A semantic framework for modelling and managing reusable and optimized cultural experiences, towards a shared MR cultural experience ecosystem


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Abstract. This paper presents SemMR, a semantic framework for modelling interactions between human and non-human entities and managing reusable and optimized cultural experiences, towards a shared cultural experience ecosystem that may seamlessly accommodate Mixed Reality experiences. The SemMR framework synthesizes and integrates interaction data into semantically rich reusable structures and facilitates the interaction between different types of entities in a symbiotic way, within a large, virtual and fully experiential open world, promoting experience sharing at the user level, as well as data/application interoperability and low-effort implementation at the software engineering level. The proposed semantic framework introduces methods for low-effort implementation and deployment of open and reusable cultural content, applications and tools, around the concept of cultural experience as a semantic trajectory or simply, experience as a trajectory (eX-trajectory). The proposed methods for tracking, monitoring and analysis of user behaviour and user interaction with the environment and other users, towards optimizing eX-trajectories via reconfiguration are presented. The SemMR framework supports the synthesis and enhancement of highly complex reconfigurable eX-trajectories, using semantically integrated disparate and heterogeneous related data. Overall, this work aims to semantically manage interactions and experiences through the eX-trajectory concept, towards delivering enriched cultural experiences. The proposed framework can be used to create and run shared cultural experience ecosystems.

Keywords: Intelligent Interaction, Semantics, Shared experiences ecosystem, Cultural Experiences
1. Introduction

Cultural applications are increasingly used for the development and delivery of cultural experiences to users. To this end, research and development activities have targeted the design and implementation of applications and related systems to support all the phases of the creation and operation of cultural applications, including content creation and organization [83], application development [34, 72], application operation within venues [20, 114] and in broad IoT environments [4, 21, 67, 68]. With respect to their application domain, cultural applications span across education/learning activities [33, 74], recreational/tourism activities and e-commerce [127].

Insofar, however, each cultural application is designed, implemented and deployed separately, increasing the associated development costs (content development, code creation and testing, infrastructure deployment and maintenance), while at the same time limiting the opportunities for sharing and reusing cultural experiences to the level of recommending isolated PoIs or coarse-grained routes [41, 42, 94]. The impact of these challenges is more pronounced in AR/VR/MR systems, for which content development, code implementation and deployment infrastructure are more complex and demanding. In addition, the diversity of the needed hardware and software systems [27, 70] poses further data integration and reuse issues.

The SemMR semantic framework proposes an integrated multi-technology and multi-entity approach towards addressing these challenges and supports current, as well future, interactive technologies that are of low-effort and cost, accessible to all businesses. In particular, SemMR is inclusive towards technologies based on MR (including AR/VR). The main ingredients of the SemMR approach are the use of semantic technology for the utilization/integration of data/information discovered on the current Web sources, the Linked Open Data (LOD) cloud and the Internet of Things (IoT). Through this approach, the SemMR framework promotes experience sharing at user level, as well as data/application interoperability and low-effort implementation at the software engineering level. The framework is based on the notion of a shared cultural experience ecosystem (SCEE), to enable and support the management of enhanced user experience in the cultural domain. IoT is the key factor of future interaction [39] and the enabler of the vast amount of semantically linked data/information. In particular, MR may be seen as the semantic bridging of AR/VR and IoT trends [27], since we conjecture that it is the only major qualifier to utilize the IoT-enabled semantic data/information to manage advanced user experiences. In order to do so, the user behaviour must drive and must be driven by the semantically integrated data/information/knowledge, thus creating a new world of seamless and immersive MR interaction between the real-world entities and the virtual entities. When specialized in the domain of MR, the SCEE ecosystem will be denoted as MR-SCEE.

SemMR is based on two main concepts; the concept of the shared cultural experience ecosystem (SCEE) and the concept of the cultural experience as a semantic trajectory (eX-trajectory).

1. The eX-trajectory notion in SemMR is used for the representation of the mapping of a semantic trajectory to an MR experience. A trajectory concerns segments of connected traces/points that represent movement of entities. A semantic trajectory is a trajectory that has been annotated with additional information related to those segments, usually to add knowledge related to moving entities in time and space and their experiences within those dimensions. Such experiences may involve a number of scenes or episodes within the segments of traces, where interconnected and interacting entities are moving and act in the MR world, situated in time and space sequences of particular application-specific interests, showing a number of different behaviours (virtual or real).

2. SCEE is the eX-trajectory ecosystem within the SemMR semantic framework, generating, semantically integrating and managing open and reusable cultural heritage content (cultural heritage experiences, data and information), cultural applications and methods. Multiple entities (human and non-human) may interact with each other at different time and space, thus creating a multi-dimensional space of shared cultural user experiences. The SemMR ecosystem maintains the shared eX-trajectories, where the length of each eX-trajectory (cultural experience) may vary. The SCEE is the enabler for advanced interaction and sharing, since expert and non-expert users may interactively author new experiences. On the other hand, those experiences may dynamically intersect and interchange during user interaction, resulting to unseen but relevant eX-trajectories.

SemMR is a semantic framework for modelling interactions between human and non-human entities and managing reusable and optimized eX-trajectories. It comprises of methods for: (1) creating and managing
open, reusable and optimized eX-trajectory content, applications and tools, (2) tracking, monitoring and analysis of user behaviour during interactions with the environment and with other entities, (3) optimizing (via reconfiguration) eX-trajectories at run or at development time, and (4) synthesizing eX-trajectories into new but still reconfigurable eX-trajectories, that are augmented using semantically integrated related data/information available in disparate and heterogeneous resources.

The contribution of this paper is outlined in the following three points:

a. The specification of the SemMR framework for enabling low-effort multi-entity interactions towards creating and managing reusable and optimized eX-trajectories.

b. The system architecture for implementing and realizing the SemMR framework.

c. The simulated performance evaluation for the deployment of the SemMR in an international cultural site.

The structure of the paper is outlined as follows: Section 2 presents the related work. Section 3 details the proposed eX-trajectory concept. Section 4 introduces the SCER, while Section 5 presents the system architecture for SemMR. Section 6 presents the instantiated implementation of SemMR for cultural experiences and Section 7 presents the user behaviour modelling. Section 8 presents the evaluation on the scalability of the proposed framework for a sizable cultural site, an archaeological museum. Section 9 discusses the proposed framework and the future work.

