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Harnessing Remote Sensing Technologies for Successful Large-Scale Projects

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Abstract: The integration of remote sensing technologies, such as Mobile Mapping Systems (MMS), Ground Penetrating Radar (GPR), airborne LiDAR, high-speed terrestrial laser scanner and airborne multispectral cameras, is transforming the execution and management of large-scale infrastructure projects. These tools enable efficient and accurate data collection without requiring operators to be physically present in the observed area, enhancing the ability to map, analyze, and model both surface and subsurface features. This paper explores the synergy of these technologies, focusing on their application in critical sectors such as climate change mitigation, smart cities, and digital twins. It examines the benefits of technology integration, the challenges of data interpretation, and the opportunities for improving project efficiency and sustainability. Through a detailed analysis of each remote sensing technology, this paper highlights their potential to redefine large-scale project execution, driving innovation in infrastructure development and to bring business benefits to organisation which implements it.

Keywords: 3D spatial data; business breakthrough; ground penetrating radar; mobile mapping system; remote sensing technologies

1 INTRODUCTION

The remote sensing technologies has revolutionized the execution and management of large-scale infrastructure projects, integrating innovative tools such as Mobile Mapping Systems (MMS), Ground Penetrating Radar (GPR), airborne LiDAR and airborne multispectral camera, terrestrial laser scanner, airborne echosounder, and high-performance computing capabilities.

Regarding the technology background, the Mobile Mapping Systems are the combination of various navigation and remote sensing technologies on a common moving platform. What makes them a remote sensing technology is the fact that the operator does not need to be physically in the observed area of detail in order to collect the spatial data on details, while the system works from a distance. The same applies to Ground Penetrating Radar. The relevant literature defines them as remote sensing technologies [1]. Also, there is an entire Special Issue of Open Access Journal by MDPI - Remote Sensing which is devoted to the latest developments in GPR systems and applications, called Recent Progress in Ground Penetrating Radar Remote Sensing [2].

When it comes to MMS, to date there were several papers which addressed the MMS capabilities and possible applications. The obvious application is mainly in road measurements and there are many research papers regarding this application [3, 4, 5]. Also, some of the research addresses other applications like geotechnical and landslide monitoring with MMS [6]. Thus, the recent research work has brought an overview of applications where MMS can be used. These include wide range of applications like road asset management and condition assessment, BIM, emergency and disaster response, vegetation mapping and detection or digital heritage conservation. On the other hand, given the complex terrain environment, a single MMS or even a few MMSs could hardly be sufficient at all levels of mobile mapping applications [7].

The Ground Penetrating Radar technology has been gradually adopted in civil engineering since mid-1990s, but after 2000, technological advancements and tremendous improvements of digital computation power have led to the blossoming of GPR applications on infrastructure [8]. The applications range from engineering geophysics, buildings inspection, to infrastructure applications like road, pavement and bridge observations, tunnel liners. The GPR usage in road layers thickness analysis is shown in [9, 10, 11], but also there are papers showing GPR application in detection of anomalies such as cracks [12, 13]. Also, the GPR is used to position and map underground utilities of different kinds like pipes or cables [14, 15].

Despite of all those previous research papers, use of GPR is still in an ad-hoc based but not regular-based, while the technology is still evolving with much future potential [8]. Furthermore, the survey results of the GPR mapping undoubtedly yield much larger errors than the above-ground surveying technologies. Therefore the GPR is proposed to be complemented with other remote-sensing technologies in this paper.

The MMS and GPR technologies present a comprehensive solution for mapping and analyzing spatial features crucial for climate change mitigation, development of smart cities, and creation of digital twins, embodying a new wave of green technology. Their application extends beyond the surface to provide detailed 3D data of underground structures, thereby enhancing project efficiency and environmental sustainability. Both have some shortcomings, thus other sensors are introduced to provide competent overall spatial data collection.

