Towards an Intelligent IoT System for the Data-Informed Museum of the Future

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Abstract

This article describes the ongoing prototypical development of an intelligent IoT system for art and cultural institutions as part of the intelligent.museum project. Partial development steps that have already taken place are described and the system is conceptually framed. The system will be used to condense data from various IoT sensors in the exhibition space and the building complex, along with data from the Internet, into intelligent data analytics. The goal is to provide human decision-makers with intelligent analytics as well as machine recommendations for action to enhance museum intelligence. This initiative, which can be tracked transparently and comprehensively via a code repository on the Internet, will enable art and cultural institutions to adapt museum experiences to the needs of visitors. In addition, a technological framework is created for artists to create computer-based works and develop interactive art experiences using this system.

Keywords

Museums, Augmented Intelligence, Artificial Intelligence, Internet of Things, Data Mining, Interactive Art, Generative Art.

DOI

10.69564/ISEA2023-64-full-Hofmann-IoT-System

Introduction

The intelligent.museum project aims to make the museum experience of the future more inclusive and accessible by developing technical solutions and rapid prototypes for human–computer interaction between the museum and exhibition visitors. From new conversational user interfaces that mimic a conversation with a real human (e.g., chatbots) to machine vision systems that enable, for example, the recognition and tracking of both objects and people, facial expressions, gestures, or postures, AI models can be deployed today that are particularly well-suited for processing the auditory, visual, and textual input of visitors. These in turn can be evaluated using AI, whereupon the museum experience can be tailored to the specific needs of individual visitors.

In order to combine live data from the museum with data from the Internet within an intelligent IoT system and make it the subject of AI-supported data analyses, various prototype developments are currently taking place within the framework of the project. These developments concern the standardization of procedures and approaches in the field of integrating sensors into an open-source IoT platform, the development of a scalable LiDAR-based visitor tracking system for the exhibition space as well as the implementation of machine learning tools for data analysis.

In addition to the partial automation of system-irrelevant processes by means of actuators reacting to sensor inputs, the long-term goal of the project is to create a system of augmented museum intelligence that is intended to expand the intelligence of human operators as well as their basis for decision-making by means of data-driven analyses and suggestions for action.

This can be best described as a system of augmented intelligence.[1] "Augmented intelligence is a design pattern for a human-centered partnership model of people and artificial intelligence (AI) working together to enhance cognitive performance, including learning, decision making and new experiences." [2] A combination of data science, machine learning and human intelligence, augmented intelligence pairs computer artificial intelligence with human intelligence, aiming to improve human decision-making capabilities. In this process, AI tools evaluate Big Data, for example, large amounts of data that can hardly be grasped by humans, in order to subsequently provide results and data analyses to human operators. In such a scenario, an AI system provides humans with a basis for decision-making so that they can make decisions even faster and more precisely. The goal is to support human decision-making processes, not to replace humans with AI.

The overall goal of this development is to improve the exhibition experience for visitors and to optimize museum operations. Used as a technical analysis tool, new potentials for visitor research should also emerge. Media artists who create interactive installations, generative visualizations or sound recordings, for example, can integrate the live data into their artistic works on the one hand, but also provide data they have collected themselves on the other. The intelligent IoT system is emerging as a tool for data-informed optimization of the museum experience and is intended as a research contribution to the potential uses of AI in museums.

The museum is gradually forming a sensory perceptual apparatus, developing cognitive capabilities and thereby becoming a cognitive system itself in the long term.[3]

Visitor interaction with the museum of the future

Through innovative technical interfaces, the museum of the future will be able to react to the needs of visitors and adapt itself accordingly.

In the *intelligent.museum* project, experiments were conducted with the use of Deep Learning in connection with linguistic user interfaces. In the field of speech-based interaction with machines, rapid development steps have been taking place for years, whereby speech has increasingly become a natural and self-evident way of interacting with devices such as Google Home, Amazon Alexa or the Siri software on Apple devices. In everyday life, then, these voice-based systems are already in frequent use. Deep Learning is being used here as well.