2. Related work

As cultural application development and use proliferates, researchers have developed a number of approaches that underpin and facilitate different parts of the cultural application lifecycle. Amato et al. [4] present SNOPS, a system that consolidates participatory sensing, IoT platforms and recommendation systems under an instantiation of the Service-Oriented Architecture, targeting to the collection of information from data sources, which are then exploited for the formulation of context-aware recommendations for users. The context of the recommendations is represented as an upper-level ontology, which encompasses classes for modelling users, objects/places of interest, time intervals, activities (either explicitly modelled or deduced), environmental conditions and devices (both user access devices and sensors). Chianese et al. [20] describe the design and implementation of a system that is able to leverage cultural spaces into smart cultural environments following the concept of Single Smart Spaces (S3), which provide enhanced user experience levels. The system proposed in [20] retrieves (a) data from sensors which perceive the real world, (b) information from structured and unstructured data sources and (c) knowledge from users moving into the smart cultural environment, and arranges for processing its input and delivering knowledge to users to facilitate a number of tasks including navigation and information finding. The concept of Single Smart Spaces is also adopted in [4, 19], where a context-aware framework for cultural heritage applications is presented. The framework presented in [4, 19] captures contextual information under a Context Dimension Tree, which represents six dimensions of the contextual information: users interacting with the system; items within the smart space; activities performed on items; situations within which activities are carried out; locations of activities; and times when activities were performed. From this information, the system continuously learns usage patterns and propagates the resulting knowledge to users.

The CrossCult H2020 project has developed an ontological framework for the representation of cultural information [117, 118], as well as a generic knowledge-based platform to support the development and delivery of cultural heritage application [22, 23, 114], complete with a multitude of technological modules that can be seamlessly integrated into the platform for addressing a wide range of requirements of cultural applications. The ontological framework is an extension of the CIDOC/CRM model [50], accommodating concepts such as reflection topics (a central concept in the CrossCult project corresponding to issues that the user can reflect upon, driven by her experiences and background, and given the opportunity to rethink about them), individual venue visits, aspects of the user profile and so forth [117, 118], as well as location provenance of cultural heritage information [81]. The CrossCult project deliverable D4.6 [24] provides a comprehensive guide on how knowledge and data repositories of CrossCult may be accessed, which services are available, how these services can be exploited to build new cultural heritage applications, and how the platform can be extended to accommodate new services and functionalities.

The INCEPTION H2020 project [67, 68] aimed provide methodologies and tools to support and integrate (a) the delivery of efficient cultural heritage experiences to users, and (b) the enrichment of scientific knowledge. To this end, the INCEPTION H2020 project has proposed an approach and a methodology for
The exhiSTORY approach [87, 115] integrates IoT and semantic technologies, together with clustering and personalization techniques to leverage exhibits within cultural venues to smart, self-organizing exhibits that cooperate with each other and provide visitors with comprehensible, rich, diverse, personalized and highly stimulating experiences. In more detail, within the exhiSTORY approach, each exhibit maintains an amount of self-descriptive data and semantic information, and communicates both with neighbouring exhibits and the smart space to create multiple meaningful collections of items. Each collection tells a story about a specific subject. Subsequently, personalization technologies are employed to select the most prominent stories to be told to visitors, after consulting their profiles.

In the following paragraphs, we elaborate on research work and technologies related to the main axes of the SemMR framework, namely (i) semantic data management, (ii) virtual entities and IoT, (iii) user profiling and (iv) mixed reality.

2.1. Semantic data management: link discovery and data integration

Link discovery (LD) is the process of identifying relations (links) between data/information objects that originate from different data/information sources, thereby facilitating several tasks, such as data/information deduplication and data/information integration. In the case of spatial datasets, the objective of LD is to discover pairs of spatial objects that satisfy a given set of relations. Existing works in this area have primarily focused on the discovery of topological relations (within, overlaps, touches, etc.) between spatial objects, while the recent work of maskLink [95] has been employed for discovering proximity relations, as well as in trajectory reconstruction and semantic enriching of trajectory segments. To avoid the cost of exhaustive comparison between each pair of objects, blocking techniques [76] are typically used that split the 2D space in grid cells (a process known as grid partitioning or space tiling), assign spatial objects to cells based on overlap and eventually compare only pairs of objects in each cell. Essentially, the grid cells allow filtering of pairs of objects, thus retaining only few candidate pairs of objects, which need to be evaluated in a refinement step. LIMES [79] is a generic link discovery framework for metric spaces, employing the concept of exemplars for representing areas in the multidimensional space. SILK [49] proposes a blocking method that uses a multidimensional index in which similar objects are located near to each other. Other related works address link discovery tasks when the property values that are to be compared are expressed in an affine space with a Minkowski distance [77, 78].

The spatial link discovery methods [78, 100] apply grid partitioning on the input data sources, to perform the filtering step efficiently, i.e., avoid comparisons between entities of the input data sources, that will not result to a link association. Then, the refinement step follows, where different optimizations are employed in order to minimize the number of computations necessary for the production of the correct result set. RADON [100] is a recent topological relation discovery approach for relations between data sources of areas and can discover efficiently multiple relations using space tiling. One of its main techniques for efficiency relies on the use of caching to avoid re-computing distances. However, this imposes non-negligible requirements for main memory, especially for large data sources. Furthermore, RADON employs an optimization based on minimum bounding boxes (MBBs) for deciding the granularity of the grid. This means that a data source providing point geometries (e.g. for touches or within relations) would force the construction of an “infinite” number of cells. This indicates that RADON cannot handle point-to-region topological relations. ORCHID is another grid partitioning method, which addresses the challenge of discovering all pairs of polygons for which their Hausdorff distance (effectively Max-Min distance) is below a given threshold [78]. It also employs space tiling to improve the filtering step. Also, it employs bounding circles as approximations of polygons together with applying the triangular inequality and already computed distances to avoid computing new distances, thus pruning areas without distance computations. Smeros and Koubarakis [103] studied link discovery on spatiotemporal RDF data by examining several topological relations that are defined on polygons. The topological relations do not take into account the proximity nor the distance to the polygon and several of those relations are meaningful only when both data sources include polygons and not points. The provided algorithm creates an equi-grid and filters out cells that contain polygons.
that cannot satisfy the relation. Finally, the maskLink approach [95, 96] tackles both topological and proximity relations. It has been implemented in a flexible framework which includes features such as:

a) streaming and archival data access,
b) efficient blocking technique for LineString geometries (minimizing the computational overhead produced by MBRs of such geometries) and
c) a suite of generic and “ready-to-use” functions that can be exploited for domain-agnostic trajectory enrichment, demonstrated for the support of complex event recognition [119].

