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INTEGRATING GIS INTO GEOSPATIAL DIGITAL TWINS FOR MINING OPERATIONS: A REVIEW OF TECHNOLOGIES AND CASE STUDIES FROM ROMANIA

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Abstract. *Mining operations require accurate and up-to-date geospatial data for safety, deformation monitoring and mine planning, while the European legal framework — the INSPIRE Directive and, in Romania, Government Ordinance 4/2010 on the INIS — mandates interoperable spatial data. On this foundation, the concept of the geospatial digital twin is developing, a direction endorsed at European level through the Destination Earth initiative. This paper is a review of the geospatial technologies used for documenting terrain and mining areas, grouped into three pillars: satellite remote sensing, UAV (Unmanned Aerial Vehicle) photogrammetry and mobile laser scanning based on SLAM (Simultaneous Localization and Mapping). Drawing on case studies, mostly from Romania, the advantages and limitations of each pillar are analysed: the broad but medium-resolution coverage of satellite data, the centimetre-level but local detail of UAV surveys, and the high-detail 3D structure, including underground, offered by laser scanning. It is shown that the value of these sources increases when they are integrated, with GIS (Geographic Information System) acting as the integration layer that brings them into a common reference system, in line with INSPIRE requirements. The conclusion is that an integrated geospatial digital twin, combining surface and underground data, provides a suitable framework for deformation monitoring and hazard assessment in mining operations.*

Keywords: *GIS; geospatial digital twin; remote sensing; UAV photogrammetry; mining*

INTRODUCTION

Mining operations need good, up-to-date geospatial data, used for work safety, deformation monitoring and mine planning. In recent years there has been a growing shift from the classical plan to 3D digital models, and with it a practical problem has emerged: how to coherently combine data coming from different sources.

At European level, a legal basis for this already exists. The INSPIRE Directive (2007/2/EC), transposed into Romanian law through Government Ordinance No. 4/2010, established the National Infrastructure for Spatial Information (INIS) and requires spatial data to be mutually compatible, accompanied by metadata and accessible through standardized services (European Parliament and Council, 2007; Government of Romania, 2010). It is precisely this compatibility that supports the integration of data into a single model.

On this basis, the concept of the geospatial digital twin has developed — a virtual, georeferenced copy of a terrain or object, which is updated from observation data and does not merely display reality but also supports analysis, simulation and monitoring. The direction is also followed

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at European level through the Destination Earth initiative, which is building digital twins of the Earth for climate and extreme events (European Commission, 2024).

A digital twin relies on several acquisition technologies. In this paper they are grouped into three pillars: satellite remote sensing, for monitoring land use over large areas; UAV photogrammetry, for detailed terrain models at local scale (SIMON et al., 2021); and terrestrial and mobile laser scanning (SLAM), for detailed 3D documentation, including underground spaces (ZLOT & BOSSE, 2014; KŘEMEN et al., 2024). Each pillar has advantages and limitations, and the results are more useful when the data reach a common reference system.

The less-studied part is precisely the integration of these sources — the role of GIS as the layer that links satellite, drone and ground data into a unitary model, especially in the Romanian mining context. This paper brings together case studies from Romania on the three pillars, analyses the role of GIS as an integration layer in accordance with INSPIRE requirements, and outlines the path towards a geospatial digital twin for mining operations, useful for safety, deformation monitoring and hazard assessment.

MATERIAL AND METHODS

This paper is a review (synthesis) study: it brings together and compares already published results, without primary field data. The aim was to group the relevant works on the three technological pillars and to analyse the role of GIS as an integration layer between them.

Sources were searched in scientific databases (Web of Science, Scopus, Google Scholar) and in field-specific journals — Research Journal of Agricultural Science, Mining Revue, Remote Sensing and ISPRS Archives — using keywords such as: digital twin, GIS, remote sensing, UAV photogrammetry, laser scanning, SLAM and mining. Recent works were preferred and, where possible, examples from Romania, for local relevance.

Three criteria guided the selection: relevance to the geospatial documentation of terrain and mining operations, the existence of an applied case study, and belonging to one of the three pillars. The materials were then organized by pillar — satellite remote sensing, UAV photogrammetry and laser scanning/SLAM. For each pillar, the discussion addresses what it brings and what limits it, and finally how GIS links these data into a unitary model, in line with INSPIRE interoperability requirements.

