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LINKING PERFORMANCE DATA AND GEOSPATIAL INFORMATION OF MANUFACTURING ASSETS THROUGH STANDARD REPRESENTATIONS

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ABSTRACT

Interoperability across emerging visualization modalities, including augmented reality (AR) and virtual reality (VR), remains a challenge with respect to industrial applications. One critical issue relates to the lack of standard approaches for coordinating geospatial representations that are required to facilitate AR/VR scenes with domain-specific information in the form of time-series data, solid models, among other data types. In this paper, we focus on the linking of manufacturing asset data via the MTConnect standard with geospatial data via the IndoorGML standard. To this end, we demonstrate the utility of this integration through two visualization-based prototype implementations, including one focused on (i) monitoring production facilities to improve situational awareness and (ii) evaluating and delivering suggested navigation paths in production facilities. We then comment on implications of such standards-driven approaches for related domains, including AR prototype development and automatic guided vehicles.

Keywords: Geospatial modeling, standards, augmented reality, smart manufacturing

1 Introduction

The digitalization of manufacturing systems has become a core focus area to improve agility, productivity, and efficiency. This trend is especially important for introducing emerging information technologies (IT), e.g., virtual reality (VR) and augmented reality (AR), into production scenarios. The combination of advanced manufacturing with IT capabilities is referred to as *smart manufacturing* [1]. Early adopters of smart manufacturing concepts have been able to lower costs, improve worker safety, and achieve deeper situational awareness [2]. To gain broad use and dissemination of such solutions, standards are vital since the collaborative communication and integration of the underlying hardware and software is critical for success [3]. However, interoperability of such applications, methods, and devices remains challenging for the broad realization of smart manufacturing [4].

In this paper, we aim to address one of the interoperability problems faced by manufacturing organizations looking to adopt technologically advanced solutions. As an anchor to more seamless integration, we focus on the representation (i.e., computer-readable data model) of geospatial definitions. Linking real-time geospatial data across production systems is critical for the proper coordination of (i) automatic guided vehicles (AGVs) [5], (ii) interface-guided navigation for human operators [6], and (iii) perspectives for higher level situational awareness for decision makers [7]. Considering the ubiquity of on-board spatial reasoning devices, e.g., Light Detection and Ranging (LiDAR) technologies on AGVs, aligning multiple coordinate systems, facilitating multiple user perspectives, and tracking multiple moving devices is not trivial.

In response, we propose the use of standards for static

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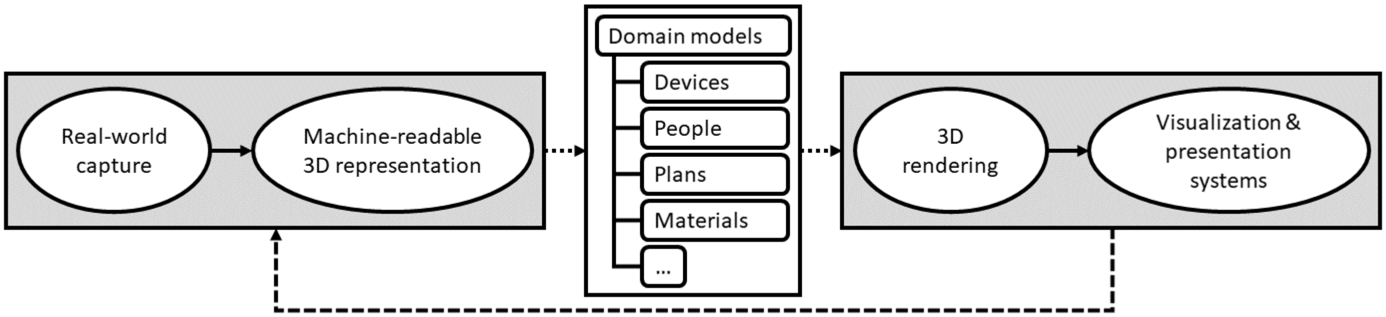

Figure 1. General pipeline for generating industrial visualization prototypes. Activities in grey and white boxes summarize standards efforts from the visualization and SMS communities, respectively. Dashed lines signal opportunities for automation.

geospatial representations that can build a bridge between such vision-based systems. As a first step, in this paper, we study the feasibility of leveraging one such standard, i.e., IndoorGML[1] released by the Open Geospatial Consortium (OGC), with an existing Smart Manufacturing Systems (SMS) standard, i.e., MTConnect[2], to facilitate the geospatial underpinnings of indoor manufacturing environments. We chose to work with these specific standards due to the publicly available tools supporting IndoorGML as well as publicly available MTConnect data via the NIST SMS Testbed (see Sec. 4).