Going beyond the state-of-the-art methods in LD and data integration, SemMR aims to develop LD algorithms for discovering spatiotemporal relations (as well as other well-defined semantic relations) between eX-trajectories, supporting the meaningful exploitation of similar and related trajectories.

2.2. Virtual Entities: IoT management and trustful interactions

The interaction with objects around in MR worlds requires sensing from physical space, or even sensing of user parameters to be able to provide high value user experience. To achieve this, a full IoT infrastructure for collecting important data for VR/AR space reconstruction, as well as device virtualization, device management and trustful interaction must be provided. In device virtualization, there are several commercial IoT-related products that aim to aggregate all the data that IoT can generate in cloud storage and expose them to developers through RESTful interfaces and libraries for enhanced service creation. For instance, Amazon, IBM, Google and Microsoft have their IoT platforms and there are other pioneers on the market, such as DeviceHive1, Xively2, Netpie3, Evrythng4, and others. While popular, such initiatives remain still bound to an information-centric view, where the main value of the things is on the information they can generate and less on the possibility to include augmented AR/VR interaction with an object and between users, offering services and actuation on it.

In IoT management paradigm, trust-related issues need also be addressed, for instance, how to manage trust between entities without the existence of a central authority. These issues may be addressed using clear and simple semantics. As trust management mechanisms have been widely studied in various research fields [91, 116, 126], it is now commonly accepted that the seamless integration of trust management mechanisms in IoT is needed [54, 55]. The recommendation and standardization of a well-defined trust negotiation language supporting the semantic interoperability of IoT context, is a challenging and open IoT-trust modelling and management topic [44, 101].

SemMR aims to deliver an integrated framework for: (a) capturing and virtualizing human and non-human (mobile and smart) entities (users, smart rooms, smart phones, smart bands, smart tags, etc.) and their interconnections, supporting their automated identification and recognition, and their open (re)use by cultural experience authoring environments, (b) modeling and computing trust for the interaction of the virtualized entities, based on principles such as friendship, ownership, collaboration, as well as on contextual information such as environmental conditions sensed by the smart tag.

2.3. User profiling

SemMR uses profiling methods to adapt user interfaces and interactions to the specific characteristics of users, particularly their age, gender and cultural background, their physical and cognitive abilities, their level of engagement and their preferences. As a consequence, it is necessary to model the user profiles at different levels: their intrinsic characteristics (physical characteristics, identity, age, disabilities, behaviour, emotional state, skills, etc.), their physical environment (location), their social environment (job position, tasks), their needs and preferences. User profiles can be built explicitly by inquiring the users for direct information, or implicitly by deducing their profile from their interaction with the system. Implicit and explicit profiles are complementary aspects. It is important to keep in mind that user profiles change over time and that, in that context, a dynamic user profile is fundamental for successful personalisation.

Various user profile (meta-)models have been proposed in Human Computer Interaction (HCI) [13] but are often oriented to specific modelling purposes such as, for instance, multimedia applications [40] or social networks [18]. Probably one of the most complete user profile meta-models is GUMO [43]. GUMO is oriented towards ubiquitous computing and enables a wide range of user characteristics, from general information (i.e. age, name, etc.) to emotional states, physical and cognitive abilities, environmental conditions, and emotional state.

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1www.devicehive.com
2www.xively.com
3www.netpie.io
4www.evrythng.com
preferences, abilities and personality traits. Skillen et al. [102] investigate static and dynamic aspects of user behaviour. They define the ability of the user to carry out the interactive task regarding its current physical and emotional state. Some of the HCI modelling standards like UsiXML [107] and MariaXML [84] also provide descriptions of user profiles through meta-models. Ontologies can also be used for user profile representation [47], fostering reasoning on profile contents, understandability and extensibility. Other works utilise the user personality traits to deduce work leadership profiles and construct harmonious and effective teams has been used [62].

User profile creation and maintenance can be supported through a multitude of inexpensive methods. Fine-grained tracking of facial expressions and body movement on the visible spectrum can be achieved using hardware such as Intel® RealSense, 3D Kinect and eye-trackers (e.g., Tobii Glasses). Moreover, biometric signals can be recorded and tracked using sensors such as NeXus EXG and Blood Volume Pulse. These allow for multimodal interaction, a very natural social form of interaction that has been shown to improve human learning and treatment of medical conditions [47, 93, 123]. Learning and user experience and acceptance may be enhanced by digital immersive interactive environments [26, 60, 92]. Learning may be reinforced by multi-sensory approaches that may be used for the personalisation of the assessment and reflection phases for improved user experience. The system may also assert aspects about the user activities beyond sentiment, knowledge, skills and performance, such as increased motivation and engagement and react to sustain engagement and support the motivational targets with certain actions for user feedback encouragement and attention catching [108].

User profiles may be associated with or abstracted to user behaviour models. There are several paradigms for user behaviour modelling and action planning for domains of varying complexity with most prominent concerning Finite State Machines (FSM), Agent-Based Modelling approaches, Social Force models and Activity-Based Models [57]. In FSM, each user action leads to a new state. Simple algebraic structures relate internal states to input and output sequences offering a general model of user behaviour. FSMs were successfully used to model human-robot interactions and dialogue behaviour [36, 51, 71, 88, 104]. To model concurrent processes of distributed systems, Petri Nets are used [112]. Agent-based systems are developed for simulating (virtual) human behaviour in a variety of disciplines, from knowledge building in collaborative online communities like wikis [64, 65] to task assignment in crowd work environments [11, 61, 98] to the way people select which exhibits to see in the physical space of a museum [63]. Users are represented as intentional rational agents. An agent model includes perception, beliefs, desires, planning/reasoning, commitment, intentions and acting, and represents a comprehensive model of user behaviour simulation [16, 58, 113].

Social or behavioural forces specify the degree of behavioural change (e.g. changes in acceleration or in direction), as reaction to external forces exerted by the environment or other agents. These forces have a stimulating or repelling effect on the motivation of humans to perform certain activities [1, 85].

Activity-based models for predicting the performance of activities by individuals have been developed [12, 110]. Such activities are planned or unplanned.

SemMR aims to model adaptive user and system behaviour in dynamic non-sequential interactions. For this, cognitive models that produce detailed simulations of human (multi-)task performance will be designed and used to implement simulated artificial agents to play a role in a multi-agent (multi-entity) setting.