With respect to that, the inclusion of remote sensing in large-scale projects poses unique challenges, including the integration of diverse technologies and the interpretation of complex data sets. This paper aims to explore the synergy of remote sensing technologies and their potential in application on large-scale infrastructure projects. By examining the advantages of technology integration, applications in critical sectors, and solutions to implementation hurdles, the discussion extends to the role of these technologies in addressing climate change, advancing smart cities, and promoting the concept of digital twins. This overview not only sets the stage for a detailed analysis of each technology's contribution but also underscores the potential of remote sensing to redefine project execution and outcomes in the face of evolving global demands.

2 THE PROPOSED TECHNOLOGIES COMBINATION IN REMOTE SENSING

The proposed technologies for enhancing large-scale projects through remote sensing are both diverse and integrated, aimed at providing comprehensive coverage and detailed data acquisition. This tested combination includes advanced systems like the Mobile Mapping System (MMS) Leica Pegasus TRK700 EVO, Ground Penetrating Radar (GPR) Leica Stream Up, and innovative tools such as underwater robots and airborne geomagnets, but also airborne echosounders. Additionally, the integration of multi-spectral cameras, such as the VUX160 LiDAR combined with a PhaseOne camera, and air-pollution measurement devices like Sniffer4D, further broadens the scope of environmental monitoring and mapping accuracy.

The synergy of these technologies not only supports traditional applications such as transportation planning and construction but also extends to innovative uses like real-estate mass valuation, emergency response planning and ad-hoc interventions, and the development of digital twins. This technological combination is a game changer in managing and executing large-scale projects efficiently, particularly those requiring rapid data collection over extensive areas.

The combination of these technologies is not only pivotal in general mapping but also in specific applications which are stressed out in the paper, such as cadastral measurements and real estate valuation. For instance, in a multi-year cadastral measurements program [16] covering 600,000 hectares, the integration of these technologies can facilitate the efficient mapping and valuation of vast land areas, optimizing both time and resources. Furthermore, the use of Multiple Regression analysis (MRA) in real estate valuation considers a variety of internal and external variables, from physical characteristics of the property to environmental factors, which all can be captured and quantified through these advanced remote sensing technologies. The use of MRA for mass real estate valuation is defined in the Regulation on mass real estate valuation [17], where the variables for the evaluation are also defined (e. g. location, area, usage, position in the building, existence of an elevator, etc.). Although, relevant experts states that there are rather more complex variables in place which impacts the value of real estate, like field of view [18], which can be seen in Fig. 1.

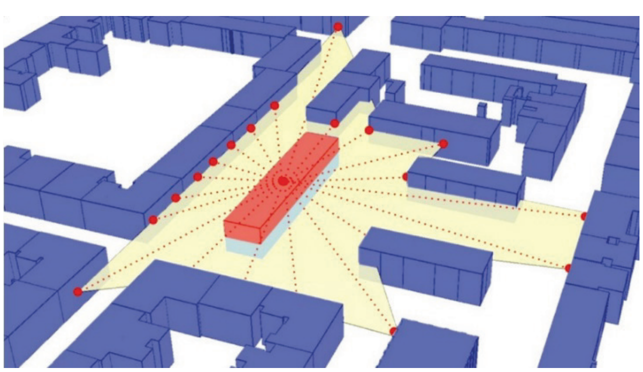

Figure 1 Calculation of a visibility polygon in GIS [18]

This can be analyzed with advanced GIS systems for which the highly defined, accurate and reliable spatial data should be collected. The government intended to implement the real-estate tax, but with delay, with the main reason of not having the appropriate datasets for the real-estate valuation. The proposed technology combination in this paper can be an efficient game changer to collect this kind of data on real-estate. Furthermore, the introduction of regulations such as ePhysicalPlans, which require thematic basemaps, showcases the growing reliance on advanced remote sensing technologies for compliance and advanced planning. These technologies facilitate the creation of detailed, multi-spectral maps essential for physical planning as well as many other thematic basemaps which are up to date. Only in 2024, there are already more than 250 municipalities which have applied for financing of the physical plan creation or amendments in new ePhysicalPlan form [19]. This creates a vast economic potential and demand for all kinds of spatial data or thematic basemaps.

