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S. J. Clement, David McKee, Jie Xu

Institutions: University of Leeds

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Service-Oriented Reference Architecture for Smart Cities

S. J. Clement, D. W. McKee, Jie Xu
School of Computing University of Leeds
Leeds, UK
{s.j.clement, d.w.mckee, J.Xu}@leeds.ac.uk

***Abstract*—The trend towards turning existing cities into smart cities is growing. Facilitated by advances in computing such as Cloud services and Internet of Things (IoT), smart cities propose to bring integrated, autonomous systems together to improve quality of life for their inhabitants. Systems such as autonomous vehicles, smart grids and intelligent traffic management are in the initial stages of development. However, as of yet there, is no holistic architecture on which to integrate these systems into a smart city. Additionally, the existing systems and infrastructure of cities is extensive and critical to their operation. We cannot simply replace these systems with smarter versions, instead the system intelligence must augment the existing systems. In this paper we propose a service oriented reference architecture for smart cities which can tackle these problems and identify some related open research questions. The abstract architecture encapsulates the way in which different aspects of the service oriented approach span through the layers of existing city infrastructure. Additionally, the extensible provision of services by individual systems allows for the organic growth of the smart city as required.**

***Index Terms*—Cloud, SOA, Services, Smart-City, Architecture, Autonomous-Systems**

I. Introduction

Smart cities is the new goal for integrated System of Systems (SoS) facilitated by developments in technologies spanning domains of autonomous vehicles, Internet of Things (IoT), smart manufacturing, healthcare, defence and aerospace, as well as the financial industry. There also remains an ongoing concerted effort to develop techniques to handle the explosion of Big Data streams [2], [3] that must be processed in a timely manner [4]. However, there remains no formal definition for how Smart Cities are going to evolve from current existing infrastructure, both physical and digital. This paper presents the current trends in smart cities research and highlights some of the key challenges that remain. We also present a reference architecture for developing smart cities.

The computational infrastructure for a smart city will be based on a combination of distributed computing paradigms, enabling the use of: low power IoT devices [5], Cloud computing virtualisation [6], [7], and the use of localised processing with Edge computing [8]. This will combine the IoT's objective of integrating components and devices as services [9] with the computational power of Cloud and HPC. Smart cities by their very nature must also consist of smart networks that are dependable and fault tolerant. This requires continued work in software defined networks (SDNs), specifically in tandem with scheduling and managing Micro-Service (μS) execution across computational infrastructure.

Furthermore IoT for smart cities requires context-aware computation allowing intelligence to be incorporated and augment the System of Systems (SoS) with a *model of reality* [1], [5]. This automated integration will require a shared *model of reality* that aggregates the different perspectives on reality as seen by the different domains and systems. This *model of reality* can then be used with the Internet of Simulation (IoS) to facilitate decision support where traditional machine learning methods are inadequate [10]. Furthermore the existing standards for service-orientation and system integration are not sufficient, as they do not capture the additional detail that would be required, and not uniform, meaning that they are not currently integrable [11]. The successful integration of all these systems and devices will allow IoT to grow to become the Internet of Anything IoA and Everything (IoE) [12].

In parallel to the evolution of smart cities is the industrial revolution of Industry 4.0 which is integrating and automating the manufacturing value chain [13], [14]. This is driven by the adoption of IoT devices in the manufacturing process, known as Industrial IoT [15], as well as data collection from autonomous systems both within factories and the marketplace. This therefore facilitates the creation of *smart factories* which are able to adapt to changing market demands [16] and have a level of self-awareness allowing a level of self-optimisation of daily operations [17].

Another emerging area of research is that of cooperative robotics which have been enhanced with the computational power of Cloud computing [18]. This domain spans both smart cities as well as smart manufacturing whereby the Cloud is used to facilitate robot interaction [18]–[20] and provide services to those robots [21]–[23], at the same time as allowing the robots to provide services including assembly-line operations and maintenance within a city [24].