2.4. Mixed Reality

MR refers to environments where real world and virtual world objects are presented together in a single display. The two most common methods for creating such MR environments are AR and Augmented Virtuality (AV). AV blends elements from the real world on to the Virtual Environment (VE), while AR works by superimposing computer-generated objects upon the Real Environment (RE). An alternative approach is Virtual Reality (VR) that constructs and displays entirely synthetic worlds that may simulate the physical properties of the real world, where users can be totally immersed in [53, 73]. In most AR applications, the RE is streamed through the camera feed of a device, such as a smartphone or a camera-equipped Head Mounted Display (HMD), with the virtual objects being superimposed on the RE by either using computer vision with fiducial markers, or sensors, to properly adjust their position and rotation [8]. Recently, however, Marker-less AR received significant attention and is now widely used in popular AR applications
development platforms such as Microsoft Hololens\(^5\) and Magic Leap\(^6\).

Nowadays, most of the popular VR and AV application development platforms, such as the HTC Vive Pro\(^7\) and Oculus Rift\(^8\), utilize sophisticated sensors to support room-scale applications, allowing hand presence in the virtual world \([52]\) and full body motion support \([89]\), along with wireless support\(^9\). Eye tracking is also exploited in some high-end HMD platforms (e.g. VARJO VR-1\(^{10}\)) to provide better experience in AV.

Wireless HMDs, such as the recently announced Oculus Quest \(^{11}\) and VIVE Cosmos \(^{12}\), feature high quality inside-out tracking, allowing developers to seamlessly blend real and virtual environment in AV and AR applications. Moreover, HTC Vive Pro Eye already features built-in eye tracking support \(^{13}\) increasing the quality of the user experience \([86]\). Finally, state-of-the art technology, such as LooxidVR\(^{14}\), enables brain activity and eye movement detection, which allows user behaviour tracking for real time personalization and enhancement of user experience in MR applications.

SemMR aims to enhance MR development systems/platforms by (a) integrating a graphical drag-n-drop code-free authoring environment for synthesizing open and reusable MR experiences, (b) developing recommendation methods for automatically suggesting related external data/info to be attached to MR content for enhancing it, and for automatically suggesting new eX-trajectories to support the reconfiguration of existing (towards optimization), (c) focusing on IoT to allow for seamless and ‘live’ interaction of interconnected trustworthy deployed entities (human and non-human ones), (d) developing and integrating tools for properly understanding human behaviour and cognition while experiencing MR worlds, (e) developing tools for semantically integrating external heterogeneous and disparate information to enrich content of the MR experiences, improving their quality and thus the quality of the user experience, and (f) developing appropriate models and methods for the reuse of connections between virtual and real objects, in more than one MR world, enlarging this way the MR environment.

3. Experience as a Trajectory (eX-trajectory)

A movement track represents the ability to capture the movement of an object or entity moving in a geographical space over some period of time. This temporal sequence of the spatiotemporal positions is represented as pairs of ‘instant’ and ‘point’. Additional data (depending on the capabilities of the movement recording device) may also be recorded, e.g., the instant speed or stillness, acceleration, direction and rotation. Such captured data is the raw data. In some applications there is no interest in keeping and analysing continuous non-stop records of raw movement data. Instead, segments of interest may be selected, i.e., a specific movement track within a ‘start’ and ‘stop’ (Begin and End) point. Trajectories are the segments of an object movement track that are of interest for a given application. For instance, considering an application that is required to track and analyse tourist movement and cultural activities in the city of Athens. For this (big) data recording example, the application identifies a trajectory for the whole track left by an individual tourist in Athens (e.g. ‘inside Athens’ trajectory), but also another trajectory tracking a specific daily cultural experience track of this individual (e.g. ‘a tourist in Athens on a Sunday tour’ or ‘a tour in the Museum of Acropolis on Friday morning’).

In some cases, application processes require to complement raw data with additional data or information from the application context. For example, in order to be able to interpret the trajectories of people in a city additional knowledge about the specific features of the city (e.g., the map or the points of interest of the city) is required. Spatiotemporal data (coordinates) can be replaced with street and crossing names, or with names of the places of interest, such as shops, restaurants and museums. For example, information about cultural events (e.g., concerts, fairs) enables traffic monitoring applications to differentiate between normal traffic conditions and exceptional traffic conditions, leveraging the interpretation of spatiotemporal data (positions). Adding information to raw trajectories is called the semantic enrichment of trajectories. Such enrichment requires the process of complementing existing data with additional data/information, i.e. annotations. Additional data/information is connected either to a trajectory as a whole or to parts (segments, points) of

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5https://www.microsoft.com/en-us/hololens
6https://www.magicleap.com/
8https://www.oculus.com/
9https://www.tpcastvr.com/
10https://varjo.com/
11https://www.oculus.com/quest/
12https://www.vive.com/us/cosmos/
13https://www.vive.com/us/pro-eye/
14http://looxidlabs.com/
it. In this context, a semantic trajectory is a trajectory that has been enhanced with annotations that adds context. In the tourist example, recording the goal of a person’s trip to Athens (e.g., business, tourism) is a semantic annotation at trajectory level. On the other hand, marking the person’s presence at a location as a visit to a temporary modern art exhibition is a semantic annotation at position level.

3.1. eX-trajectory modelling

Trajectories are widely defined as the segments of the object’s movement track that are of interest for a given application [105] and semantic trajectories are trajectories that have been enhanced with semantic annotations and/or one or more complementary segmentations [82]. To enhance the knowledge captured by trajectories one may superimpose a structure of homogeneous segments that are meaningful for the particular application. These homogeneous segments are called episodes. Episodes are defined as a maximal subsequence of a trajectory such that all its spatiotemporal positions comply with a given predicate [82].

Existing approaches for the representation of semantic trajectories impose limitations on the structure or the elements of trajectories. More specifically, they either:

a. use plain textual annotations instead of semantic links to other entities [3, 9, 15, 28], hindering the provision of a fully-fledged representation where trajectories are semantically linked with other data or with semantic resources associated with the behaviour of moving objects, or
b. constrain the types of events that can be used for structuring a trajectory [3, 9] or
c. make assumptions on the ingredients/parts of trajectories [15, 35, 80].

