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► **To cite this version:**

Daniel Balouek, Julien Pettré. Collaborative services for Crowd Safety systems across the Edge-Cloud Computing Continuum. CCGridW 2024 - IEEE 24th International Symposium on Cluster, Cloud and Internet Computing Workshops, May 2024, Philadelphia, France. pp.92 - 97, 10.1109/cc-gridw63211.2024.00017 . hal-04775145

**HAL Id: hal-04775145**

**<https://hal.science/hal-04775145v1>**

Submitted on 9 Nov 2024

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# Collaborative services for Crowd Safety systems across the Edge-Cloud Computing Continuum

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**Abstract**—Crowd or mass gatherings at various venues such as entertainment events or transportation systems are faced by individuals on a daily basis. Crowd management for large-scale planned events is essential, and depends on behavioural and mathematical modelling to understand how crowds move in different scenarios. In this paper, we propose the creation of a set of collaborative and services, the CrowdMesh platform, to allow for processing, analysis, and sharing of crowd monitoring datasets constructed over the Edge-Cloud Continuum. Comprehensive tools and best practices are needed to ensure that analysis pipelines are robust, and that results can be replicated.

**Index Terms**—Crowd Safety, Edge Computing, Computing Continuum, Urgent Computing, Cyberinfrastructures

## I. INTRODUCTION

Crowd management refers to planning and monitoring of large groups of people in the aim of organizing comfortable, safe and secure environment for mass events. Examples of crowd management include: gatherings at sport events in stadiums, at cultural events in festivals or concert halls or at religious events such as pilgrimages, but also flow management in transportation systems. Furthermore, this issue has garnered a lot of attention in France because of the 2024 Paris Olympics, which are projected to result in large crowds at stadiums, major train stations, and other locations.

Despite a significant growth in the availability of sensors and communication technologies, researchers are still faced with major obstacles to transition from simulations to real-life experiments, in spite of the huge demand for Crowd management systems and applications at scale [1], [2]. Although, the idea of scaling to millions of devices is attractive, the crowd analysis community relies on experiments with either short-term user contributions or small numbers of users [3]–[6].

The Computing Continuum paradigm promises the fluid integration of sensors and actuators between the edge of the network, computing servers in the core, and resources in-between along the data path to support dynamic and data-driven applications [7], [8]. Particularly, the combination of Edge Computing for processing machine-generated data closer to users, and Artificial Intelligence for finding patterns in structured or unstructured data have shown benefits in several domains. It offers systems and applications features of computation offloading and service operation to build systems able to collect data and take decisions from insights in a timely fashion [9], [10].

This position paper explores how Crowd management systems can benefit from leveraging the Computing Continuum. Motivation scenarios requires to collect data associated to smartphones and video feeds at a scale of thousands of users, analyze this data to gather spatial and temporal insights, and facilitate decision-making backed up by crowd management models [11], [12]. We argue that there is a need for collaborative and reusable services that can be executed on general-purpose architectures. We then identify design goals and discuss research challenges associated to an ecosystem for crowd management systems across the Edge-Cloud Computing Continuum.

The rest of this paper is organized as follows. In Section II, we discuss the requirements of crowd management in the larger context of Urgent Science. In Section III, we discuss the characteristics of the Computing Continuum paradigm and related works. In Section IV, we propose building blocks for modelling crowd management scenarios across Edge and Cloud resources. In Section V, we introduce CrowdMesh, a set of collaborative services to support an hybrid of real-time data and crowd simulation models. Section V concludes the paper with future works.

## II. URGENT SCIENCE AND CROWD MANAGEMENT SYSTEMS

### A. Urgent Science

Urgent science refers to a class of time-critical scientific applications that leverage distributed data sources to provide real-time insights and decision-making capabilities. As available data increases in scale, heterogeneity, and richness, these applications require rapid processing and analysis of large volumes of data to identify context-sensitive features and deliver actionable information under strict time and quality constraints [10], [11], [13].

Examples of urgent applications span various domains, ranging from emergency response systems to weather forecasting and disease outbreak detection [14]–[16]. For example, Earthquake Early Warning (EEW) systems must detect the initial seismic waves, estimate the location and magnitude of the earthquake, and issue alerts to surrounding areas within seconds to minutes before the damaging waves hit, while dealing with operational constraints arising from the uncertainty of data and the availability of computing resources [14].