This paper therefore presents an overview of current research in smart cities before focussing on the architectural challenges that have yet to be solved. In Section II current city architecture is considered as the starting point from which a smart city must evolve without interfering with day-to-day operations. Subsequently we present a smart cities reference architecture defining the relationship between the various Service Oriented Architectures (SOAs) from each domain to be integrated. We then summarise in Section IV the research

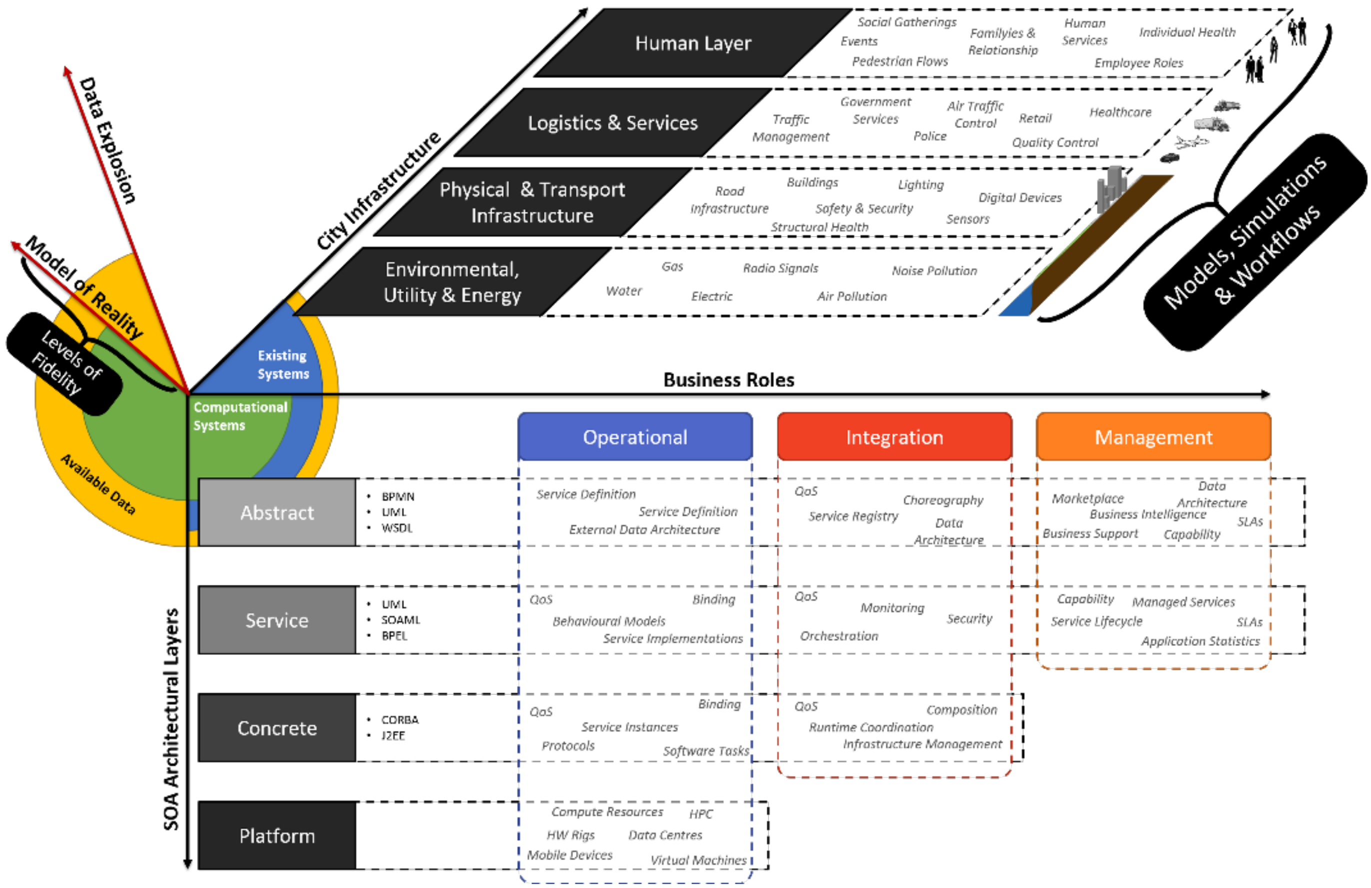

Fig. 1. A reference architecture for smart cities incorporating the viewpoints of the traditional city infrastructure, services and business roles. [1]

directions that require significant attention in order for smart cities to become a reality.