For example, in some works, semantic trajectories are sequences of sub-trajectories [15], while in others they are sequences of episodes [35]. In the work of daAcrorn ontology [97], the representation of trajectories at multiple and interlinked levels of analysis is supported. In related work, a rich set of constructs for the representation of semantic trajectories is presented as sequences of episodes, each associated with raw trajectory data and (optionally) with a spatiotemporal model of movement, although without a fine association between abstract models of movements and raw data [35]. In Bogorny et al. [15], a two-level analysis is presented, where semantic trajectories are lists of semantic sub-trajectories, and each sub-trajectory is a list of semantic points. Regarding events and episodes, these are connected to specific resources at specific levels of analysis: events that are mostly related to the environment rather than to the trajectory itself are connected to points only (something that may lead to ambiguities in certain cases) [15], while episodes concern things happening in the trajectory itself and may be associated to specific models of movement [35]. Finally, contextual information is related to movement models, episodes or semantic trajectories, which is quite generic [35], while environmental attributes are associated to points only and are assigned specific values [15].

3.2. eX-trajectory management and analytics

A trajectory behaviour is defined as a set of specific characteristics that can be used to identify a particular connection or link to a moving object or to a set of moving objects. The behaviour is defined by a predicate that expresses whether a given trajectory (or a given set of trajectories) shows the corresponding behaviour [82]. For instance:

a. a “Tourist” behaviour might concern a daily trajectory that shows the Tourist behaviour, if (a) its departure (Begin) point P1 is a place of type “Accommodation”; (b) it makes at least one stop in a place of type “Museum” or “Tourist Attraction”,

b. a “Meet” behaviour might concern a set of trajectories that show the specific (meet) behaviour, if every trajectory of the set roughly ends at the same space (point) and at the same time (instant).

A trajectory can be characterized by several behaviours. For instance, a trajectory can show both a “Speeding” and a “Tourist” behaviour and simultaneously be part of a group of trajectories showing the “Meet” behaviour. For each behaviour the predicate relies on different characteristics. The trajectories of tourists visiting Athens may be analysed for building tourist profiles and suggesting personalized tours and services, regulating the flows of tourists in the attractions, etc. All this relies on analysing the similarities and dissimilarities among the trajectories (and their characteristics), classifying the trajectories into types of similar trajectories, and extracting the common characteristics that distinguish one group from another. A set of distinguishing characteristics (called patterns or behaviours) forms a summary description of the group of trajectories.
Several systems for trajectory data management and analysis exist. PIST [17], BerlinMOD [31] and TrajStore [25] propose specific storage structure and indexes targeting traditional database engines. SharkDB [122] adopts a columnar data schema to provide better query and analysis performance. However, these systems are designed for centralized architectures, thus, they are inefficient for, or incapable of, handling massive volumes of trajectory data. In addition, as the storage structures are constrained by the underlying database engine, the system flexibility is limited. SpatialHadoop [32] and Simba [124] enable distributed spatial analytics based on the MapReduce paradigm. Nonetheless, they do not exploit the characteristics of trajectory data for efficient data management and analytics. A cloud-based system by Bao et al. [10], CloST [110], PARADASE [66], and Elite [125] provide distributed solutions for big trajectory data. They utilize specific partitioning strategies in distributed environments to support data retrieval. Other systems that offer distributed storage and computing also exist. SnappyData [75] integrates Apache Spark and Apache Geode15 to support efficient streaming, transactions and interactive analytics. Apache Ignite16 also integrates Apache Spark with its key-value store to enable data sharing across Resilient Distributed Datasets (RDDS) [59]. The IndexedRDD project [48] maintains an index within each partition. Although these systems provide solutions that enhance Spark and eliminate inefficiencies of heterogeneous systems, they do not provide flexible operations and optimizations for trajectory data analytics. Latest related work presented in UltraMan [29] adopts a flexible framework that supports customizable data formats, partitioning strategies, index structures, processing methods and analysis techniques, which offers better support to realize optimizations and complex analytics. UltraMan adopts a unified engine that support efficient trajectory data management and analytics.

4. Mapping Cultural Experiences to Semantic Trajectories

SemMR integrates key technologies such as semantic and IoT technologies for user interaction, in order to advance cultural experiences within a new shared cultural experience ecosystem (Fig. 1), accommodating provisions for supporting MR-based interaction.

Fig. 1. The Shared Cultural eXperience Ecosystem (SCEE)

The key concept in SemMR is the handling of real-world information as part of virtual entities (VE) that change and evolve, either individually or as part of related groups. The VE are collaborating to create experiences and they may interact with human experiencers or with each other in scenarios or stories. Such interaction (that can be seen as a dialogue between multiple types of entities, human and virtual) may be dynamically shaped when trajectories of previous and recently authored experiences coincide or become relevant. Multiple users may interact with multiple entities at different times, thus creating a shared experience user space (in cultural or another domain). The SemMR ecosystem maintains the shared experiences that are complete, allowing for variable length (number of visiting points of interest/events/activities and their duration). User behaviour is monitored by employing interaction metrics and sensor data from wearables, such as smart bands, on the users. Through the analysis, the shared experiences are reconfigured and presented to the SemMR entities for selection and interaction. The SCEE is the enabler for advanced interaction and experience sharing, since experts may author interactive experiences while the experiences themselves may dynamically intersect and interchange during the interaction, providing the users with new relevant cultural interaction.

5. System Architecture

Based on the SemMR framework, this section elaborates on the proposed architectural design of a SemMR-based system, which constitutes its first realization/instantiation. The proposed system (Fig. 2), is considered a sample instantiation of the framework, without limiting SemMR only to the proposed architectural design presented in this paper. However, the architectural design presented below is based on one-

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15https://geode.apache.org
16https://ignite.apache.org
to-one mapping of its components (methods and tools) to the concept specified in SemMR.

The main components of the proposed SemMR-based system are the following:

a. eX-trajectory management and analytics,

b. IoT/VEs management,
c. semantic data and information management,
d. user behaviour monitoring and analysis,
e. the cultural application authoring environment.