Through this demonstration, we showcase two use cases derived from the underlying mapping between the standards. The first use case shows the quick three-dimensional (3D) rendering and presentation of a shop floor for situational awareness. The second use case presented demonstrates a tablet-based guidance for navigation from one job to another on the shop floor. Both use cases were generated by leveraging existing tools and methods already produced in accordance with the standards. In our minds, this demonstrates the power of standards in that leveraging tools that interface with standard data representation is much easier than building each component from scratch. To conclude the paper, we discuss implications of building additional bridges, i.e., mappings and toolkits, across standard interfaces to improve VR, AR, and mixed reality (XR) interoperability.

2 Motivation and Background

Industrial visualization-driven installations, e.g., AR and XR implementations, are often the production of one-off prototypes, wherein the domain models, e.g., machining performance models, digital solid models, and user manuals, are tightly coupled with domain-agnostic interfaces, e.g., rendering modules, presentation modalities, and visualization engines. After years of many organizations developing their own one-off installations, interoperability has become more of a pipe-dream. Solutions to help solve the problem are severely lacking. To address such needs, standards development organizations, such as IEEE, OGC, and the Khronos Group, have worked to contribute standard representations, modules, and languages. However, these efforts suffer from severe silo-ing and seem to fail to communicate with one another. This is especially true for domain-agnostic groups, e.g., World Wide Consortium (W3C) and Khronos Group, communicating with domain-heavy groups, e.g., American Society of Mechanical Engineers (ASME), the MTConnect Institute, and the OPC Foundation.

However, both perspectives, domain-specific thinking, e.g., for manufacturing and field maintenance, and visualization-specific concerns, e.g., real-world capture and scene rendering, are vital. SMS-specific standards, e.g., MTConnect and OPC-UA, provide the necessary semantic descriptions of concepts, such as information about devices, people, and materials. Figure 1 showcases the current state of industrial prototype development. From a high-level view, the visualization community is focused on two separate efforts, (1) digitizing real-world information (shown in the box to the left of Fig. 1) and (2) rendering and presenting scenes through the appropriate visualization modalities (see box to the right of Fig. 1). To produce successful and meaningful user experiences, it is vital to connect to domain-specific models. However, in the current state, automating these data transformations is expert-driven and requires many iterations and human hours. To this end, there is significant opportunities in automating (or self-automating) these transformations (indicated as dashed lines across Fig. 1).

In this paper, we particularly focus on the potential of standards to help contextualize geospatial information with streaming data collected form the shop floor. Below, we review relevant work related to (1) representing indoor spaces specifically for production environments and (2) leveraging those representations for navigation purposes.

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[1] Available at https://www.indoorgml.net/

[2] Available at https://www.mtconnect.org/

2.1 Indoor Space Definition for SMS

Since the majority of manufacturing processes are located inside buildings [8], modeling indoor spaces is required to fully represent production systems virtually. Often, the initial description of such environments begins with a map or layout of the workshop floor. Such maps are helpful in (1) supporting AGV tasks, (2) tracking tools, components and fixtures, as well as (3) facilitating guided navigation for operators [9, 10].

One of the core challenges of leveraging maps of production systems is the disparate nature of their source and intent. For example, AGVs, depending on brand and purpose, construct their own maps at various levels of detail [11]. In such cases, some AGVs leverage on-board LiDAR systems to build maps in order to avoid walls and other obstacles. To curate such maps, additional manual labor is required. Other AGVs have used camera systems that read optical markers on the floor or the ceiling to follow a predefined path through the workshop [12, 13]. Both solutions work for their specific use case, but the created maps cannot be interchanged easily. This example demonstrates that even in cases of similar technologies, e.g., two different types of AGVs, relating geospatial data and aligning coordinate systems represents significant redundant work.