RESULTS AND DISCUSSION

Satellite remote sensing and GIS

Satellite remote sensing tracks land cover and land use changes over large areas, which is useful in mining regions where the landscape changes rapidly. An example from Romania is the study by Vorovencii (2024), which analyses the surface coal mining basin in the Jiu Valley (the Rovinari and Motru Jilț perimeters, about 107,700 ha) over the period 1988–2017, using Landsat 5 TM and Landsat 8 OLI satellite imagery. Through supervised classification — the best model being SVM-RBF, with accuracy between 86.6% and 90.7% — and change detection, the author shows a strong increase in built-up areas (+110.7%), a reduction of waste dumps (−53.0%, through revegetation), the expansion of forest (+30.1%, on abandoned land) and a decrease of pastures (−47.7%). These changes are linked to the shift, after 1989, from underground to surface mining and to the stricter environmental regulations after 2007.

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UAV photogrammetry

Drone photogrammetry fills the resolution gap of satellite imagery, producing terrain models and orthophotos at centimetre resolution, at local scale. SIMON et al. (2021) use a WingtraOne VTOL drone, equipped with a 42.4 MP camera and a GNSS system, for the 3D mapping of the Labașinț locality (Arad County) in the Pix4D Mapper software; the imagery yields orthophotos, a digital terrain model (DTM/DSM) and point clouds, presented as a basis for digital terrain analysis.

The same method also works with affordable equipment. In an own study (MANOLE, 2024), a consumer drone (DJI Mavic 2) together with ground control points measured by GNSS in the Stereo70 system was used to document a site with an elevation difference of about 72 m; processing produced a digital terrain model, an orthophoto and a topographic plan drawn up in accordance with Order 600/2023, at a resolution (GSD) of about 1 cm/pixel. The example confirms that low-cost solutions can also generate georeferenced geospatial products.

Laser scanning and SLAM

Terrestrial and, above all, mobile laser scanning based on SLAM provide the highest level of detail, including in GNSS-denied spaces such as underground galleries. The principles of SLAM and the accuracy assessment of mobile scanning systems are treated extensively in the literature (CADENA et al., 2016; NOCERINO et al., 2017; SAMMARTANO & SPANÒ, 2018; CONTI et al., 2024), while 3D documentation of structures through laser scanning is well established (REMONDINO, 2011). KŘEMEN et al. (2024) test a handheld SLAM scanner (Emesent Hovermap ST-X) on a mine tunnel of about 750 m in the Josef mine, comparing the results with a static terrestrial reference scan. The local accuracy remains very good, around 7 mm regardless of distance, but a systematic deviation appears that grows with distance from the control points: the transverse error reaches about 186 mm for a single pass and drops to about 69 mm for a double pass, while the SLAM cloud is slightly "shrunk", by about 10 cm per kilometre. The authors recommend scale-corrected transformations and periodic control points for long galleries. On an even larger scale, earlier work demonstrated the mobile mapping of kilometres of mine galleries (ZLOT & BOSSE, 2014).

The same technology was also applied by the authors to a public building (MANOLE, 2026): a handheld SLAM scanner documented the ground floor, the first floor and the exterior in a single session, with over 240 million points and a local accuracy below one centimetre, independently verified. However, limitations typical of the method also appeared — doubled points on glazed surfaces and a colourisation quality that varied with the trajectory — exactly the kind of problems that, at the scale of a mine gallery, must be controlled.

Table 1

The three geospatial pillars — products, advantages and limitations

Pillar	Main product	Scale / resolution	Advantages	Limitations
Satellite remote sensing	Land cover/use maps; time series	Large / tens of m	Wide coverage, free data, long record	Low spatial detail
UAV photogrammetry	Orthophoto, DEM/DSM/DTM	Local / cm	High resolution, flexible, on demand	Small area/flight, weather, regulations, needs GCP
Laser scanning / SLAM	3D point clouds, 3D models	Detail / mm–cm local	High detail, GNSS-denied/underground, fast	Drift over long distances, reflective surfaces, colourisation

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GIS as the integration layer

The three pillars yield useful results separately, but their real value appears when they are brought together. This is where GIS comes in, as an integration layer: it provides the common georeferencing framework, the spatial database and the analysis tools through which satellite, drone and laser scanning data reach the same system and can be queried together. Each pillar thus becomes a layer — the satellite brings the surface context and changes over time, the drone brings the detailed terrain, and laser scanning/SLAM brings the 3D structure, including the underground one.

