systems based on six (6) significant criteria. The overall research indicated that the performance of both IRT and LiDAR techniques is improved in the criteria of speed and capability and worsened in the criteria of cost and ease of use when combined with UAV systems while on the other hand the performance of GPR and CRP techniques is not significantly affected. In general, the total performance of both the NDT and RS techniques is affected by the use of UAVs, thus resulting in potential differences in the final ranking of the techniques.

Considering the above, advancements in port infrastructure monitoring based on UAV employment can optimize inspection processes. Further research is required to achieve a quantitative assessment of the performance of the considered monitoring techniques. Towards this, MCDA methods that analyze experts' opinion data are considered a reliable approach for scoring and, consequently, ranking the monitoring techniques.

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Author Contributions

Konstantina H. Chelioti contributes to methodology, validation, analysis, investigation, data collection, and draft preparation. Christina N. Tsaimou contributes to conceptualization, methodology, validation, investigation, draft preparation, manuscript editing and visualization. Vasiliki K. Tsoukala contributes to conceptualization, methodology, validation, manuscript editing, review, visualization, supervision, project administration, and funding acquisition. All authors have read and agreed with the manuscript before its submission and publication.

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