In complex environments that are ubiquitous in SMS, the overhead of reconstructing geospatial definitions is significant. As a result, there exist standard efforts for constructing and curating data representation that define such geospatial information. Here, we specifically focus on modeling indoor spaces. Standards have been used across domains to limit redundant work. The most widely used standards for representing indoor spaces relate to Building Information Model (BIM) activities, an approach with a suite of standards built using the Industry Foundation Classes (IFC) [14, 15]. The IFC standards and developed and maintained by buildingSMART[3]. To support complex BIM modeling, there are other standard data representations that facilitate lower level modeling. In this paper, we specifically focus on two OGC standards, namely CityGML[4] and IndoorGML[5]. More information about each standard is provided below in Sec. 3.

Defining the boundaries of indoor spaces is not complete without the full expression of affixed and mobile objects in that space. This is especially true in production environments, wherein the location of objects, such as handheld tools and devices, is a practical challenge [16, 17]. Carrasco et al. [18] argues that there is a strong need for low-cost solutions for indoor localization technologies to support small and medium enterprises (SMEs). Such technologies include WiFi or Bluetooth Low Energy (BLE)-based location mapping. The downside of these technologies is that they can only deliver an accuracy of about 1-2 meters. To facilitate more precise positioning, there are systems that utilize RFID chips, Ultra Wideband (UWB), Indoor GPS, or simultaneous localization and mapping (SLAM)-based approaches. These systems are in general more expensive, but can deliver accuracy down to a few centimeters.

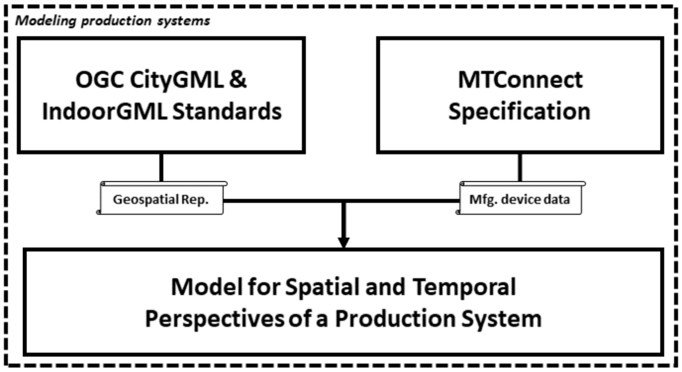

Figure 2. One instance of combining two disparate standards for quick AR prototype deployment for situational awareness and indoor navigation in smart manufacturing systems. We focus on leveraging OGC standards in concert with MTConnect.

2.2 Indoor Space Navigation for SMS

With a geospatial definition of an indoor space, an apparent use case of such a representation is centered around navigation purposes. Referencing a formal description of indoor building entities, such as walls, structural columns, corridors, and other obstacles, finding physically viable paths can be facilitated. Navigation tasks are commonly derived in SMS across a variety of clients. For example, to accomplish their intended tasks, such as material transport [19, 8], AGVs must navigate complex manufacturing environments and avoid unforeseen obstacles, e.g., plastic barriers, ramps, and other devices.

Since maintenance costs of buildings are much higher than its construction costs [20], balancing expenses of maintenance tasks is important. Lee et al. [21] observed and analysed tradespeople in maintenance fieldwork to investigate their current practices. They showed that up to 50% of time in maintenance is spent on field navigation and object localization. In response, they developed an AR-based software application [6] that utilizes an Operations and Maintenance (O&M) information model to support O&M fieldwork. Their prototype showed a reduction of up to 51% of time needed to locate target areas. Many more examples exist for how computer-supported, often AR-based [22], maintenance tasks require indoor navigation approaches.

3 IndoorGML – MTConnect Integration

Figure 3 depicts the main goal of this paper to achieve a standards-driven model for spatial and temporal perspectives of

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[3] Available at https://technical.buildingsmart.org/standards/bcf/