This integration is not only a technical matter but also one of standards. The INSPIRE and INIS requirements regarding metadata, interoperability and standardized services (European Parliament and Council, 2007; Government of Romania, 2010) are precisely the binder that allows layers from different sources to work within a single model. On this framework the geospatial digital twin is built — a georeferenced and updatable model that not only displays reality but supports analysis, simulation and monitoring (European Commission, 2024). The way the three pillars are linked through GIS is shown schematically in Figure 1.

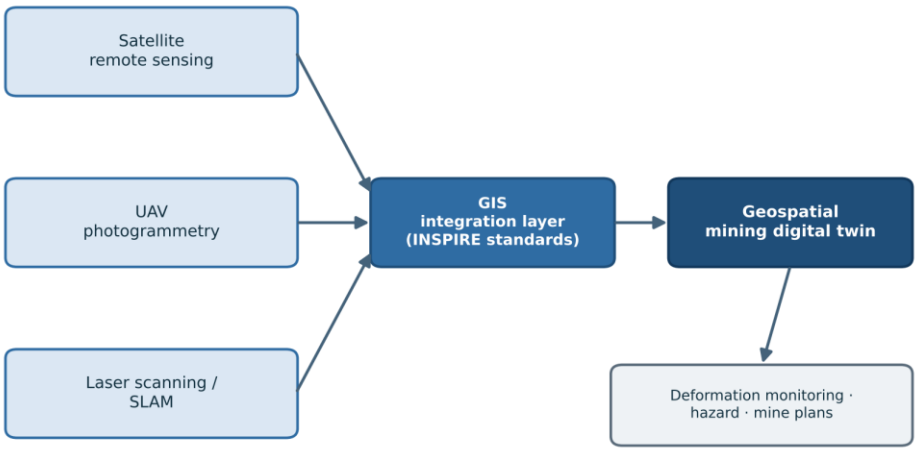


Figure 1. Integration of the three geospatial pillars through GIS, into a geospatial digital twin for mining operations

Current gap and mining applications

In Romanian practice, the three pillars are usually used separately, for specific purposes. Their real integration into a single geospatial digital twin for mining operations remains little addressed, although this is precisely where the greatest potential lies — for safety, digital mine plans and, above all, deformation monitoring and hazard assessment.

A relevant example is the study by HERBEI et al. (2022), which measures, using geodetic methods (GPS), the tilt and displacement of the land caused by coal mining in the Jiu Valley (the

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Maleia area), obtaining tilt values between about −4.8 and +4.9 mm/m, analysed statistically. Such deformation data, integrated into a digital twin alongside the satellite, UAV and 3D scanning layers, would allow subsidence to be tracked over time and a better assessment of mining hazard. It is precisely this integration — deformation data over the geospatial model — that the present topic opens up.

Table 2

Synthesized case studies

Author (year)	**Pillar**	**Area**	**Method**	**Key result**
Vorovencii (2024)	Satellite	Jiu Valley (Rovinari–Motru)	Landsat + SVM	Built-up +110.7%, dumps −53%, forest +30.1% (1988–2017)
Simon et al. (2021)	UAV	Labașinț (Arad)	WingtraOne + Pix4D	Orthophoto + DTM/DSM for terrain analysis
Manole (2024)	UAV	Corvin Castle (Hunedoara)	Mavic 2 + GCP	DEM + orthophoto + topographic plan, GSD ~1 cm
Křemen et al. (2024)	SLAM	Josef mine (CZ)	Hovermap ST-X	Local accuracy ~7 mm; drift with distance
Manole (2026)	SLAM	University building (Cluj)	RS10 handheld	>240 M points, below 1 cm local
Herbei et al. (2022)	Geodesy/deformation	Jiu Valley (Maleia)	GPS	Tilt −4.8…+4.9 mm/m

CONCLUSIONS

This paper reviewed three geospatial technologies — satellite remote sensing, UAV photogrammetry and laser scanning/SLAM — through case studies, mostly from Romania, showing for each what it brings and what limits it. The satellite provides the long-term surface context, the drone provides detailed terrain at centimetre resolution, and laser scanning/SLAM provides the 3D structure, including in underground spaces. None of them, taken alone, covers the needs of a mining operation. The value comes from their integration, and GIS — supported by the INSPIRE and INIS standards — is the layer that links them into a geospatial digital twin. For mining, such a model would support deformation monitoring, digital mine plans and hazard assessment. The way forward is the actual building of an integrated digital twin for a real mining perimeter, with emphasis on combining surface data with underground data.

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