Beyond the need for developing responses and triggering appropriate actions, complex urgent applications require to deal with uncertainty due to the transmitted data being incomplete or inaccurate such as in situations with limited sensor coverage. Additionally, if there are delays in processing and transmitting the data due to technical issues or network congestion, the ability of the system to issue timely alerts and prevent damage may be severely hindered.

### B. Crowd Management

Crowd management refers to the process of effectively controlling and guiding large groups of people in order to maintain safety and prevent chaos. It is crucial for many applications, including public safety, emergency services, traffic flow and management in private and public spaces, and analyzing group behaviors during large events [17]. When the density of a crowd is about six people per square meter or more, bodies are jammed together so tightly that they can no longer choose where they go and they begin to behave like a fluid [18]. Pressure waves can travel through them and they lose control.

Traditional approaches consists in using cameras and sensors to track crowds and monitor traffic flow in real-time [11], [12]. Recent works builds on the convergence of three key technologies: *Ubiquitous Computing*, *Ubiquitous Communication* and *Intelligent User-Friendly Interfaces* [16], [19]–[21].

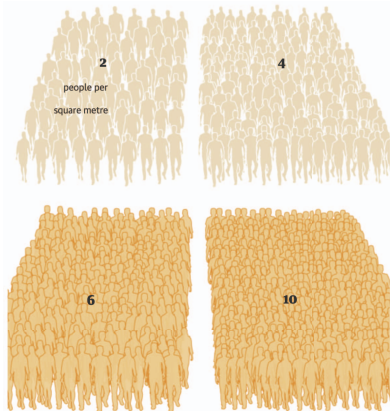


Fig. 1. At a density of approximately six individuals per square meter, the bodies become tightly packed to the point where they lose the ability to control their movement and start exhibiting fluid-like behavior. They become capable of transmitting pressure waves and experience loss of control. Adapted from [22], [23].

### C. Limitations

Building crowd monitoring and management systems to assess situations in real-time and perform experiments at scale typically faces two major challenges:

- **Time and energy costs of resolving a robust, scalable, and visually attractive application and infrastructure:** As the cloud is inherently a distributed environment, it fabricates gaps in communication and coordination

between stakeholders, resulting in complex process models [24], and scalability challenges related to the performance and delivery of service as the number of end-users and terminals increase.

- **Human related issues such as privacy, incentives, and quality of data:** Incentives lies in the difficulty in accessing data or test and validate algorithms for detecting and preventing stampedes from occurring, as it would require a lot of resources, permissions, and cooperation from various stakeholders of the different events [21]. Also, security is related to exposition to threats and malignant access, both for the service delivery platform and the client access.

Additionally, Martella et al. puts in light several limitations associated to current practices. In particular, (1) the inability to generate unforeseen conditions, (2) the difficulty in collecting data in real time and (3) the inability to provide timely sensitive feedback to the crowd [25]. While several works have attempted to integrate Internet of Things (IoT) into crowd management systems, their approaches either focuses on data collection for offline analysis or do not integrate the underlying infrastructure into their mathematical models for feedback [26]. Similar to challenges found in Urgent science, there is a critical gap in the knowledge base that pertains to programming crowd management systems while managing important trade-offs of cost and quality.

The proposed line of work aims at leveraging the Computing Continuum by contributing to the programming support and the resource management of infrastructure and services. Previous works [7], [10] have highlighted the importance of the synergy between workloads, applications, and infrastructures for time-critical decisions in complex systems.

## III. THE COMPUTING CONTINUUM PARADIGM

### A. Concepts

The Computing Continuum represents a fluid integration of the computational, storage, and network resources located at the edges, in the cloud, and in-between [8], [9]. The data is generated at the edges by sensors, scientific instruments, and personal devices. Edge devices are usually limited in computational power and storage; their principal function is to collect data and transmit them for analysis. In-transit nodes are then in charge of performing aggregation, filtering or preprocessing along the data path. Finally, far from the data sources, the cloud provides the abstraction of unlimited resources in well-provisioned datacenters.

Traditional solutions focus on one particular dimension at a time. Hence, most of the solutions are built on the premise that data ingestion, management, and processing can be done in the cloud, without the use of edge and in-transit tiers. Several edge-based middleware solutions exist in the literature; however, they often lack a uniform programming model framework for resource management, data processing, and application servicing between edge and cloud [27], [28].