[4] Available at https://www.opengeospatial.org/standards/citygml

[5] Available at https://www.opengeospatial.org/standards/indoorgml

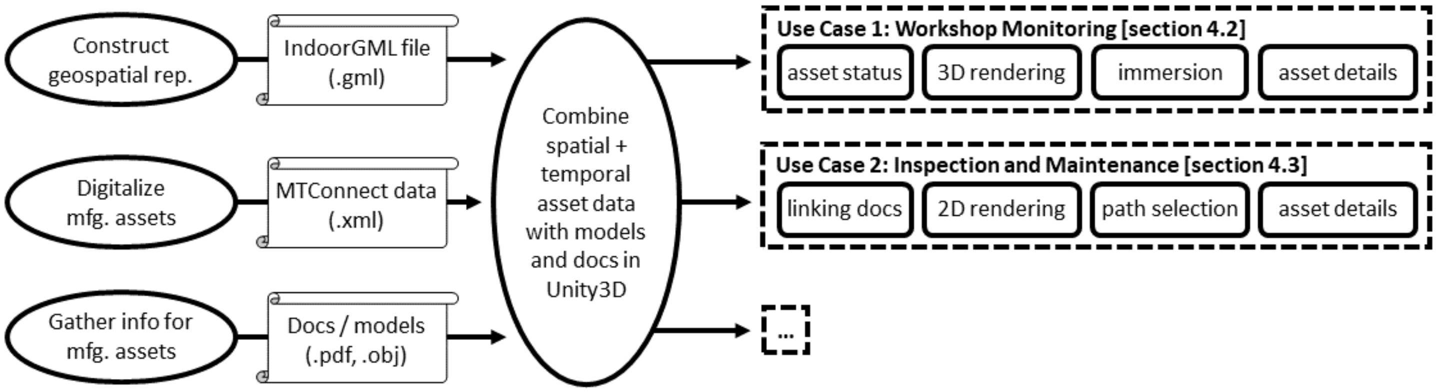

Figure 3. Process workflow of our implementation. In parallel, we construct a geospatial representation of the SMS Test Bed, access near-real-time data from the MTConnect data streams, and obtain auxiliary information about the connected devices. Through Unity3D, we achieve the IndoorGML-MTConnect integration to facilitate the discussed use cases.

a production system. In this section, we describe each standard's data model and considerations for their integration.

IndoorGML is a standard developed by OGC that describes indoor spatial information in an open data model within an eXtensible Modeling Language (XML) Schema Definition (XSD) [15]. The standard focuses on modeling indoor spaces including its properties and the underlying topology. Intentionally, this standard was designed to be used for indoor location-based services, such as navigation or geo-tagging. One of the core concepts of IndoorGML is the definition of rooms as cells with its properties, e.g., name, ID, and purpose of the room, as well as whether it is navigable or non-navigable. Cells are not allowed to overlap each other, but they can share a common boundary. Additionally, it is possible to define nodes (or states) which can be connected by edges (or transitions). They are mostly used for indoor navigation where the transitions operate as paths and the states as way-points. IndoorGML provides the possibility to define topological information of cells by creating a Node-Relation-Graph (NRG). The NRG describes the connectivity and adjacency of cells and simplifies the 3D representation of an indoor space to enable use by complex computational processes. To create a NRG, the Poincaré duality is used. With that a k-dimensional object can be transferred into an n-dimensional space by creating an (n-k)-dimensional object. For example a 3D cell becomes a zero-dimensional node and a two-dimensional boundary becomes a one-dimensional edge. Another feature of IndoorGML is the multi-layered description of indoor spaces. The same space can be divided in cells by rooms, corridors, and staircases; in cells defined by WiFi coverage; or in cells described as restricted and public areas. Each of these layers have their own semantics and NRG.

While IndoorGML focuses on the topological and semantic representation of indoor spaces, it is purposefully limited when modeling interior geometries of these spaces, including objects such as windows, columns, and furniture. This is due to the fact that it was designed to allow integration with other standards such as OGC's previously defined CityGML. As the name suggests, CityGML is meant to be a standard capable of modeling entire cities, at multiple levels of detail (LoD). In CityGML, there exist five LoDs, wherein LoD 0 and LoD 4 are the highest and lowest abstractions, respectively. In particular, LoD 4 allows the geometric representation of building interiors. Ryoo et al. [23] present a comprehensive comparison between the IndoorGML and CityGML LoD 4 standards and their respective strengths and weaknesses. Kim et al. [24] further discuss the integration of the two standards, along with issues and potential solutions.

Here, we study the integration of IndoorGML with SMS data, assuming to be compliant with the MTConnect standard. MTConnect is a semantic standard with controlled vocabulary, types, and relationships for data collected from manufacturing assets. This data could be used to analyze and optimize manufacturing processes or to monitor machines from a workshop floor. The data can contain information like device identity, attributes about its components, and machining parameters, e.g., maximum speeds and axes lengths. Ideally, MTConnect data is captured in near-real-time and collected by *agents*, which share the data via Hypertext Transfer Protocol (HTTP). Stored in a non-proprietary XML-format, MTconnect data streams are read-only, prohibiting command messaging to the monitored machines.