Example As part of the exhibition *BioMedien* at the ZKM, the prototype of an AI-supported museum label for the exhibition space was presented, which was developed as part of the *intelligent.museum* project. This prototype can recognize the national language from the spoken language of visitors and, as a result, automatically translate given texts into the corresponding language. For the training of the speech recognition, audio samples of the speech corpus *Common Voice* by Mozilla were used. In addition, to make the model more robust to noise, Google's dataset *AudioSet* was used. This dataset contains manually annotated ten-second audio recordings from the online video platform YouTube.

To find out how much data is needed to distinguish between two similar languages, an experiment was conducted in which the neural network was challenged to distinguish English from German. This experiment found that 30,000 audio samples did not provide enough data for the model used, despite data augmentation. At 5 seconds per audio sample, that's over 40 hours of speech data. For most languages, 40 hours of training data is not yet available in the Common Voice training dataset used. Thus, in order to train the system on many languages in the long run and thereby make the museum experience more accessible and inclusive for visitors of different nationalities, the availability of open-source international speech data needs to be increased. In the medium term, languages from the global South in particular need to be more strongly reflected in relevant language datasets. [4] With this motivation in mind, the *Artificially Correct* Hackathon, hosted by the Goethe-Institut in partnership with the ZKM from October 1-3, 2021, issued a challenge to develop a non-contact capture station for crowdsourcing an international language dataset. Developed collaboratively between ZKM and three international developers at the end of 2021, the interactive *Data Collection Kiosk* allows visitors to create new language datasets by recording their own language. In addition to recording them, the Kiosk also serves to validate the recordings: They can be listened to and accepted or rejected for archiving. The speech samples that are created during the exhibition period are collected and integrated into a multilingual speech dataset. This will serve the further development of AI-supported speech dialog systems over the exhibition period of *BioMedien*.

This example will help to determine to what extent art and cultural institutions can contribute to the development of data sets and thus demonstrate to what extent the existence of a special sensor-technical infrastructure can favor the crowd-based collection of this data. Especially through the use of AI systems, as indicated above, new and innovative visitor interactions with the museum become possible. The following part will therefore describe the prototypical development of an intelligent IoT system to stimulate novel modes of interaction between visitors and the museum and to enhance museum intelligence.

Sensors

Similar to the sensory organs with which we humans perceive our environment, sensor technology enables the conversion of chemical or physical properties into electrical signals. From kitchen scales to smartphones, such technical sensors are omnipresent in our everyday lives. The atriums of the ZKM are also equipped with numerous sensors: Multisensors measure CO2, light intensity, temperature or fine dust in the exhibition rooms, smart recording systems count exhibition visitors and provide information about the power consumption in the building. Both active sensors (e.g., LiDAR, ultrasonic sensors, etc.) and passive sensors (e.g., cameras, microphones, light sensors, etc.) are used.

In order for visitors to be able to interact with the intelligent museum of the future, its technical infrastructure must enable environmental parameters to be recorded via sensors on the one hand and certain actions to be triggered via so-called actuators on the other. Just as there are different types of sensors, there are also different types of actuators—from mechanical actuators (e.g., electric motors) to optical actuators (e.g., light bulbs, LEDs, screens) to acoustic actuators (e.g. loudspeakers). An example of a sensor-actuator system is an escalator: A light barrier (sensor) detects the presence of a person, which causes a motor (actuator) to set the stairs in motion.

IoT System

As Researcher-in-Residence, Dr. Andreas Kugel is working with the project team on a best-practice example of sensor-based data collection and provision as part of *intelligent.museum*. This is intended to be a first development step towards an intelligent IoT system, with the short-term goal of allowing things to communicate with each other and the medium-to long-term goal of establishing the data basis for AI-supported analyses. As an extension of the decision-making capabilities of museum staff, learning systems should be able to analyze and draw conclusions from the various data. In the future, for example, digital artworks should be able to be integrated into the IoT ecosystem—also for the purpose of remote maintenance, data mining or against the background of many other conceivable needs.