The basic idea of leveraging the computing continuum for crowd management is trying to consolidate the concepts of

sensing with a holistic perspective for tight coupling between experiments, observations, simulations and analytics over a large number of sensors, smartphones, cameras and actuators from the physical world such as barriers or signage. The data obtained through stationary sensors utilizing conventional sensing methods is replaced with data obtained from user-generated content on social media or smartphone applications [29]. This generates a substantial volume of data, integrating sensor data with the viewpoints and personal encounters of individuals.

### B. Related work

Motlagh et al. discussed a scenario of crowd surveillance using unmanned aerial vehicles (UAV) and face recognition. Rather than local video data processing, the task was offloaded to a remote node [30]. Similarly, Al-Sheary et al. have developed a crowd monitoring system using UAV. They used color segmentation to identify the pedestrians. Their method was able to identify the crowd accurately in case of Hajj, an annual Islamic pilgrimage to Mecca, Saudi Arabia [31]. Alotaibi et al. developed a deep Convolutional Neural Network (CNN) based on a crowd counting technique using Internet of Things [32]. Darsena et al. does mobility in the context of covid and points the lack of a comparative statistical performance evaluation (numerical and/or experimental) of such sensing techniques for each outlined indoor/outdoor scenarios [33].

Most of these works are application-specific and do not offer abstractions for reusable services in a generic-purpose system. Recent works in crowd simulation demonstrate that systems can capture and simulate many complex and subtle crowd interactions in varied scenarios, while having the ability to generalize unseen situations and generate consistent behaviors [34]. Building on these results, our strategy for crowd management across the continuum aims for a general approach with little assumptions on both the data and resources capabilities while offering reusable services for contextualizing raw data and learn new models.

## IV. MODELING CROWD MANAGEMENT SCENARIOS ACROSS THE COMPUTING CONTINUUM

Resolving crowd congestion in real time requires continuously collecting data on the current condition of the environment and adjusting the movement of crowds accordingly. This process is akin to loop behavior. For example, applications have the ability to manipulate the movement of users by managing tasks like opening and closing doors to alter routes within a station, or toggling the ceiling lights of hallways in emergency scenarios. This control over speed and direction is achieved through these observe-and-act actions [35].

Our focus is on situations where a significant number of sensors and actuators can be utilized for activities that have a major impact on the public. These activities require the exchange of information between users and can be facilitated by the edge-cloud infrastructure. By using the infrastructure, data fusion algorithms can be implemented on the gathered

information. Dynamic and mobile sensing serves as a versatile platform that can replace fixed sensing infrastructure to support a wide range of applications, including smart city applications, safety measures, and environmental monitoring.

### A. Behaviour model

We introduce the classification of behavioral principle of crowd model defined by Hoogendoorn et al. [36]. The crowd factors were divided into three distinct levels: the operational level, the tactical level, and the strategic level. The operating level focuses on micro-scale elements and specifics of each pass, such as the impact of obstructions or collisions between users. The tactical level involves determining the specific path chosen to reach the target and the specific staging stations that people will pass through. At the strategic level, macro-scale aspects are addressed, including the choice of destination, the number of people who ultimately relocated, and the time it took to reach the destination.

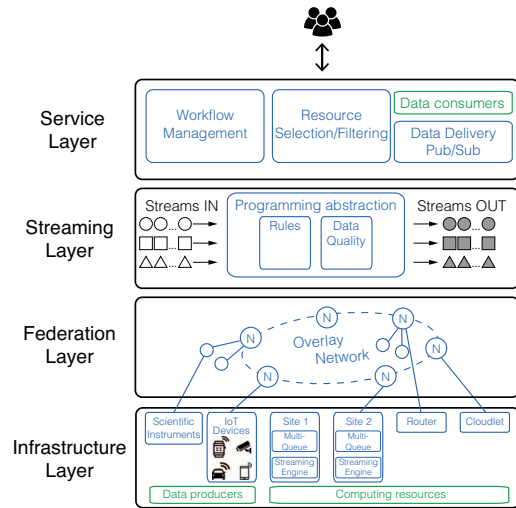


Fig. 2. Architecture of the unified framework (extracted from [8]). Each layer exposes operators provided by the building blocks and enabling technologies, to enables data-driven workflows across the computing continuum.

### B. System model

A schematic overview of the system model is presented in Figure 2 and is described below.

**Data collection** (Infrastructure and Federation layers), with the help of an expert group to maintain a broad participant base and verify data usefulness.