The functionality of each component is detailed in the following paragraphs.

a. eX-trajectory management and analytics: This component is responsible for managing and analysing eX-trajectories using methods for representing, storing, querying, linking, synthesizing and enriching eX-trajectories. It identifies similarities between eX-trajectories, that is the types of relations between one or more eX-trajectories. It supports a variety of analytic tasks for eX-trajectory behaviour, computation of statistics and advanced mining methods for eX-trajectory data co-movement pattern mining. It utilizes input from the components of (a) user behaviour analysis for recommending reconfiguration of eX-trajectories based on user behaviour analytics, (b) IoT/VE management for VE integration in eX-trajectories and (c) data/information management for eX-trajectories data and information enrichment.

b. IoT/VEs management: This component is responsible for (a) facilitating connectivity between the types of entities (human and non-human), (b) enabling abstract representation (virtualisation) of those entities using the semantics of the SemMR ontology, (c) managing VEs by efficiently storing and querying the data/information they create during their involvement in eX-trajectories and (d) modelling and computing trust between them, towards facilitating trustful interactions in the context of cultural spaces.

c. Semantic data/information management: This component is responsible for facilitating (a) search and discovery of disparate and heterogeneous domain-specific data and information related to eX-trajectories (from the Web, the LOD cloud and even the RDBMSs via the utilization of virtual RDF graphs and Ontology-Based Data Access methods), (b) transformation of data to RDF and data integration under a common view, based on domain-specific ontological models and on the SemMR ontology and (c) delivery of the integrated/unified data/information as recommendations for enhancing related eX-trajectories, using semantic matchmaking methods.

d. User behaviour monitoring and analysis: This component is responsible for facilitating (a) tracking and monitoring of human entities in terms of their behaviour during interaction, (b) analysing user behaviour to identify states such as boredom, frustration, confusion, uncertainty, etc., (c) the decision on intervening actions through comments, recommendations for changing path, additional content presentation, according to the user affective mental state and preferences, (d) building (dynamically) the users physiological profile, on top of the initial profile already in SemMR and (e) providing feedback through an integrated interactive interface.

e. The cultural authoring environment: This component is responsible for authoring eX-trajectories and for developing cultural apps with low effort. It provides the following: (a) a graphical drag-n-drop code-free authoring interface of eX-trajectories, (b) methods for the synthesis of open and reusable eX-trajectories, (c) methods for the integration of VEs into eX-trajectories and (d) methods for the enhancement of eX-trajectories via their semantic enrichment. The output of this environment is a domain-specific cultural application that is delivered to users for exploitation. The cultural authoring environment interfaces with the MR devices and, in general, the infrastructure required for the MR application delivery and makes these interfaces available to developers as objects and APIs for a higher level of abstraction. In this fashion, MR application development is disassociated from the idiosyncrasies and peculiarities of the hardware and, therefore, can be performed more efficiently and with better portability.

In the heart of SemMR is a triple store for storing and querying integrated data in Resource Description Framework (RDF) data model [120] and the SemMR ontology encoded in the OWL W3C ontology language [121]. The SemMR ontology is designed to represent eX-trajectories, VEs and the required domain specific data/information, that is (a) sensor data from the tracking and monitoring of human behaviour and their interactions with the environment and (b) Web/LOD/RDBMS data that will be used for eX-trajectory enhancement (semantic enrichment). The design of concepts and properties in the SemMR ontology regarding semantic trajectories is based on the definitions provided by the daAcron ontology for the representation of semantic trajectories of moving objects [97] and the semantic trajectories design patterns by Hu and Janowicz [45]. While other generic ontologies related to the objectives of the SemMR framework (e.g. DUL, SSN) are also taken into account, we have based our first ontological design (used in the simulation and evaluation presented in following section) in the CrossCult ontology [117, 118] for the representation
of cultural heritage data, venues, users and related activities e.g., visits at cultural spaces (sites, buildings, rooms). The SemMR ontology development process will follow a collaborative workflow such as the one specified in the HCOME methodology [56], using the collaborative ontology engineering tool WebProtégé and discussion threads via e-mail and Google docs/groups. In the architectural diagram illustrated in Fig. 2, three stores are depicted as a conceptual approach to the organization of the SemMR data/information management; however, this is not necessarily the case of implementing three different physical stores.

The SemMR key offerings and supported technologies are depicted in Fig. 3.

6. SemMR example ontological specifications

6.1. Cultural Heritage domain

The CrossCult ontology (IRI: http://kb.crosscult.eu/) organizes cultural object semantics in
multiple layers, aiming to underpin the representation of connections between cultural heritage data. The CrossCult ontology extends the basic CRM modelling of CH data semantics, by accommodating the modelling of users (of applications) and visitors (of venues) as well as venues (sites, buildings, rooms, etc.). Furthermore, it defines semantics such as interest and review ( subclasses of E73 Information Object in CRM). Moreover, to offer a more comprehensive coverage of concepts of interest, the CrossCult ontology reuses elements from the namespaces of FOAF (e.g., for modelling persons, their activities and relationships between persons), Dublin-Core (to describe periods of time and specialised datatypes), and SKOS (to model relationships between concepts), as well as DBpedia (primarily for enriching instances of the Upper-level ontology with links to DBpedia concepts).

A modelling choice of CrossCult ontology that is adopted in the SemMR ontology modelling, is the reuse of the specialised CIDOC CRM [50] classes such as E22.Physical Man Made Object and E24.Physical Man Made Thing, which provide a unified view to a wide range of concepts. Artefacts, paintings, museum exhibits, monuments, are modelled as instances of those CRM classes. This design choice also enables the use of standard semantics for modelling spatial, temporal, geometrical, and other semantic relationships. Fig. 4 depicts a description of an exhibit (PoI), while Fig. 5 illustrates the exhibit (PoI) modelling within SemMR.

The CrossCult definition of a Visit (and related classes i.e., Visitor and VisitingStyle) in its UserModel namespace has a central role in the representation of the knowledge in SemMR. In the example depicted in Fig. 6, we illustrate how individual routes followed by users are linked with a particular visiting style (e.g. ant, grasshopper, butterfly etc. [63]). Note that a relationship between users and visiting styles is also accommodated at user profile level, indicating which visiting style a user typically follows, however, as shown in the example, it is possible to represent differentiations from the typical user behaviour, occurring at the individual route level. The visiting style of each individual visit is determined by analysing the user traces against the locations of the exhibits.

Marble statuette of goddess Demeter enthroned. The goddess wears polos and her hair is shaped in tentacles. She bears a reaching to the feet sleeved chiton and a cloak covering the lower part of her body. The goddess removes the garment from her face with her left hand. She holds an apple on her right hand, on the level of her shoulder. Originated from Vlahokerasia and dated to the 4th century B.C. Dimensions: Height 0.40m, width 0.19m. Location: Room 15, 1st floor.

Fig. 4. Textual description of an exhibit (PoI)

Fig. 5. Informational model for an exhibit (point of interest) in the SemMR ontology
6.2. Semantic Trajectories

Motivated by real-life needs in critical domains such as aviation and maritime, the datAcron ontology provides a coherent and generic representation of semantic trajectories for moving objects [97]. It reuses the ontologies: DUL, SimpleFeature, NASA Sweet and SSN. As shown in the ontological definitions in OWL syntax depicted in Fig. 7, a semantic trajectory consists of a sequence of temporally non-overlapping trajectory parts that can be either semantic nodes, raw positions reported from sensing devices, or trajectory segments. Each trajectory part may be associated to a specific geometry, representing a point or region of occurrence and a temporal entity specifying an instant or time interval of occurrence.