The open-source ThingsBoard platform was selected as the temporary backbone for the IoT system. The main tasks of the ThingsBoard platform here are the storage of data as well as its post-processing and visualization. The concept of ThingsBoard is that different devices can be created, i.e., normally each external sensor is connected to its own device in ThingsBoard. The devices can be created automatically. In order to cover a certain number of different scenarios, so-called device profiles can be defined and new devices can be added for them (automatically, if necessary).

For the visualization of data by means of dashboards, standardized display types—from tables to heat maps to bar, line, pie or bubble charts—can be selected. However, widgets can also be customized—for example, a visitor counter could be displayed as a Brownian molecular motion.

Example On the occasion of the exhibition *BioMedien*, a ZKM-specific dashboard was developed at the end of 2021 with the platform ThingsBoard, which can be viewed in the exhibition space and online. Via the dashboard, (sensor) data of the ZKM from the indoor and outdoor areas as well as from the internet will be visualized in real time. This multifaceted data is generated by smart devices, sensors and other IoT devices. Indoors at ZKM, these include the multi-sensors installed in the exhibition space that measure CO_2, light intensity, temperature, and particulate matter. Also, LiDAR sensors, ultrasonic sensors and optical hand tracking modules. From the employee elevator, a sensor sends the elevator position with associated time stamp, which in turn can calculate the speed. There are also IoT sensors in the outdoor area of the ZKM (meadow in front of the ZKM/HfG building + rented meadow orchard), which use the long-range energy-efficient LoRaWAN (Long Range Wide Area Network) for information and data transmission. [3] On the Internet, data is collected through API calls (for example, to retrieve data from websites), tracking tools (for web analytics), or web crawlers. [Figure 1]

Figure 1: Exhibition view *intelligent.museum Dashboard*, BioMedien at ZKM | Karlsruhe, 2021/2022. Copyright: ZKM | Karlsruhe, screenshot: Paul Bethge

Some of the data is already used for a ZKM-specific data set on the occasion of the hackathon *{COD1NG DA V1NC1}*. This dataset called *We are data - The ZKM as a living organism* does not present work data or digitized data of museum collection objects, but is intended to represent the everyday life of a living and constantly changing cultural institution. In addition to the sensor data mentioned above, it also includes, for example, data on which books the library of the ZKM and the Staatliche Hochschule für Gestaltung Karlsruhe lends out per day or how many words the ZKM's publications department edits. The dataset contains day-based values for the month of March 2022 and was published under the open-source license CC BY-SA 4.0.[4]

Sensor-based visitor tracking

In addition to the aforementioned data from IoT sensors, tracking data represents a pertinent resource for the data-informed museum of the future. In order to be able to track people and objects indoors and outdoors in a way that complies with data protection laws and preserves privacy rights, a LiDAR-based system for two-dimensional real-time location has been developed since the end of 2021 by Bernd Lintermann—artist and software developer at ZKM—and was released open-source in 2022.

The system was initially developed for two use cases. The first use case envisions the media-artistic use of the system for interactive installations, for example. In this area, optical sensors are often used to receive input from users by tracking people in the installation's catchment radius. The second use case sees the system as an analysis tool for museum operations, providing information on how museum areas are used, visitor flows, and where visitors spend most of their time. This should help to successively improve the exhibition experience and enable museum operators to optimize the museum infrastructure.

LiDAR (Light Detection and Ranging) is a telemetry method related to radar, based on time-of-flight measurement with pulsed laser beams in the eye-safe range.

The application areas for LiDAR-based acquisition systems range from geosciences—e.g., in meteorology or geodesy—to the automotive industry—e.g., for driver assistance systems or in the field of autonomous driving—to robot navigation. Increasingly, LiDARs are also being used in consumer devices. For example, since 2020, support for LiDAR scanners has improved AR applications in iOS devices.