II. Re-factoring City Architecture

The structure of cities can be defined in terms of urban artefacts, their geographical location and area, as well as their ownership [25]. As shown in figure 1, the city and its infrastructure already exist as complex governmental, economic and social systems that has continually evolved over time. These span domains including utilities, communications, government, transport, emergency services and retail. Often these systems are operate independently or at best in a producer-consumer model; very little information is shared between them and there is almost no cooperation. For cities to continue to develop towards the smart city vision, these systems will require more automation and intelligence and more interaction.

Some of these systems are cyber-physical and already facilitate some level of integration with IoT. However, the majority of the city systems are purely physical or in the case of the city population are human elements. The challenge of creating a smart city involves re-factoring the city in a non-intrusive fashion, not just existing software services [26]. As city systems become *smarter* and as they are integrated there will also be emergent behaviours and properties to be managed. The concept of T-changes will provide a strong basis for ensuring that all systems evolve in a manner that ensures compatibility and from the populations perspective should be seamless, for example allowing for new IoT-enabled systems and methods to replace legacy systems as a vertical change [27].

Finally as shown in Figure 1 both SOAs and cities in general have a layered nature. By building on the core strengths of service-orientation, particularly loose-coupling, it is possible to iteratively service-orient a city enhancing individual elements with digital functionality and exposing them as services within the relevant domain, such as the electrical grid. Subsequently systems that already utilise those facilities will be able to be augmented with additional intelligence now available to them and then themselves be exposed as services. In the next section a architecture for smart cities is proposed.

III. Smart-Cities Architecture

Cities are already highly complex SoS, the emerging trend in urban planning is towards adding *smart* systems to the urban environment with the goal of improving the quality of life for inhabitants. There is no single, agreed upon definition for what constitutes a smart city [28] though the one characteristic that is common among all definitions is the heavy reliance on a computing infrastructure. Caragliu et al. [29] define a smart city as a synthesis of hard infrastructure (or physical capital) with computing and communication infrastructure as well as social capital. Batty et al. [30] provide a more sociological viewpoint on the smart city, emphasising its human aspects and the ability for its systems to improve the quality of life of its residents. Another definition of the smart cities identifies six characteristics in order to rank a city's *smartness*. These are: economy, mobility, environment, people, living and governance [31]. Others rely on a more concrete definition, referencing the automation of city infrastructure through large-scale computing.

Computing is entering the era of massive-scale distributed systems enabling automated cyber-physical systems such as those expected in smart cities. A primary component of these systems is the IoT [9] which makes available a network for sensing and measuring city infrastructure using low-cost devices. This allows for extensive data collection resulting in large, comprehensive datasets [32], [33]. A combination of Cloud [34], Edge [35] and Fog [36] computing as well as high performance computing (HPC) [37] provides the infrastructure to process the data generated by the devices [38] and uses data this to provide intelligence to systems [39]. This is facilitated by a growth in the network infrastructure, especially in wireless technologies such as 5G and LTE [40].

Given this growth in computing infrastructure the potential systems aggregated within a city are numerous. Zanella et al. [41] identify a number of domains in which IoT and *smart* systems can provide beneficial services for the city. These include: the structural health of buildings; waste, air quality and noise management; traffic reduction; energy consumption monitoring; parking; lighting; and building automation. Intelligent systems are also being considered for the underlying infrastructure of the city, for example, moving energy generation, storage and distribution towards a managed, intelligent, distributed power grid [42], [43].

