

for robots and autonomous systems over the past three decades. Mobile robotic mapping is a crucial challenge in robotics since robots need accurate maps to effectively navigate their environments. As Simultaneous Localization and Mapping (SLAM) has emerged as a significant area of focus within robotics research, addressing the mapping problem head-on. A wealth of publications has proposed efficient solutions to this challenge (Chabert and Jaulin, 2009; Freitas et al., 2016; Mustafa et al., 2018). SLM is a critical technique in robotics and autonomous systems that enables a robot to construct a map of an unknown environment while simultaneously keeping track of its position within that map. This process helps robots navigate and interact effectively with their surroundings. SLAM involves two main tasks: a) Localization: Estimating the robot's position relative to the map it is building, given its sensor measurements and previous knowledge of the environment and b) Mapping: Using sensor data to update the (base)-map while accounting for uncertainty and noise in the measurements.

Various algorithms and approaches have been developed to solve the SLAM problem, including Extended Kalman Filters (EKF), Particle Filters, Graph-based SLAM, and many others (Thrun et al., 2005; Weingarten and Siegwart 2005; Ravankar et al., 2015). These techniques vary in complexity, computational requirements, and robustness, making each suitable for different applications and environments. Although most of these algorithms perform well enough in static surroundings, in dynamic environments, the performance of traditional SLAM frameworks often suffers because of interference caused by moving objects. These frameworks typically assume that the environment remains static, and any changes introduced by dynamic objects can lead to inaccuracies in the generated maps and localization estimates (Su et al., 2022; Xujie, 2021; Xiao, 2019).

1.3 Cartographic and Robotic Mapping Overlaps

So-far Robotic Mapping and Cartography research areas has been running in parallel and are not heavily intertwined and overlapped primarily due to differences such as in focus, scale, and data source. Robotic mapping including SLAM primarily deals with real-time localization and mapping for autonomous systems or robots, whereas cartography is more concerned with the general representation and design of geographic information, often on larger scales as mentioned by ICA (2022). Furthermore, Robotic mapping generally operates at smaller spatial scales, often dealing with a robot's immediate environment, such as indoor or urban settings. In contrast, cartography addresses a wider range of scales, from local to global, for various purposes beyond robotics such as urban planning, transportation, natural resource management. Another interesting technical difference lays in the fact that Robotic mapping relies on sensor data from robots or autonomous systems (such as lidar and cameras), whereas cartography uses different data sources like satellite imagery, aerial photography, and diverse geographic information systems (GIS) databases.

Figure 1 tries to schematically show the two important aspects of Cartographic Mapping namely Map **M**aking and Map **U**se in a two-dimensional matrix to show the overlaps with Robotic mapping.

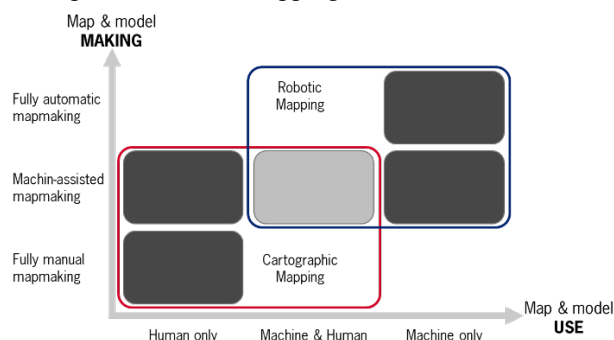


Figure 1. Schematic Human-Machine mapmaking and map-use matrix

The figure 1 shows all (9) possible options available to make and use maps with different automation degrees; mapmaking can be fully manual, semi-automatic, or fully automatic, and map users can be only humans, both humans and machines, or only machines. Cartographic mapping has been mainly concerned with humans as main users and maps are created traditionally either manual or with the help of GIS tools and in some cases automatically from satellite or aerial images. On the other hand, Robotic mapping considers machines as mere users of created maps through SLAM methods. An area that both fields overlap is where maps created in cartographic mapping approaches are used for instance as base-maps for SLAM algorithms, which is schematically shown in the middle of the matrix with a grey box. In other areas of the Matrix in the figure 1 no boxes are drawn, as they are also minimum explored such as fully manual mapmaking for machine-only users.