**Communication medium** (Infrastructure layer), which could be 3G/4G/GSM, WiFi or Bluetooth depending on the required range of transmission.

**Data aggregation/fusion** (Streaming layers), which receives sensor node data, pre-processes it, then transfers it to another node/base station depending on a decision criterion.

**Data storage and classification** (Service layer), which combines human and machine intelligence to extract knowledge from data.

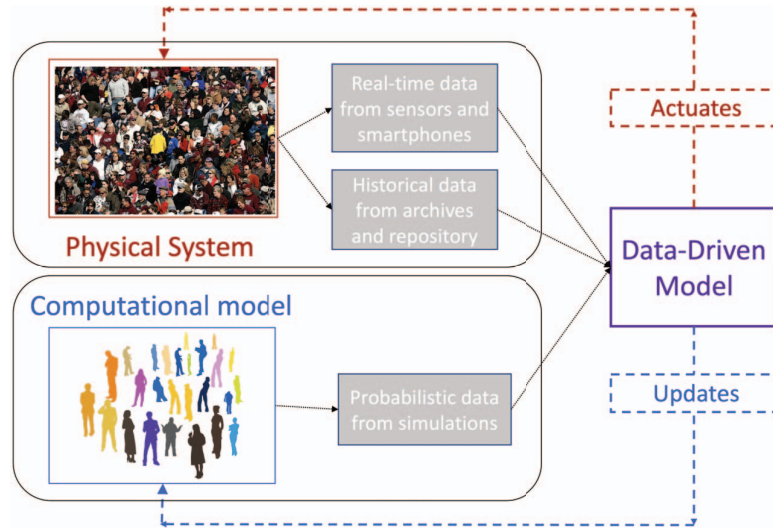


Fig. 3. The ideas of digital twins focus on automatically controlling the state of data-driven and computational models by comparing the current state, derived from historical and real-time data, with the ideal or desired state gained from simulation.

### C. Control and optimization model

As previously stated, crowd dynamics management techniques exhibit loop behavior. Hence, in order to depict the collective behavior of applications in a single mathematical framework, it is necessary to incorporate each activity involved in the formation of the loop behavior into the same model in a suitable manner. Therefore, we utilize feedback control theory to incorporate state variables (known information), decision variables (variables to be managed), external events (new information and uncertainty), transitions (changes in state variables), and objective functions (metrics for performance) [37]. In this way, feedback control theory is well-suited for creating the comprehensive behavioral model of crowd dynamics management applications. Figure 3 describes a simplified feedback architecture for simulating the future state of a crowd management scenario based on the fusion of historical and real-time data using digital twin principles.

## V. CROWDMESH: COLLABORATIVE SERVICES FOR CROWD MANAGEMENT SYSTEMS

### A. Vision

The proposed platform and its associated services seek to transform current research practices through using curated and new datasets associated with crowd monitoring and management. The system leverages and improves upon existing advancements in data and compute ecosystems to efficiently access various data sources (Zigbee, Bluetooth, Wi-Fi, and cellular), sanitize collected data for reuse, and integrate them with crowd management models to establish an effective structure for cataloging, managing, and sharing data.

The platform aims to improve the methodology and study of science and engineering in crowd safety by providing a

comprehensive framework for crowd management and monitoring. In addition, it has the capacity to facilitate data-driven analytics on general infrastructures instead of constructing specialized systems for each individual event. This is achieved by enabling improved real-time responses and the management of both mobile and fixed sensors for opportunistic and participative sensing.

### B. Design goals

We define a set of design goals, and use them as guidelines for characterizing and comparing to state-of-the-art solutions and production systems in future works.

**Edge-Cloud operational tools.** End-to-end data processing is generally performed via data analysis pipelines and workflows. For this reason, many research and engineering communities depend on services to create scalable scientific workflows and integrate data, computation, analysis, and monitoring capabilities. Robust tools face operational issues including offloading, cost benefit analysis, energy management, mobility management, network connectivity, cloud selection, and activity detection.

**Privacy, Security and Integrity.** Ensuring the integrity, privacy, and security of data and code is of critical significance in this platform. Edge computing offers to process personal information in a distributed fashion, in close proximity to the user in order to temper some of the privacy risks. However, it also introduces new security vulnerabilities and privacy concerns, especially when these technologies are designed and utilized on a massive scale. In order to instill trust and assurance among all parties involved, it is imperative to address these concerns in order to facilitate the secure and appropriate exchange of data and code.