Similar to the above definitions, but in a more simplified and generic way, the semantic trajectory design pattern [45] presented in the OWL snapshots depicted in Fig. 8, defines a semantic trajectory as a number of segments and fixes (synonym to points in other vocabularies). According to the authors, it defines a number of interfaces to incorporate additional geographic information, domain knowledge, and device data.

Fig. 6. Linking of visitors, visits and visiting styles

Fig. 7. Semantic trajectory definition according to datAcron ontology

Fig. 8. Definition of a semantic trajectory as a number of segments and fixes
In SemMR, we aim to link/connect any of the two semantic trajectories representation to the CrossCult ontology, in order to be able to formally represent the eX-trajectory (as defined in this paper). To do so, we propose a number of simple design patterns in the SemMR namespace, as described below. In the description of the design patterns, the following prefixes are used:

<table>
<thead>
<tr>
<th>Prefix</th>
<th>IRI</th>
<th>Ontology</th>
</tr>
</thead>
<tbody>
<tr>
<td>traj</td>
<td><a href="http://descartes-core.org/ontologies/trajectory/">http://descartes-core.org/ontologies/trajectory/</a></td>
<td>Semantic trajectory design pattern</td>
</tr>
<tr>
<td>cros</td>
<td><a href="http://kb.crosscult.eu/">http://kb.crosscult.eu/</a></td>
<td>CrossCult</td>
</tr>
<tr>
<td>crm</td>
<td><a href="http://erlangen-crm.org/160714/">http://erlangen-crm.org/160714/</a></td>
<td>CIDOC/CRM</td>
</tr>
</tbody>
</table>

a. Define new concept :eXtrajectory as subClassOf traj:SemanticTrajectory
   
   :eXtrajectory ⊑ SemanticTrajectory

b. Link/connect traj:SemanticTrajectory to cros:Visit (which represents a specific visit by a particular user) via an object property (:visitMade)
   
   :eXtrajectory ⊑ ∃𝑣𝑣𝑆𝑆𝑣𝑣𝑆𝑆𝑒𝑒𝑣𝑣𝑒𝑒𝑣𝑣𝑒𝑒

c. Link/connect traj:SemanticTrajectory to crm:E28_Conceptual_Object, to allow the explicit representation of the semantics associated with a trajectory. Similarly, traj:Segment and traj:Fix are linked/connected to crm:E28_Conceptual_Object, to allow the representation of semantics associated with trajectory segments and individual points. Under this arrangement, all representational levels of eX-trajectories may bear relationships to semantics. It should be noted, however, that the semantics appearing at the highest level used at any context are the ones conveying the actual meaning of the trajectory more accurately, overriding the lower-level ones. For instance, an eX-trajectory exTr0001 may be comprised of the segments “visit to a museum” (associated with cultural semantics), “launch at a restaurant” (associated with food service and local cuisine semantics) and “shopping at a fleamarket” (associated with street market and local products semantics), however the eX-trajectory exTr0001 may be associated with tourist behaviour semantics, modelling the overall behaviour and not the lower level details of the constituent parts.

d. Link/connect cros:Visit to crm:E28_Conceptual_Object, to allow the explicit representation of the semantics targeted by a particular user visit. This is required since different users may be following a specific semantic eX-trajectory (which is linked to the cros:Visit object), focusing on diverse semantics of the eX-trajectory. For instance, a visitor may follow the “Acropolis of Athens” eX-trajectory focusing on the ritual aspects of monuments, while another visitor may follow the same eX-trajectory, focusing on the architectural aspects of monuments. By capturing the point of view of each individual user, more elaborate analytics can be produced and more accurate matching can be performed, leading to better recommendations.

7. User behaviour modelling

Modelling adaptive user and system behaviour in dynamic non-sequential interactions is at the core of the SemMR framework. This is of key importance for a number of settings including (a) cultural sites as well as cities with tourist attractions, since their visitors are free to roam and view the site points of interest in no particular order and (b) learning environments, where learners are able to choose between learning paths or access and use learning material in distinct sequences, collaborating with other learners or instructors. Towards this, cognitive models that produce detailed simulations of human (multi-)task performance were designed and used to implement simulated artificial agents to play a role in a multi-agent (multi-entity) setting. AI agents compute the most plausible task action(s) given their understanding of the context, actions of others, their preferences and goals, provide alternatives and plans, roll out possible outcomes and, therefore, are able to adapt their behaviour to their partners. They also know why they select a certain action and can explain why the choices made lead to what specific outcome (explainable AI). Agents can be built using rather limited real or simulated expert and/or interactive data: an agent is supplied with initial state-action templates encoding domain knowledge (as eX-trajectories enriched with VE and IoT information), the user’s profile and preferences. Over time, the agent learns from the collected interactive experiences. Suggestions and optimizations are performed by finding prior experiences (instances) that are the most frequently or recently used and/or are most similar to the current situation (contextual parameters, user affective state, his goals and preferences), blending the instances together to the extent that they match the interactive state.

Instance-Based Learning [38] that utilises the ACT-R matching functions [5] and k-NN classification algorithms, as well as Reinforcement Learning models [109] are utilised for learning to interact. The advantage of the SemMR approach is that it requires far less experiences for the system to be able to interact
with the user in a sensible way and that it incrementally improves as its set of instances increases in size. It also allows utilizing experiences of others to guide and enrich the experiences for new users. Additionally, growing data from the eX-trajectories Store paired with increased computational power, can be used to apply modern powerful Artificial Neural Networks (ANNs) and Deep Learning (DL) approaches, which showed a significant impact on many AI and HCI applications [6, 106]. Finally, the SemMR model assumes a non-perfect user, that is it supports the modelling of user understanding errors and the integration of a memory and interest model reflecting the individual and changing configurations of the user’s mind.

8. Evaluation

In order to evaluate the feasibility of the approach, the appropriateness of the recommended eX-trajectories and the scalability of the proposed framework, we ran a set of simulation experiments with artificial users. In this set of experiments, eX-trajectories recommendations were formulated and served to (artificial) users with diverse profile characteristics. Then the suggestions were evaluated for suitability against the relevant user profiles. Furthermore, the simulation process entailed concurrent formulation of recommendations to measure the execution time required for different levels of concurrency and quantify the response time of the SemMR instantiation.