As a result of these very limited overlap, all databases, software tools, and GIS systems for the field of cartographic mapping are built by considering humans in the centre as both mapmaker and map user, and in the field of Robotic mapping machines are considered mainly as mere users of created maps by robots. Although these assumptions have been valid for decades, even today we see readily that machines becoming by far the biggest users of maps and GIS models and humans need to use created real-time and dynamic maps by Robots and machines. This highlights a white spot on the research agenda of not only Cartography and GI-Science community but also Robotic mapping society to engage more with the question how these fields can converge and benefit from each other and what are the implications that need to be analysed and evaluated carefully.

In the next section, the convergence of Cartographic and Robotic mappings is investigated. In section 3 key questions to ponder upon are comprehensively elaborated and discussed. In section 4 the way-forward to build the common-ground between the two disciplines is briefly discussed and finally section 5 concludes this article.

2. Cartographic and Robotic Mapping: The need for Convergence

2.1 Common Challenges and Opportunities

The fields of cartography and robotic mapping have traditionally been considered distinct, with cartography focusing on the creation of maps for human users and robotic mapping primarily targeting autonomous systems. However, as complexity of the real-world increases, the need to perform in dynamic environments grows, and technology advances, the potential for collaboration and convergence between cartography and robotic mapping has become increasingly apparent.

Indeed, both cartography and robotic mapping face common challenges, such as the need to accurately represent complex, dynamic environments and to create maps that can be easily understood and used by their target audience humans and machines who readily co-exist at the same time in the same environments (Polous 2023; Su et al., 2022; Linhui, 2019). Furthermore, as autonomous systems become more prevalent, the demand for high-quality maps that can be used by both humans and machines will continue to grow. Hence, the convergence of cartography and robotic mapping will be essential for meeting this demand and ensuring that the needs of all users are met. Another important reason is the growing demand for real-time spatial data in various applications, such as navigation, disaster response and management, and environmental monitoring, can drive the convergence of cartography and robotic mapping. Both fields can contribute to the development of real-time mapping solutions that can capture and representing dynamic spatial information. This convergence could lead to the development of more efficient and effective spatial representation and mapping solutions, benefiting a wide range of applications and industries.

2.2 Technical Reasons for Convergence

On the other hand, several technical reasons underscore the need for the convergence of cartography and robotic mapping:

- Cartography and robotic mapping both aim to create spatial representations of the world, albeit with different goals and perspectives. The development of common representation frameworks, such as event-based models or ontologies (Polous, 2016; Polous 2023), could facilitate the convergence of the two fields by providing a shared machine-readable language for describing and understanding real-world spatial information.
- Both cartography and robotic mapping increasingly require a deeper understanding of the semantics of the environment being mapped (Polous 2023; Xiao, 2019). This entails not only capturing the geometric and topological aspects of the world but also understanding the meaning and relationships of the objects and features within it. Developing shared methods for

semantic understanding of the geographical reality could contribute to the convergence of the two fields.

- As the demand for high-resolution and up-to-date maps grows, both cartography and robotic mapping face challenges in terms of the scalability and efficiency of their mapping algorithms. Addressing which requires the development of novel techniques and approaches beyond Multi-resolution mapping, Incremental mapping algorithms, and data compression and optimization.
- Modern cartography and robotic mapping often utilize diverse data sources, such as remote sensing, LiDAR, and ground-based measurements and sensors. The integration of these different data types requires advanced data fusion techniques and more sophisticated methods for combining and interpreting multi-source data, while reducing the impact of individual sensor limitations.

These are just few scientific reasons highlight the potential for cartography and robotic mapping to converge as they continue to advance and tackle similar challenges. By learning from each other's techniques and perspectives, the two fields may eventually develop more integrated and comprehensive solutions for spatial representation and mapping.