3 TECHNICAL INFORMATION AND EXAMPLE USAGE IN A LARGE-SCALE PROJECT

For the first technical demonstration it is aimed to show how these devices can be used in multi-year cadastral measurements and real estate valuation - speeding up the existing workflow significantly. The aim of this project is to scan all buildings fast and efficiently utilizing more scanning angles. From the software side the following is needed: speed up the vectorization workflow while retaining precision.

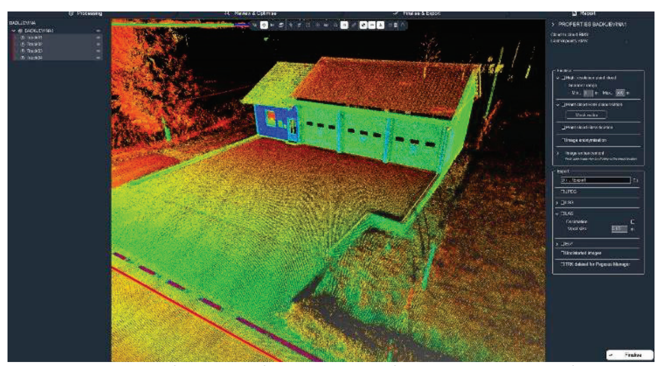

Figure 2 Example of a building facade captured from the street inside of Pegasus Office

First up - aerial scanning LiDAR solution is utilized. While not much different from any other solution on the market the VUX 160 offers one main benefit - nadir-forward-backward facets in the scanning mechanism are used to get as much coverage on the facades as possible. The system offers selectable pulse repetition rate which allows for greater accuracy of the laser beam [20].

Paired with an external inertial measurement unit AP+50 system can be mounted on a smaller aircraft or an unmanned aerial vehicle. Limitation of this technique is not being able to pick up finer details in the more complex buildings and their eaves.

Advantage of this scanner is in option for defining own customisable set of parameters for each flight mission in RiParameter. Since the aim is to capture as much detail in -

10 and +10 degrees from nadir, the scan rate is maximised to 400 lines per second - achieving a point every 4 centimetres and a new line every 2 centimetres. This can be further improved by lowering the flight speed.

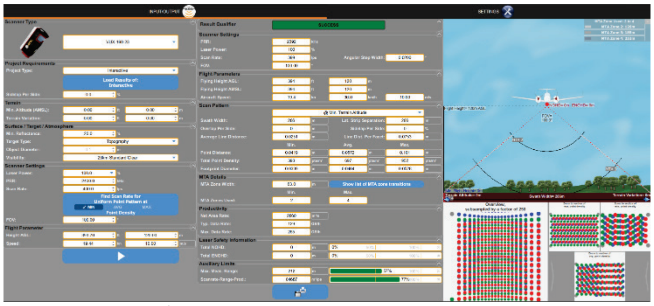

Figure 3 Defining aerial LIDAR scanner parameter in RiParameter

Another tool is the mobile mapping system - TRK 700 Evo. Utilizing a phase-shift LiDAR allows for greater precision at the cost of range which is opposite from time of flight LiDAR systems [21]. Majority of urban areas can be accessed from the roadways. Mobile system needs to be initialized beforehand because the inertial unit needs to be adapted and trained for the upcoming data collection. Having two Z&F 9020 laser profilers allows for 2 million points per second which allows greater driving speeds thus enhancing the operation. Limitation of this approach is the laser obstruction along the driving lane.

These two systems collect about 80% of needed data - there are still some gaps which cannot be measured beneath eaves and more complex buildings.

Last tool used is the VZ-600i. Its main advantage is the integrated GNSS antenna, IMU sensor and a fast pulse repetition rate (2200 kHz) resulting in the scan times of 30 seconds, delivering on-site registered point clouds. The field workflow is straightforward which means that the remaining gaps can be measured wherever there is an RTK connection available. Only one scan position outside the building is needed, then the remaining positions indoors can be scanned and everything is within the specified accuracy. This system would actually be the best for completing the project but its drawback is the speed of acquisition.