By enriching geospatial data conforming to IndoorGML with near-real-time data conforming to MTConnect, it is possible to create a static representation of a workshop supported by dynamic process data. We created a virtual scene in Unity3D[6] that is capable of leveraging both standards. We expanded the IndoorGML file with additional information, such as the HTTP-address of the MTConnect-stream and position as well as ex-

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[6] Available at https://unity.com/

ternal references to the geometrical shape or further documents of objects, e.g., machining centers. The Unity3D-scene creates a 3D representation of the workshop based on the spatial data, placing the defined objects within the scene. Once the scene is rendered, connection to the MTConnect data streams is established and the received data gets processed. This data can now be used to display the current state of each machine. The scene creation is explained in detail within the use cases in Sec. 4.

4 Implementation

To show potential use cases in merging a geospatial description with near-real-time process data, we developed two virtual scenes. These scenes were developed within Unity3D, which is mostly used as a game engine but can also be leveraged for the use in visualization and simulation in other domains. For this prototype, we used the SMS Test Bed[7] as a geospatial representation of a typical workshop. Some of the machines of the SMS Test Bed are connected by the MTConnect standard, which is also used for this prototype. Figure 3 presents a workflow for our two uses cases derived from the same data integration process. As shown in the figure, we anticipate the production of additional use cases through this integration.

4.1 Testing Facility and Setup

The SMS Test Bed represents a digital architecture built on top of a real contract manufacturer at the National Institute of Standards and Technology (NIST). Academic and industrial researchers leverage the SMS Test Bed as both a reference implementation of a set of MTConnect-enabled devices with varying levels of capabilities as well as a rich data source [25]. In our demonstration, we parse near real-time MTConnect data streams from the SMS Test Bed and track the availability of the floor's resources. Note that our prototypes rely on whatever data is available from the NIST shops at the time it is run.

4.2 Use Case 1: Workshop Monitoring

The first use case demonstrates the potential benefits realized by the IndoorGML-MTConnect integration for a supervisor of a workshop. In the case, the supervisor requires a simple way to understand the current status (i.e., machine tool availability) of the floor. With the tendency to implement more automated workflows in manufacturing processes, such a prototype can help to get quick feedback about the production floor's current state.

Once the virtual scene has been initialized, the user selects and loads the modified IndoorGML file. A 3D view of the workshop floor is then rendered displaying all machines defined within the space. The models of the machines are defined by an external reference to an object file (.OBJ) as part of the IndoorGML file. The image section visible to the user is defined by a camera object inside Unity3D. This camera can be moved around freely inside the scene or set to a map-like view.

When the connection to the MTConnect stream has been successful, the machines are attributed a color according to their status, e.g., availability status and alarm codes, which in our particular case is set by the status of availability. There are three possible options: available (green), unavailable (red), and unknown (yellow). This helps to quickly get an overview over the whole workshop and identify potential problems easier. Figure 4 shows a 3D view of a workshop with its machines. Since most of the machines in the NIST Shops are not yet digitilized via the SMS Test Bed, many models are colored yellow. Based on the accessible data, it could also be helpful to add the status of current machining process and any occurring errors or unexpected events. When users want to obtain detailed information about one specific machine, they can click on it in the 3D view, which will open a window displaying all data that available through the SMS Test Bed. Another scene feature is the ability to switch the camera into first person view. Users are now able to navigate around the workshop and interact with virtual doors to enter other rooms. While activating this mode, the collision with walls and objects is enabled, so users can move around as workers would be able to in the real world. This is helpful when planning the layout of a workshop and to quickly see if the position and rotation of a machine is useful in terms of productivity, maintainability, and user friendliness.

Despite not being implemented in this prototype, it would be trivial to modify the first person view so that the virtual scene can be leveraged on a head-mounted display in a VR environment. Migrating to AR systems requires more work since synchronization between the virtual and physical spaces is required.