3. Toward convergence, key questions to ponder upon

The rise of machines – such as autonomous driving vehicles – raises the question for GI-Scientists and cartographers as; how well machines – beside humans – as both mapmaker and map users of geographical data and maps should be considered in creating maps, developing GIS tools and systems, and representing geographical information in GIS databases. Hence, in this section, we explore three key questions that require investigation.

3.1 How best (geographical) data and maps can be represented for machines to use?

The best representation of geographical data and maps for machines depends on the specific application and the requirements of the machines. However, in general best representation of (geographical) data for machines is a representation that allows machines to read, manipulate, process, and analyse data, and make decisions fastest, with minimum needed network and processing power, and with maximum needed accuracy, as they might have only fractions of a second to make a decision. Author suggests following high level guidelines, as minimum requirement for the representation of geographical in a manner that is optimized for machines to read, manipulate, process, and analyse, facilitating fast and accurate decision-making processes:

- Choose a data format that is easily readable and writable by machines and robots, such as GeoJSON and TopoJSON, or a binary format like

Protocol Buffers and FlatBuffers. These formats allow for efficient parsing, processing, and analysis of geographical data.

- Organize geographical data in a hierarchical manner or graphs, such as using a quadtree or octree structure, to enable efficient spatial indexing and querying. This allows machines to quickly identify, query, and access relevant data based on their spatial location.
- Utilize vector-based representations of geographical data (e.g., points, lines, and polygons) as they allow for precise representation of spatial features and efficient geometric operations.
- Annotate geographical data with semantic and topological information to help machines understand the relationships between different spatial features and their attributes. This can facilitate complex spatial reasoning and decision-making processes.
- Tailor the representation of geographical data to the specific tasks that machines need to perform. For example, if a machine needs to perform real-time path planning, optimize the data for fast routing algorithms.
- Apply compression techniques to reduce the size of geographical data, minimizing network and processing overhead while maintaining sufficient accuracy for the task at hand.

Although several of these suggestions are already applied for mapmaking and map use in the field of Cartography, extra attention is needed to be made when making these data available for autonomous machines.

3.2 Which data, information, or knowledge of dynamic (geographical) reality of our environment should be made readily available for machines?

Furthermore, agreeing to the inevitable rise of machines as main mapmaker and map user in human lives, helps to remove two key restrictions on maps; a) amount of information represented in a map or a GIS model, and b) complexity level of spatial reality that can be mapped in a map or even in a GIS model for humans to understand and comprehend. This raises the second question for scientists “Which data, information, or knowledge of dynamic (geographical) reality of our environment should be made readily available for machines?”. The goal here is to help machines make the best possible decisions, enhance their autonomy, and improve their interaction with the environment. Here are some key factors to consider when determining what information should be provided to machines:

- The geographical data provided to machines should be dynamic, continuously updated, and able to capture real-time changes in the environment. This includes information on the location and movement of objects, the status of infrastructure, and other evolving spatial features.

- Temporal data, such as time stamps, intervals, and durations, should be integrated into the geographical data to provide machines with a better understanding of the temporal aspects of events and processes. This will enable machines to anticipate changes, track trends, and make more informed decisions based on the timing of events.
- Machines should have access to contextual data that provides information on the broader context within which events and processes occur. This may include data on environmental conditions, socio-economic factors, cultural norms, and other relevant factors that can influence decision-making.
- Semantic data, such as metadata and annotations, should be incorporated into the geographical data to help machines better understand the meaning and relationships between different spatial features, events, and processes. This can support more sophisticated reasoning and decision-making.
- Multi-modal data from diverse sources, such as remote sensing, ground-based sensors, social media feeds, and expert knowledge, should be integrated and fused to provide a more comprehensive representation of the environment. This can help machines to develop a more holistic understanding of the environment and make better decisions based on a wide range of information.
- Uncertainty information, such as error estimates, confidence intervals, and data quality indicators, should be provided alongside the geographical data to help machines assess the reliability of the information and make more robust decisions in the face of uncertainty.