When integrated into smart applications, LiDARs open up new practical sensing opportunities. However, a LiDAR-based scalable system for real-time two-dimensional location of people and objects indoors and outdoors, based on open-source software, does not exist at the time of writing.

For the tracking system, 2D LiDAR sensors are used on the hardware side. 2D LiDAR sensors use 1D LiDAR sensors that rotate clockwise and whose optical distance measurements can be combined by the computer into two-dimensional environmental data. The most powerful LiDAR sensors tested during the system's development measure distance data approximately 8000 times per second.

The data from all the sensors in the system is combined by Lintermann's software and transferred to a unified virtual space in which the detected objects are distinguished from one another. The system checks where the objects were located in the previous frames. If there is a positional discrepancy, the system assumes that an object has moved. Detected objects are tracked and IDs are assigned to them. The system can track the movement of objects and determine if certain objects have left an area or how long certain objects have been in an area. [Figure 2]

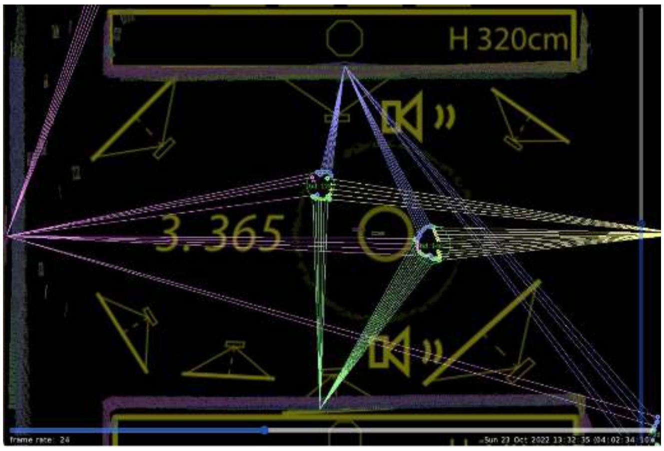

Figure 2: Screenshot Tracking System by Bernd Lintermann in the ZKM exhibition *John Sanborn. Between Order and Entropy*, October 2022. Copyright: ZKM | Karlsruhe, graphic: Bernd Lintermann

The software design of the system aims to be as user-friendly as possible. This means that the software should first be as easy to install as possible and then as easy to use as possible via an intuitive graphical user interface.

The affordability of the system is also intended to increase broad accessibility, which is why different LiDAR sensors from various vendors and price ranges were tested. The software uses SDKs (Software Development Kit = collection of programming tools and program libraries used to develop software) from different manufacturers, whose respective model range —from low to medium to high-priced devices—is to be covered.

The system is also scalable, which in this context means that theoretically any number of LiDAR sensors can be used. This means that a large physical space can be covered, but it is also possible to interconnect multiple spaces, thereby creating particularly individual tracking areas.

The software offers the possibility to log the accruing movement and whereabouts data and to write them to files in a common data format—JSON—that can be processed very well by machines. These logging files record when objects have changed their location, i.e., moved several centimeters to the side, for example. A new entry is then created, with a timestamp, so that it can be traced how long which object was in which position and over what distance it moved.

A special feature of the system is the logging of this data in graphics, because the movement and dwell time data can be used to generate so-called heat maps, from which it can be read where people have been particularly frequently.

The logging data can be configured and put into a temporal structure so that, for example, a new file is created for each freely definable period of time—if users are interested in specific periods of time, they only need to look at the files for these specific periods.

Compared to conventional camera technology, LiDAR sensors offer both advantages and disadvantages when used for data acquisition systems. First, LiDAR sensors are faster and less computationally intensive than camera technology, making the terminals used to process the data more cost-effective. LiDAR sensors also do not rely on ambient light, whereas conventional cameras are inefficient in adverse weather conditions or darkness. Thus, no artificial lighting needs to be considered for the use of LiDAR sensors.