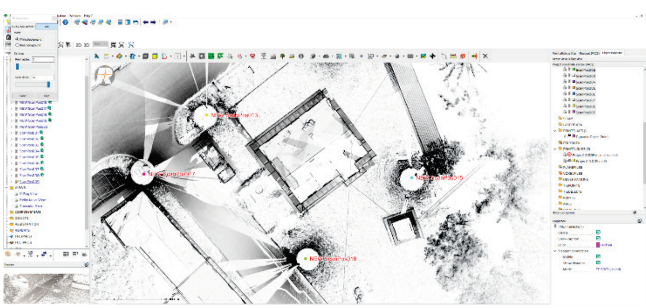

Figure 4 Automatic registration of scans inside RiScan Pro.

As the data is acquired in the field - each scan position on the scanner saves its RTK position, IMU heading, roll and pitch value. Having this additional data enables the onboard computer to calculate the scanner's position and orientation "on-the-fly" without the operator needing to roughly fit the scans in post-processing. This results in very quick turnover time with no user input required. Inside the software it is also possible to remove the noise generated by moving objects.

Moving to the software and modelling side - all data sources need to be registered and data quality needs to be confirmed against checkpoints. Although the data lies well within the specification stated by the State Geodetic Administration [22] there are still vertical discrepancies which can be resolved by utilizing plane patching and multi-station adjustment inside the RiScan Pro software.

After all three data sources are optimized the next step is vectorization. This research tries to resolve the problem with two various methods: semi-automatic vectorization using TerraScan and manual extraction using Microstation Connect with Topodot. Each method has its own pros and cons. The semi-automatic method gives the outlines for the whole area way faster than manual extraction but at the cost of having polyline artifacts and miscellaneous errors. Using manual extraction the user is slower but has utmost control along the whole process, utilizing various quality assurance and checks along the way.

Another example usage in a large scale project would be ground penetrating radar for archeological purposes.

As GPR is a non-invasive/non-destructive method of collecting subsurface data [23], its use over a possible archeological area is described. The instrument used is IDS Stream Up - having 2 crossed antennas at 200 mHz and 600 mHz and the scan width of 1.6 meters while being mounted on a vehicle, area can be scanned significantly faster than other solutions.

Figure 5 The IDS Stream Up device mounted on a vehicle

Using proprietary software IQ Maps tomography data is analyzed to extract existing pipelines and point out areas of archeological interest before the site is demolished.

One example usage of this device is the archeological need for detecting possible historical remains and to detect unregistered utilities. To ensure the best possible coverage, the site is scanned after closing all of the traffic on the site. Through using RTK antenna, total station or even mobile mapping system (tested TRK700 EVO) the data is generated and filtered in IQMaps software. Afterwards the B-scans of the GPR data were generated and from there it was possible to assess existing underground utilities and possible areas of archeological value. Data can be exported as linestrings, points or hatches straight to any CAD program.

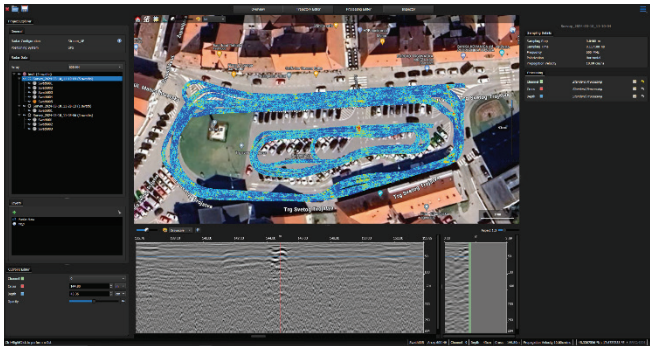

Figure 6 IQMaps software showing the data gathered in passes.

The same procedure can be applied to observation of any road, underground utilities, bridges, tunnels, or any large-scale infrastructure object. With respect to stated issus regarding GPR in the Introduction, by combining with the MMS it is rather more efficient to map the underground structures, and by introducing other data collection methods it is possible to perform the accuracy assessment and data quality control, but with almost on-the-fly performance and delivery of the results.