By making this rich, dynamic, and contextually relevant information readily available to machines and autonomous systems, we can enable machines to handle more complex spatial realities and make better decisions. This shift towards a more machine-centric approach to cartography and GIS will necessitate new methods, tools, and standards for representing, managing, and analysing geographical data, ultimately transforming the way we think about maps and geographical information systems in the age of machines.

3.3 which ethical, religious, cultural information and norms about different regions and environments are essential for an autonomous entity?

As geospatial data becomes increasingly integrated with autonomous entities, it is vital to consider the ethical, religious, cultural, and social aspects of various regions and environments to ensure harmonious coexistence with humans. Author suggests in the following some key considerations for designing and implementing autonomous systems in the context of geospatial data,

however this requires voluminous work in the coming years:

- Geospatially aware autonomous entities should be designed to respect ethical principles such as fairness and transparency. Their decision-making processes should be unbiased, explainable, and subject to human oversight, with particular attention to how they use and interpret geospatial data.
- Autonomous systems utilizing geospatial data should adhere to relevant laws and regulations in different regions, including those related to privacy and data protection. This may require adjusting their behaviour based on the specific legal requirements of each jurisdiction.
- Geospatially aware autonomous entities should respect and adapt to the cultural norms and values of the regions they are operating in such as aligning with local customs, traditions, and perceptions of space and place.
- Autonomous systems should be respectful of religious practices in different regions like accounting for religious landmarks, adjusting routes to accommodate prayer times.
- Though very challenging, autonomous entities should be designed to support and enhance human social interactions, rather than replacing them. This includes leveraging geospatial data to facilitate human collaboration, promote social inclusion, and foster a sense of community.
- Geospatially aware autonomous systems should be designed with environmental sustainability in mind, minimizing energy consumption, reducing waste, and promoting eco-friendly practices through for instance optimizing routes based on environmental impact.

By addressing these few factors, we can create autonomous systems that use geospatial data responsibly and effectively, while respecting the diverse ethical, religious, cultural, and social norms of different regions and environments. The goal should be to enable geospatially aware autonomous entities to coexist harmoniously with humans, providing the best possible support and assistance to the people they aim to serve.

All three questions above deserve a comprehensive evaluation and exploration by GI-scientists, cartographers, philosophers, sociologists, psychologists, and technology developers. We need a paradigm shift in how we see maps and GIS, how we represent data in maps and GI Systems, and how we make and use maps, as physical and nonphysical robot assistants will be more and more an inseparable part of our human lives and will make more and more complex important decisions for us. The importance of above is becoming more apparent, if we consider the fact that humans and machines read, understand analyse fundamentally different. Machines love binary data to read, process and analyse, while we humans work with sentences and signs and symbols.

Humans look at the world very object-oriented and objects are the primary elements of reality for us, while computers are very good with events and processes and can see objects in space and time merely as information elements of the events, which are connected to other event elements through internal or external processes (Polous 2016). Finally, we humans make decisions based on feeling and computers just see logic.

4. Way-forward

4.1 Build the common ground

The convergence of these two fields is essential to fully harness their respective strengths and capabilities, paving the way for more comprehensive and efficient spatial solutions for our complex dynamic world in near future. To achieve this convergence and build a common ground between cartography and robotic mapping, several steps can be taken: from building cross-disciplinary collaboration and building joint research groups to better understand unique challenges and opportunities of each field, share knowledge and tackle spatial problems from both a cartographic and robotic mapping perspective. To developing common standards and frameworks and data formats that can be used by both cartographers and roboticists. This facilitates the exchange of information and data between the two fields, making it easier to integrate cartographic and robotic mapping techniques and technologies.

One promising avenue for building a common ground between cartography and robotic mapping lies in the concept of event-mapping. Event-mapping is an approach that represents spatial information such as states of objects and processes as the key elements of events and events are considered as the main container of spatial information and knowledge (Polous 2016). This approach aligns well with the needs of both cartography and robotic mapping since it acknowledges the dynamic nature of the environment and provides a flexible and adaptable ontology-based framework for spatial representation and analysis.