**Integration, Interoperability and Reusability.** Emerging applications need to handle data and software from various

sources that may differ in terms of type, syntax, and semantics of the data, data quality, software platform and interfaces. Creating resilient, scalable, and adaptable solutions that enable seamless communication across these intrinsically diverse and distinct data and software components is a key requirement.

**Analytics and Visualization.** Advanced data analytics and visualization techniques can be used to synthesize and gain insight from massive, dynamic and even conflicting data. Converting data into new knowledge can be achieved through the utilization of sophisticated data analysis tools and interactive visual interfaces that encourage collaboration. In this way, researchers will be able to detect the expected and discover the unexpected, uncovering hidden associations within vast data sets and making new scientific breakthroughs.

**Energy and Mobility management:** Mobile sensors and devices needs energy in the form of storage, processing capacity, and battery life time. This energy is limited and needs to be managed in an optimized way. Based on the storage and processing, the decision needs to be taken whether to offload the task to the cloud or not. In case of local processing, mobile energy prediction is required without sacrificing the ability for devices to roam in different networks.

### C. Services

The overall objective of the CROWDMESH platform is to investigate how an ecosystem that integrates scientific data sources, a knowledge base for urgent science models and an understanding of these by interdisciplinary research communities can accelerate crowd management research enabled by continuum computing platforms. The key elements of the envisioned ecosystem (as outlined in Figure 4) are listed as follows:

**Distributed Computing Continuum.** There is a need for data access, transfer, streaming, and sharing services that can seamlessly support the entire range of computing devices and systems, from small-scale edge devices, sensors, and IoT devices to large-scale clouds and supercomputers. An effective approach to achieve this goal would involve relocating the computation process to the specific location of the relevant data, or alternatively, extracting the generated data, applying filters or transformations, and proactively transferring them to locations where they can be evaluated either offline or in real-time. The proper set of abstractions must be provided to enable applications to specify their resource requirements and execute efficiently in an environment with shared resources.

**Data Curation, Provenance and Findability.** Significant efforts are required to curate datasets, which involve tasks such as cleaning, enhancing, and standardizing the data. Additionally, it is necessary to document the context and semantics associated with the data, as well as the analyses conducted on the data. These efforts aim to enhance the value of the datasets for scientists engaged in data exploration and analysis. Research in automated data tagging, metadata generation and registration, semantic representation methods, ontologies, and provenance of data and software is crucial

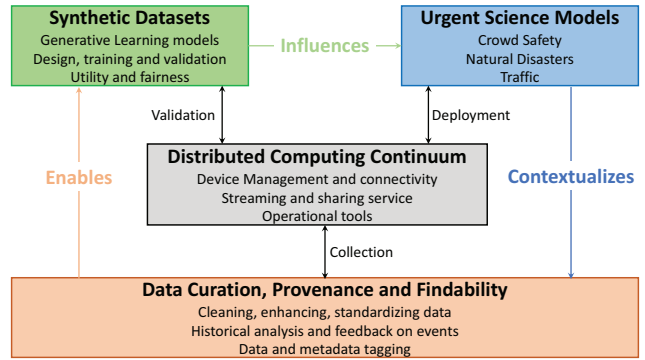


Fig. 4. CROWDMESH services interactions

for enabling domain-scientists to discover and collaboratively explore all pertinent data.

**Synthetic Datasets.** The objective of this module is to generate synthetic yet realistic crowd management data for model design, training, and validation while maintaining utility and fairness characteristics. Among the several generative learning models, Generative Adversarial Learning [38] appears out for its ability to produce realistic data and enhance them with context-awareness and privacy characteristics.

## VI. CONCLUSION

People deal with crowds or big gatherings on a regular basis at a variety of locations, including entertainment venues, airports, hospitals, and transit systems. Crowd management for large-scale planned events is essential, and depends on behavioural and mathematical modelling to understand how crowds move in different scenarios through experiments.

In this work, we propose to build a set of collaborative and services, the CROWDMESH platform, that will enable the collection, processing, and sharing of crowd safety datasets constructed over the Edge-Cloud Continuum.

In the future, we want to investigate the proposed platform by identifying qualitative enhancements in the ease of building crowd management applications, and quantitatively assessing implementation and operations, such as datasets generation, collection, and application performance.

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