4 DISCUSSION AND PROPOSAL FOR APPLICATIONS BEYOND TRADITIONAL BOUNDARIES

Latest amendments of Law on Forests are now more data-driven, thanks to remote sensing technologies. Also, the new ISPU (Information System of Spatial Planning) [24] assists in creating a comprehensive Green Infrastructure Register, crucial for sustainable development. The data of greenery should yet be collected, which is a huge task for geodetic operatives. Recently, many local self-government (LGU) units in Croatia are procuring the services of making Strategies of Green Urban Renewal, and are bringing them into force [25-27]. The Guidelines for making the Strategies for Green Urban Renewal [28], define that within the scope of delivery of every strategy, the team behind the strategy should prepare the dataset for the Green Infrastructure Register. The Ministry of Spatial Planning, Construction and State Property created the Green Register infrastructure, a new module of the ISPU system, which enables input, maintenance and analysis of data on green infrastructure for urban areas in the Republic of Croatia and entry of spatial data from the above-mentioned strategic documents. The entry of data into the Register is overseen in accordance with the Typology of Green Infrastructure, which are defined as open spaces, green and blue areas, which make up the green infrastructure in construction areas. Green urban renewal strategies need to be created in accordance with the mentioned Typology green infrastructure. But as most questionable instruction from the Guidelines stands the one that the strategy of green urban renewal must include cartographic representation in open GIS format (GDB or shp) and must contain:

- the scope for which the Strategy is being prepared
- the area which includes planned green urban renewal projects
- and the mapping of existing green infrastructure in accordance with the Typology of Green Infrastructure.

Therefore, it is instructed that, on the level of making strategic document, the green infrastructure in urban areas should be mapped and delivered in a specific GIS format. When considering the economic engagement and the amount of procurement contract for the strategies, which is mostly on the level of making a strategic document which does not predict the terrain spatial data collection, this presents a gap in the initiative, while most of the green infrastructure mapping are missing in the strategies. Therefore, it is a leverage to have the ability to rapidly collect the spatial data in urban areas based on which one can map the initial state of green infrastructure within the scope of strategic document making. Also, from the perspective of economic feasibility, the solution is in MMS in combination with other technologies presented in this paper.

eBuildingInspection is announced, while the combination of remote sensing technologies streamline building inspections and enhance the efficiency of the supervision process by providing detailed subsurface data, crucial for safety and compliance. Through periodic monitoring with remote sensing, primarily with combination of MMS+GPR can aid in identifying changes in transport infrastructure and detecting non-evidenced landslides, crucial for maintaining safety and continuity.

Furthermore, reality capture technologies used to create Digital Twins enable precise modelling of physical assets, which can be crucial in emergency response scenarios. Although, previous and recent research in this area stresses the issue of integration of massive data from remote sensing into the digital twins; they conclude that future work should consider the development of methodologies and protocols to integrate the massive data streams coming from heterogeneous sensors and complex systems [29]. These heterogeneous sensors are for sure in modern time exactly the ones used here.

The potential applications of remote sensing technologies are extensive and largely underexplored. Their advantages become particularly evident when integrated with various professions and scientific fields. Some additional prospective applications of these technologies include forest biomass estimation, landslide detection, real estate valuation, tree root detection, mass grave identification, automated road asset extraction, and the creation of pollution maps.

Furthermore, there are several existing ideas that, despite their potential, have not been widely implemented in practice. For example, the swift scanning of crash accident sites could minimize road closures time periods. Previous research related to road accident site investigation [30] include the application of UAV drones for data collection on site of the accident. Their conclusion is that they bring progress in terms of the time needed to record the scene of the accident, but problems related to the presence of illumination poles, overhead electricity and telecommunication lines, as well as road-side trees, may present challenges for accident investigators, especially in urban areas. Furthermore, that research found that higher altitudes of UAV result in lower image resolution, potentially diminishing the overall accuracy of the data. On the other hand, combination of technologies like in this paper which includes MMS and high speed terrestrial laser scanner would potentially eliminate identified problems in applying consumer level UAV in order to increase the speed of scene investigation, and to prevent long road traffic closures. In addition, the technology like applied here is more likely to be faster than the time measured in previous research related to this issue.