Event-mapping allows the seamless integration of static and dynamic spatial information, enabling a better understanding of the complex and ever-changing spatial relationships in the world. By adopting event-mapping as a common ground, cartographers can benefit from the real-time data capture and processing capabilities of robotic mapping, while roboticists can leverage the rich cartographic knowledge and semantics to enhance the accuracy and efficiency of their mapping solutions.

Moreover, event-mapping facilitates the representation of complex, interconnected spatial phenomena, which is crucial for addressing the dynamic and diverse challenges faced by both fields. The focus on events, states, and processes as the primary elements of spatial reality enables the development of more sophisticated spatial models and representations that can be readily understood and utilized by both humans and machines.

4.2 Event-based Mapping as Common-framework

Event-based mapping and models, which are built upon event ontologies, can help to improve the representation of geographical data for machines. By adopting an event-centric approach, cartographers and GIS scientists can better model the dynamic nature of the environment and facilitate more effective machine-based processing, analysis, and decision-making.

Event-based mapping and models allow for a more comprehensive representation of dynamic phenomena, capturing not only the spatial aspects but also the temporal and causal and causally like relationships between various component of a spatio-temporal Information System. This can provide machines with a deeper understanding of the environment and its ongoing changes, enabling more informed decision-making (Polous 2016). Furthermore, by incorporating event-based ontologies, machines can better understand the semantics of geographical data and reason about the relationships between different spatial features, historical and in progress occurrences, and ongoing processes. This can help machines to make sense of complex and dynamic situations, facilitating more sophisticated decision-making procedure.

Two positive side-effects of event-based mapping and models are that they are inherently scalable and adaptable, as they can accommodate new events, processes, and states as they emerge. This makes them well-suited for representing dynamic environments and supporting machine-based decision-making in rapidly changing contexts. Furthermore, event ontologies can serve as a common framework for integrating and fusion of data from diverse sources, such as real-time sensor readings, historical records, and expert knowledge. This can lead to a more complete and accurate representation of the environment, which can be leveraged by machines to perform various tasks.

Indeed, event-based mapping and models, can provide a powerful framework for representation of geographical data in a way that is more conducive to machine-based processing, analysis, and decision-making. By capturing the dynamic nature of the environment and its underlying processes, event-based approaches can help to bridge the gap between traditional cartography and the emerging needs of machines and robots operating in complex and dynamic environments.

5. Conclusion

the convergence of cartography and robotic mapping is essential to fully harness the strengths and capabilities of both fields, paving the way for more comprehensive and efficient spatial solutions in our increasingly complex and dynamic world. By addressing key questions related to data representation, information availability, and ethical considerations, we can ensure that autonomous systems effectively utilize geospatial data while respecting the diverse norms of different regions and environments. Building common ground through cross-disciplinary collaboration, joint research groups, and the adoption of event-mapping as a common framework will facilitate the

integration of cartographic and robotic mapping techniques and technologies.

The development of event-based mapping and models, which incorporate the dynamic nature of the environment and underlying processes, will play a crucial role in bridging the gap between traditional cartography and the emerging needs of machines and robots operating in complex environments. These approaches enable the seamless integration of static and dynamic spatial information, allowing for a deeper understanding of ever-changing spatial relationships.

Furthermore, event-based mapping provides a foundation for representation and data fusion from diverse sources, leading to a more complete and accurate representation of the environment that can be leveraged by machines for various tasks.

As we continue to witness the rise of machines in our daily lives, a paradigm shift in our understanding and approach to maps and geographical information systems is necessary to enable geospatially aware autonomous entities to coexist harmoniously with humans, providing the best possible support and assistance. By addressing the challenges and opportunities presented by the convergence of cartography and robotic mapping, we can advance both fields and ultimately transform the way we think about maps and geographical information systems in the age of machines. The exploration and development of novel methods, tools, and standards for representing, managing, and analyzing geographical data will be instrumental in achieving this transformation and ensuring the successful integration of autonomous systems into our world.

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