4.3 Use Case 2: Inspection and maintenance

The second use case focuses on aiding maintenance and inspection in production systems. After the modified IndoorGML file and the connected MTConnect data stream have been loaded (akin to the first use case), a map-like view of the workshop is presented to the user. Additionally, the states and transitions are displayed to indicate possible routes around the workshop. As discussed before, IndoorGML supports graph-based representations, wherein each state and transition represents a node and edge, respectively. This is especially useful for informing indoor navigation. To demonstrate this point, our prototype allows users to select a way-point or a machine, either by clicking on it or choosing it from a drop-down list, as a start and endpoint. Since the system of way-points, paths and their length is known, we leverage Dijkstra's algorithm to calculate the shortest path between the start and endpoint. The calculated path and its total length is displayed (see Fig. 5). This feature enables mainte-

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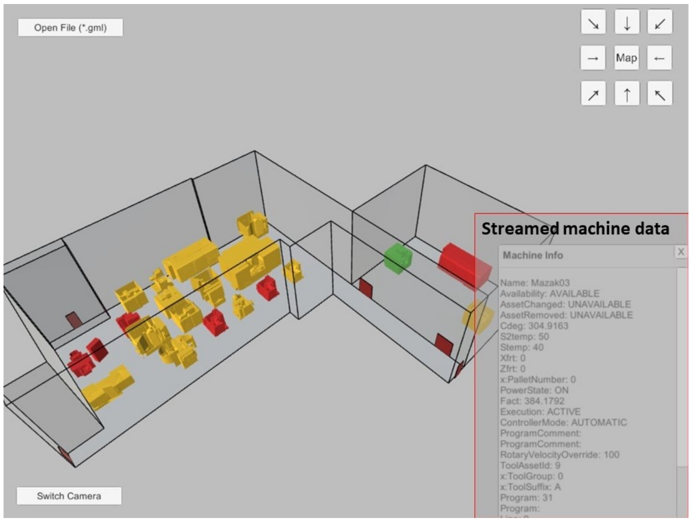
[7] Available at https://smstestbed.nist.gov



Streamed machine data

Machine Info

Name: Mazak03
Availability: AVAILABLE
AssetChanged: UNAVAILABLE
AssetRemoved: UNAVAILABLE
Cdeg: 304.9163
S2temp: 50
Stemp: 40
Xfrt: 0
Zfrt: 0
x:PalletNumber: 0
PowerState: ON
Fact: 384.1792
Execution: ACTIVE
ControllerMode: AUTOMATIC
ProgramComment:
ProgramComment:
RotaryVelocityOverride: 100
ToolAssetId: 9
x:ToolGroup: 0
x:ToolSuffix: A
Program: 31
Program:

Figure 4. 3D view of a workshop with machines colored based on availability. MTConnect stream of chosen machine is displayed on the right.

Length: 46.58m

Start
● choose on map
○ choose machine
Mazak QTN

End
○ choose on map
● choose machine
Hurco01

Figure 5. View of the calculated path between two way-points

nance workforce to quickly find the machines to which must be attended, if they are not familiar with the layout of the workshop.

For the purpose of maintenance and inspection, it is helpful to procure further details about the machine once the worker has reached it. Therefore, we created an additional tab labeled ”Machine” (see Fig. 6). This enables users to choose a machine from a drop-down list to obtain an overview outlining the available information according to their choice. Our prototype shows live data available via MTConnect, pictures of the machine, and additional documents akin to a handbook, programming manual, or hints for maintenance.

4.4 Limitations of Use Cases

Within the current state of our software prototype, there are limitations which can be tackled through future work. With respect to the representation of the shop floor, we currently only place machine tools into the virtual scene. In reality, there are additional objects that could be considered, including static objects, such as desks and cabinets, as well as dynamic objects, such as humans, carts and AGVs.

Machine: Hurco01

Machine Data

Name: Hurco01
Availability: UNAVAILABLE
AssetChanged: UNAVAILABLE
AssetRemoved: UNAVAILABLE
Spindle_Speed: UNAVAILABLE
RotaryVelocityOverride: UNAVAILABLE
EmergencyStop: UNAVAILABLE
Feed_Rate: UNAVAILABLE
Line: UNAVAILABLE
Program: UNAVAILABLE
ProgramEditName: UNAVAILABLE
PartCount: UNAVAILABLE
Execution: UNAVAILABLE
ToolNumber: UNAVAILABLE

Available Documents

Maintenance and Safety Manual
Programming and Operations Manuel
Hurco CNC Machine Specifications
Maintenance Hints

Figure 6. Detailed view of machine information via the “Machine” tab

Considering whether an object is affixed to some coordinates or has the ability to move is handled through CityGML. Note that we have not yet fully implemented this integration aspect but plan to in the near future. As Fig 7 suggests, `MTConnectAssets` can be modeled as `BuildingFurniture` within CityGML. Movable entities are meant to be modeled using the `BuildingFurniture` element. The static objects, i.e., `MTConnectDevices`, could follow the modeling paradigm of the `BuildingInstallation` element defined within CityGML. With objects that are dynamical in position, finding the indoor location of these objects and transferring those positions to the Unity3D scene are both required. Such extensions would especially be helpful for tracking commonly misplaced objects on the floor, such as tooling and measurement devices.