Similarly, roads could be monitored to detect potholes, swelling, and rotting, thereby enabling the early identification and remediation of potential defects.

5 ADVANTAGES WHICH MAKE THESE TECHNOLOGIES COMBINATION A REAL GAME CHANGER

Mobile Mapping Systems (MMS) and Ground Penetrating Radar (GPR) work in tandem to provide detailed surface and subsurface data. This is crucial for projects requiring detailed geological assessments or for locating underground utilities without excavation.

Underwater robots and airborne geomagnetics play a pivotal role in exploring and monitoring aquatic and remote terrains, which are often inaccessible to traditional survey methods.

Multi-spectral cameras and airborne echo sounders facilitate the analysis of environmental conditions by capturing data across different wavelengths, thus providing insights into vegetation health, water quality, and other critical environmental indicators.

The integration of advanced remote sensing technologies significantly enhances the efficiency and environmental sustainability of large-scale projects. These technologies facilitate rapid and accurate data collection, which minimizes the environmental impact typically associated with extensive physical surveys. For example, the use of mobile mapping systems and multi-spectral cameras allows for precise data acquisition without the need for disruptive land-based activities, thereby preserving natural habitats and reducing carbon footprints.

They are cost efficient, because implementing these technologies can lead to substantial cost savings by reducing the need for physical inspections and the associated labor and travel expenses. There is a potential for developing a new method for continuous geodetic monitoring of transport infrastructure development and maintenance, which can now be dynamic due to an affordable data collection.

In a project-oriented economy, this technology combination is making a real contribution in time efficiency as well. Projects in regions with harsh climates or limited survey windows benefit immensely from these technologies. For instance, in projects with stringent administrative deadlines, the integration of geodetic equipment with this technology accelerates data collection, ensuring projects stay on schedule.

The ability to gather precise data in challenging outside conditions without physical intrusion makes remote sensing technologies particularly valuable. This is evident in tasks like air-pollution detection and the exploration of underground structures, where traditional methods might falter.

6 CONCLUSION

Implementing remote sensing technologies in large-scale projects involves complex challenges that require strategic solutions. One of the primary hurdles is the integration of various sensors and systems. These technologies, although powerful individually, must be synchronized to work seamlessly together which is believed to be the greatest challenge for successful utilization. This synchronization ensures that the data collected is coherent and can be processed efficiently. The proposed technology combination can provide the solution which fills the gaps identified in the Introduction. The confirmation of this is in the fact that with shown set of instruments, the operator is able to collect the spatial data above ground, underground, concrete data and abstract data (air-pollution detection with Sniffer4D), accessible areas as well as inaccessible areas, and with desirable accuracy to meet the strict requirements of engineering applications as well (now with subcentimeter accuracy for large area and rapid data collection). This could be called a total spatial data collection, such as desired in Digital Twins applications.

Advanced remote sensing technologies are becoming indispensable in the realm of large-scale infrastructure projects. Their application significantly enhances the efficiency and accuracy of projects such as road constructions, tunnels, and extensive cross-regional infrastructure developments. The future announced initiatives at the state level for the establishment of various spatial databases, harmonization of spatial planning documents and their digitization, as well as tackling the integrity of cadastral and land registry records for the entire territory of the Republic of Croatia through large projects financed by the EU, not only that they promise business opportunities for the application of this combination of technologies, but also set the basis and necessity for the application of advanced technologies and new processes in geodetic tasks so that all national plans and priorities in this area can be realized on time.

The future work should address the analysis and development of a specific workflow for combination of the mentioned technologies, considering the development of Unified Modelling Activity Diagram (UML), or a process diagram to achieve a standard operating procedures for different case scenarios of data collection. This can include scenarios for different phases of infrastructure development, i.e. design phase, construction phase, and maintenance phase, but also for different infrastructure facilities and objects.

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