However, there are also aspects of technology ethics that argue against the large-scale use of cameras in the exhibition space for a room-scale detection system for people and objects. These aspects relate to security, anonymity and privacy, because cameras naturally also capture biometric information, whereas the data generated by LiDAR-based systems do not allow any conclusions to be drawn about individuals. Neither body poses nor gestures and facial expressions of individual visitors can be captured with the system.

The "shadowing" of persons in the exhibition space by other exhibition visitors requires that significantly more LiDAR sensors be used under real conditions than would be the case under laboratory conditions.

Implementing Communication Protocols

In collaboration with artist and software developer Bernd Lintermann and researcher-in-residence of the *intelligent.museum* project, Dr. Andreas Kugel, Dan Wilcox—one of the project’s two permanent software developers—is currently working on using the open-source ThingsBoard IoT data server as a streaming data platform for the recently developed LiDAR-based tracking system mentioned above. The idea is to develop simple, open tools that allow creative programmers to interface with the ThingsBoard. This way, other artists can easily connect and receive live tracking data or general sensor data from the ZKM.

As part of this development strand, *thoscy* (**Th**ingsboard **OSC** Relay) was developed and released open-source. [5] This is a collection of scripts for relaying messages between a ThingsBoard server and the OSC network protocol. These scripts act as relay servers for forwarding device events between a ThingsBoard server via MQTT/WebSockets and OSC (Open Sound Control) messages. thoscy-send forwards messages from OSC to a ThingsBoard host via MQTT, while thoscy-recv listens for ThingsBoard events via a WebSocket and forwards them via OSC. This is especially useful for software tools that work natively with OSC messages but do not have built-in MQTT or WebSocket support.

Outlook and Desiderata

In the next part, going beyond the technical development of the intelligent IoT system, various desiderata will be outlined by way of example, which are to be fulfilled with the system and which will be implemented prototypically.

Example 1: Data Mining for Museum Visitor Research

While data analytics is used to optimize business processes and decisions in the corporate sector, it is still comparatively rarely used to optimize museum operations. As a best practice example from the Barberini Museum shows, data mining can be used in the museum sector to improve the museum experience for visitors. [8] The Barberini Analytics analysis platform is used to collect, process, analyze and present available data relating to museum visits with the aim of improving the museum experience. Barberini Analytics was developed for the Museum Barberini between 2019 and 2020, but also includes approaches transferable to other art and cultural institutions. The suite was compiled by the Hasso Plattner Institute and the Museum Barberini in Potsdam, founded by the Hasso Plattner Foundation, as part of a bachelor's project supervised by Prof. Dr. Felix Naumann at the Hasso Plattner Institute in Potsdam entitled Data Analytics - Optimizing Museum Experiences with Data Analysis. The program codes were published as an open-source project via a code repository on GitHub. [9]

Figure 3: Visitor forecast as part of the *intelligent.museum* project using a predictive AI model. Copyright: ZKM | Karlsruhe, graphic: Paul Bethge

While predictive models can be developed for museum operations, for example, to help forecast visitor flows and numbers,[10] [figure 3] new potentials of the system described above as an analytics tool for visitor research can be anticipated in particular.

In 1983 Veron & Levasseur conducted ethnographic observations in an experiment at the Louvre in Paris and analyzed the visiting style of museum visitors. They classified them into four categories. The categories are named after animals, because the behavior of the visitors is supposed to be similar to the behavior of these animals: "ants," "grasshoppers," "butterflies," and "fish." While the visitors classified as "ants" follow a certain path through the exhibition space and look closely at all exhibits, the visitors identified as "grasshoppers" seem to prioritize some previously selected exhibits. The group of "butterflies" includes visitors who wander aimlessly around the museum, but are very interested in the exhibits and try to get more information. Visitor:ings classified as "fish" spend most of their time moving around the center of the room without seeming interested in details of individual exhibits. In the mid-1990s, Tsvi Kuflik, a professor of information systems at the Faculty of Social Sciences at the University of Haifa in Israel, and a team conducted the mobile museum guide experiment with 143 participants, using two different clustering methods (artificial neural networks and the k-means algorithm) and comparing them. [11]

Using the already described LiDAR-based tracking system as a sensor within the also already described intelligent IoT system, another experiment will be initiated with reference to Veron & Levasseur and Kuflik et al. respectively, for which AI can be used to analyze the "visiting style" of exhibition visitor:s in the intelligent museum. This experiment will investigate the suitability of the intelligent IoT system as an analysis tool for visitor research.