Another limitation lies within the digital models themselves. First of all, the solid models of the machines are separated from the modified IndoorGML file. Even though this separation allows for modification of the models without affecting the geospatial representation, this solution is not a fully integrated one. In the future, we plan to consider embedding these models within the CityGML description of objects within the indoor space. The `lod4Geometry` element of CityGML offers native support for the description of object geometry. Additionally, the used 3D models are rigid and their geometry has been simplified, so that their shape can be described with fewer polygons, which led to a better performance of our prototype. Their purpose in our prototype was to leverage these models to recreate a quick, decently realistic layout of the existing workshop. If there exist emerging needs to display the movement of digital assemblies, the models must be split into multiple objects based on their independently

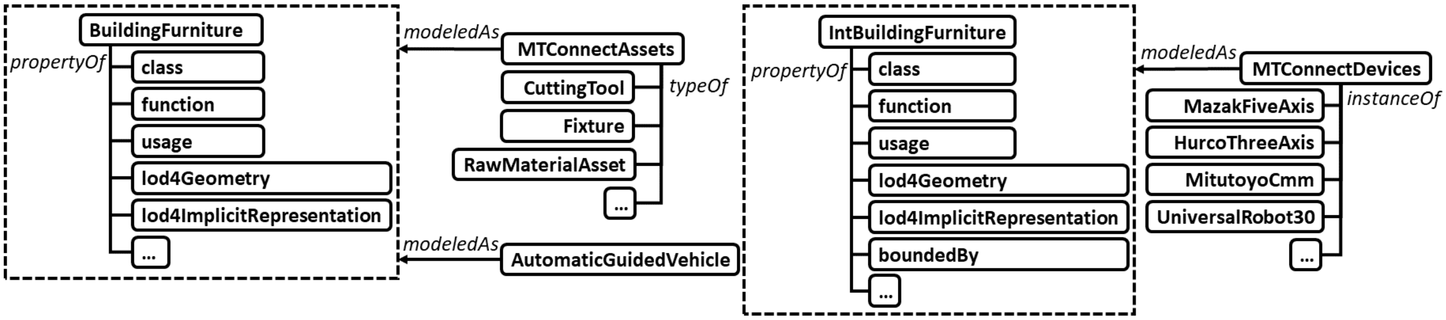


Figure 7. Elements and attributes represented in the CityGML object types critical to our integration. (A) `BuildingFurniture` can be used to model production floor tooling and other equipment that is expected to change its positional data often. (B) `IntBuildingInstallation`, traditionally used to model columns and other practically immovable objects, is used to model large production devices, e.g., CNC machining centers.

moving sub-assemblies and then realigned based on their position and kinematic properties.

When the layout of the workshop is extended over multiple floors, it is still possible to display that within our prototype since IndoorGML offers multi-floor modeling. However, in our prototype, extending to a multi-floor instance could cause user interaction and experience issues, e.g., occlusion challenges. To include machine-specific data within our modified IndoorGML file, significant manual labor is required. These activities could be (semi-)automated by either (1) formally appending the CityGML and IndoorGML with data elements designed to capture production-specific scenarios or (2) mapping similar elements that already exist in these data structures with knowledge graphs. Improving the automation of such procedures would expedite the initial process of implementing our prototype in other workshop environments. With more formal methods deployed, it would also be possible to develop an editor tool to visually construct our modified spatial representation on the fly. Additionally, a formal amendment to the schema representation would allow for proper governance and validation procedures.

5 Extensions to other technologies

Based on the research opportunities described in the previous section, we describe the technology implications for two domains: augmented reality and automated guided vehicles. Moving forward, we plan to test these geospatial representations and concepts to meet challenges faced by both domains.