For these experiments we used two machines. The first one was equipped with 2x Intel Xeon 8-Core CPUs, 64GB of RAM and 480GB SSD with a transfer rate of 550MBps; the total estimated cost of this machine is less than 1.5K Euros, refurbished. This machine hosted the proposed framework, as well as the SemMR instantiation (database and MR eX-trajectory services). It also managed the database items, exhibit locations and semantic descriptions (already pre-processed as VEs), user profiles and trajectories, new content from IoT links (already retrieved but not pre-processed) and recorded and analyzed the user paths. The second machine created the pool of concurrent users-visitors, where for each one the current trajectory was built, compared to existing trajectories and synthesized the suggested trajectories randomly between 2-5 trajectories and 4-7 suggestions for each user tour. The machines were connected through a 1Gbps local area network.

For the cultural experience validation, we simulated scenarios for the visitors of the Acropolis Museum in Athens, which contains nearly 4,250 works of art and welcomes an average of 4.5K visitors per day (nearly 1.5M per year) and assuming that less than half of them visit it at the same time.

The user profiles utilized in the validation experiment were synthetically generated and included the following aspects: age, music choices, game choices, art preferences, museum theme preferences, mood, visiting style, gender, place of origin and a returning visitor indicator, following the results of the study presented in Alexanderssion et al. [2]. Each user profile could be matched to one of the six personas (predetermined user stereotypes) identified for the Acropolis museum in [7], however the degree of similarity for the best match varied from an absolute match to 5/8 attributes (the “mood” and the “returning visitor indicator” were not part of the stereotype modelling, appearing only in the user profile). Similarly, the eX-trajectory database was populated synthetically: firstly, descriptions of landmark exhibits were crafted according to the permanent collection descriptions offered in the museum website and subsequently areas of the museum were also modelled using information from the Acropolis Museum application in the Google Arts and Culture website complemented with information from in-situ visits. Both landmark exhibit and museum area descriptions were semantically tagged, with semantic tags including the thematic area of the objects (e.g., religion, everyday life, wars, death, mythology etc.), the artefact era and the type of the artefacts (statues, household objects, buildings, grave goods). Then, eX-trajectories with varying duration and spatiotemporal patterns were created and inserted into the eX-trajectory database, observing the profiles of the users. For instance, visitors with ant-type visiting style move sequentially along the areas of the museum, increasing their speed when the theme of the museum area does not intersect with their theme preferences while moving more slowly in areas having content they are interested in; on the other hand, grasshopper visitors approach only certain exhibits falling in their interests spending a significant amount of time in front of them, crossing empty spaces and moving at a fast pace in other cases [63]. Physical fatigue was also considered in the generation of spatiotemporal sequences, with the effect being more significant in spatiotemporal sequences associated with older persons, as asserted in [2]. Overall, 100 user profiles and 620 eX-trajectories

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1https://en.wikipedia.org/wiki/Acropolis_Museum
2https://artsandculture.google.com/partner/acropolis-museum

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were generated and inserted into the virtual entities and eX-trajectory data store.

The eX-trajectories proposed by the system were parsed and evaluated for appropriateness to each user profile and visitor path. They were found to be in alignment with the user’s visiting style, thematic preferences and associated stereotype. For approximately 70% of the user/path combinations, 1-3 of the suggestions contained exhibits beyond the user profile thematic preferences, fostering thus novelty and serendipity [90, 99]. As far as performance is concerned, Fig. 9 indicates the overhead of formulating the eX-trajectory recommendations under varying degrees of concurrency.

In Fig. 9, we can clearly see that the overhead is small per execution (approximately from 0.18 to 0.3 seconds, depending on the level of concurrency) and scales linearly with the number of concurrent executions (users). However, for concurrency levels higher than 200, the machine was saturated, and performance dropped rapidly, indicating that a second machine (of the same specifications, as the one used in our experiment) must be added.

Overall, in order to fully support a museum of the size of the Acropolis Museum, the cost required for the machines hosting the SemMR framework is estimated to be less than 17K Euros, which is deemed reasonable and affordable.

9. Discussion and Conclusion

This paper presented SemMR, a framework for creating a new ecosystem of shared and optimised cultural experiences, offering the potential to accommodate MR interaction. It adopts the principle of interactive technology sustainability [14], argued under the concept of sustainable interaction design, and extended according to two major categories, sustainability through design and sustainability in design [69]. The SemMR approach employs semantic technology for the utilization/integration of data/information discovered on the current Web sources, the Linked Open Data (LOD) cloud and the Internet of Things (IoT), promoting experience sharing at user level, as well as data/application interoperability and low-effort implementation at the software engineering level. SemMR is based on a sustainable-in-design cultural experience ecosystem that includes all stages of development and deployment of the integrated technologies, from authoring to synthesis to validation of cultural experiences, as similarly discussed and presented by the related works of Huang [46] that expressed the importance of validation in real-world situations, and DiSalvo et al. [30] that strongly encouraged the use of formative user studies and environment awareness, in the sense of exploiting the qualities of the associated environment for sustainability. Sustainability is ensured by the validation of the framework in real-world use cases involving both end-users as well as paired technology integrators from industry that not only aim to deploy SemMR but also to create the experiences per situation and lead the formative user studies for usability evaluation focusing on the integration and long-term impact of the integrated technologies to the specifics of the application environment.

The SemMR framework, along with the proposed architectural design for its implementation and the scalability metrics based on a use case instantiation, are presented in this paper. The presented work introduces methods and tools for multi-entity interactions.
between entities of different types, to create reusable and optimized cultural experiences with low effort, towards a shared cultural experience ecosystem. Specifically, the SemMR framework introduces methods and interfaces for code-free implementation and deployment of shared and reusable MR content, applications and tools, emphasizing the notion of the eX-trajectory. The SemMR instantiations (implementation) of the framework deliver high quality cultural experiences, facilitating the interaction between a variety of entity types which interact in a virtual and fully experiential world. In addition, SemMR proposes methods for tracking, monitoring and analysing user behaviour and the user interaction with the environment and other users, towards optimizing MR experiences by recommending their reconfiguration in two modes, that is at run-time (dynamically) or at development time (statically).

For future work, the SemMR system implementation that includes all components presented in Fig. 2 that correspond to all key technologies described in this paper will enable the system deployment to real users for formative evaluation. Such endeavour is expected to create new content that may be evaluated by both users and experts, like museum curators. For the latter, an open research challenge is the automatic selection of the most relevant content from external sources and its seamless integration to the authored content, for a seamless, yet enhanced, cultural experience.

References