Example 2: Automatizing Museum and Exhibition Technical Services

In the technical museum operation, repetitive tasks can be automated sporadically by software and algorithms, such as the regulation of lighting and sound in the exhibition space—from the light intensity of the ceiling lighting to the volume of sound installations. Since 2020, systems have been in use in the ZKM's exhibition operations that link the unmuting of videos in the exhibition space to the presence of visitors within a freely definable retraction radius defined by the museum's technical staff, and thereby couple the distance of the visitors to the playback device with the volume parameter. This can prevent cacophony in the exhibition space when many videos with sound or sound installations are presented simultaneously in one exhibition space. Used carefully, automation can lead to a sustainable improvement of the exhibition experience for the visitors—both in terms of ecological (light) and design aspects in the exhibition space (sound). However, automation should only be used very sparingly and exclusively in less sensitive areas.

There are many other potential applications in the field of technical services for museums and exhibitions, such as predictive maintenance or anomaly detection to monitor and, if necessary, maintain computerized exhibition exhibits.

Example 3: Framework for Interactive art

In addition, the intelligent IoT system will provide artists with a technical framework for developing interactive art experiences. In the medium term, it should become possible for artists to feed and operate generative data visualizations and sound recordings, interactive installations and environments with sensor data from the system. Similarly, many media-art artworks now generate data on their own, which they can in turn feed into the intelligent IoT system.

In this context, Dr. Andreas Kugel is already working in parallel with the artist Katrin Hochschuh of the artist:in duo Hochschuh/Donovan on the resource-efficient transmission of position data of a robot swarm (artwork *Empathy Swarm* by Hochschuh/Donovan, which has been further developed within the project *intelligent.museum*) to a ThingsBoard device.

Conclusion

The diffusion and successive improvement of AI tools has enabled many new interactions between visitors and the museum. In the analysis, it became clear that for an efficient integration of these into museum operations, the technical infrastructure in particular needs to be looked at and that specialized systems would need to be developed to perform intelligent analyses via data mining so that they can actually extend museum intelligence via suggested action suggestions to museum staff. As Harry Armstrong et al. point out "[...] for many arts and cultural organisations there is a long way to go before it is possible to extract value from the data they hold. Data input and analysis both require skills and specialisation in the workforce.
Currently, in many institutions or organisations data is often not systematically collected and, even where it is, it may not be analysed in depth. Developing the sector’s capabilities in this area will require attention at all stages of the skills pipeline [...]" [12] The ongoing prototypical developments described in this text are running towards the development of an intelligent IoT system in the medium term. What seems particularly interesting in connection with the development of an intelligent IoT system is that both museum operational data mining scenarios and those concerning the museum in general but also purely artistic scenarios can be realized, which immensely increases the spectrum of possibilities for use. The most important criteria of the described system are its transparent and open- source development, which makes it possible to reuse the codes used, e.g. by other art and cultural institutions, and ensures that the technologies used have as little potential as possible to cause harm to museum visitors, be it through discrimination or inherent forms of bias.

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Biography

Yannick Hofmann (*1988 in Offenbach a. M., Germany) lives and works as an artist and researcher in Karlsruhe. As the artistic director of the intelligent.museum project since 2020, he collaborates with a team of software developers and museum visitor research experts, pushing the boundaries of hybrid formats and applications for the future of museums. Having spent almost a decade at ZKM | Center for Art and Media, he co-directed their artistic research and production department before joining the Deutsches Museum for a one-year research stay in 2022. Since mid- 2023, Hofmann works for the Fraunhofer Institute for Industrial Engineering.