5.1 Implications for Augmented Reality

Current AR systems suffer from interoperability issues caused by a lack of a shared coordinate system in which to operate. This is made obvious when trying to use different devices, e.g., tablets and head-mounted displays, AR frameworks, e.g., Vuforia, ARKit, and ARCore), or tracking techniques, e.g., marker-based tracking or marker-less tracking. Such techniques and technologies are often incompatible with each other in many ways, including the understanding of the space in which they operate. For instance, a marker-less AR application built using Apple's iOS exclusive framework ARKit[8] might place a virtual object in space relative to a feature map that would be incompatible with Google's ARCore[9] toolkit. Moreover, a marker-based AR application would not be able to make sense of the position of the virtual object since it would not track the features to which it is relatively positioned. To this end, most industrial AR installations exist as isolated use-case-specific prototypes that are only *aware* of their immediate surroundings rather then the larger context of the manufacturing floor. As a result, most AR applications are unable to share spatial information consistently.

While infeasible for many AR applications, in environments that can be easily predefined, such as manufacturing floors, standard geospatial representations can help define a shared underlying coordinate system on top of which applications can be built. This would lead to a better integration of industrial AR and virtual reality (VR) systems regardless of the devices or frameworks used. This notion has garnered attention from the standards development community. Recently, the OGC has chartered a new standards effort for representing device and camera poses with respect to global coordinates. We hope these efforts will realize a new standard representation that is already consistant with existing OGC standards, i.e., CityGML and IndoorGML.

5.2 Implications for Automated Guided Vehicles

Automatic (or automated[10]) guided vehicles (AGVs) presents another domain for which geospatial representations can

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[8] Available at https://developer.apple.com/augmented-reality/arkit

[9] Available at https://developers.google.com/ar

[10] In this paper, we consider automatic guided vehicles and autonomous vehicles, e.g., mobile robots, as the same. To learn more about their distinction, refer to ASTM Committee F45. F45 addressed issues related to performance standards and guidance materials for AGVs. More information is available at https://www.astm.org/COMMITTEE/F45.htm.

help performance. Clearly, AGVs already have on-board capabilities for constructing ad-hoc maps of indoor spaces and avoiding obstacles. However, there still remain challenges related to the lack of semantically rich data available to AGVs. For example, consider a robotic arm mounted on an AGV tasked to approach a table and engage with some physical object. Without formally encoding that the AGV is allowed to get very near, the AGV could stop short of the target table in fear of collision. This simple example demonstrates the importance of formally preserving the context of the physical environments. The target area should be treated differently than walls, columns, or other hazards. We envision that the integration of point cloud-maps built by AGVs with semantically rich geospatial representations would enhance their mobility and navigation.

Additionally, relating other information standards with such geospatial representations, as we have demonstrated here with the MTConnect standard, can further increase the information available to AGVs at any given time. Looking forward, achieving this kind of integration would enhance the situational awareness of AGVs for better planning and routing purposes. For example, an AGV could move and perform tasks automatically based on machine availability and readiness captured by near-real-time MTConnect data streams. Theoretically, this could enhance the agility and flexibility of a fleet of AGVs servicing tasks related to MTConnect-enabled devices, including loading, unloading, and material transport.

6 Closing & Looking forward

The full realization of smart manufacturing systems remains a work-in-progress. We believe that standardizing spatial data representations for production systems is vital for fully describing factories digitally. To this end, we presented a prototype that makes use of existing standards to combine geospatial descriptions (via IndoorGML) and real-time process data (via MTConnect) of machines. We set up two different use cases, focusing on both monitoring and navigation, to demonstrate the usefulness of merging these two areas.

Further development should consider creating a framework that supports the the combination of multiple sources of information that already exist in modern factories. This can include positions of workers and tools, RFID-sensor readings, video feeds of surveillance cameras, or energy consumption measurements. By bundling such information, the development of applications which support the control of smart factories can be developed much easier since the acquisition of data would be standardized. In other words, from a design perspective, leveraging standards for representing geospatial and device data in production systems facilitates more flexible prototype interface development. The more consistently information is represented, the simpler development of new applications becomes.

Furthermore, we see significant research opportunities in sensor fusion for more precise geospatial alignment. One example is leveraging on-board sensors from AGVs and more contextually defined, static geospatial definitions, such as those offered by IndoorGML and CityGML. If successfully integrated, such definitions could enable safer AR installations. For example, adding context to a 2-D point cloud delivered by an AGV could help avoid dangerous occlusion problems, e.g., rendering a digital object and effectively blocking view of a safety hazard. We are currently planning a partnership with the Robotics Program at NIST to investigate these research topics.

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