Mobile robotic platforms are also of interest in the smart city, the most prominent being driverless vehicles [44], [45], as well as the emerging domain of autonomous passenger-carrying aerial vehicles [46]. Though often independent systems, the possibility of interconnecting vehicles together into an *Internet of Vehicles* or a *Vehicular Cloud* [47] could allow for the sharing of sensor data and even allow the city systems to perform holistic traffic management. Repair, maintenance and inspection could also be performed using robotic platforms [48], [49].

Figure 1 captures many of the dimensions of the smart city [1] and forms the basis of our reference architecture. The traditional city architecture layers of environment, infrastructure, logistics and human elements are not expected to change within the smart city. Instead these systems already in place are augmented by a computing infrastructure based around SOA principals. In the smart city these computing elements and business roles are expected to traverse across several levels of city architecture from the utilities through to the service provisions.

Just as current cities are an evolution of independent but interacting systems, the smart city must evolve from a traditional

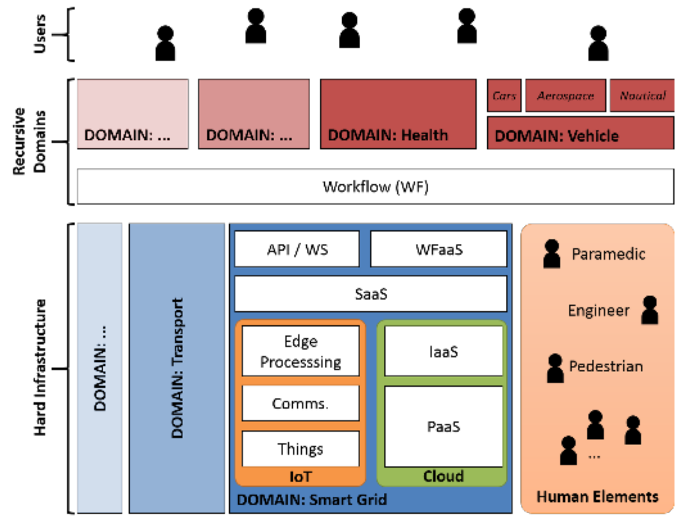

Fig. 2. Smart IoT-based systems providing infrastructure in specific domains interface with cloud computing and provide services for use by the city.

city. The intelligence and automation expected must grow with the city and build on other systems. For this reason, we expect the computational systems in the city to each provide a set of services that may be utilised by other systems. The model of reality included in figure 1 is expected to be a basis of the intelligence of the city, utilising simulation so that system can predict future outcomes and react accordingly. As this simulation data is added to the data being generated by IoT systems, we expect a data explosion, where it will be vital to process data selectively in order to deal with the expected data flow [1].

A. Smart City Services

Cities present particular challenges given the prospect of increased automation. For one thing, even without considering the social aspects, cities are massive immobile collections of systems, business, services and infrastructure. Often these collections have evolved over many years, with the city growing from a small settlement to a metropolitan hub. The aim of the smart city trend is to continue this growth using automation and computing systems. However this increase in automation and intelligence must be incorporated into the legacy physical infrastructure not replace it. An expressly new smart city could be constructed given enough investment and capital, however, it is more likely that existing cities will have ot adopt these systems. Crucially, this means that the existing systems cannot cease to function and any increase in automation must be an incremental augmentation on the existing infrastructure. Additionally, the scale and complexity of some of the system being proposed (e.g. driverless vehicles, smart grid, etc.) requires some existing smart infrastructure in place before it can be deployed. Therefore, moving towards a *smarter* city requires the continual development of infrastructure services to facilitate new systems [50]. Many system may require similar functionality, so an additional benefit to the use of service is the reuse of existing functionality for new purposes; reducing the cost of development.

With each connected system in the city providing services and micro-services in the SOA sense [51], increasingly complex systems can be created which utilise the existing infrastructure. Business models around the use of services, provided both by private and public enterprise could result in a service economy being the cornerstone further city developments [52]. Workflows can be used to compose multiple services, possibly provided by different systems, together into a single process which can be executed [53]. These workflows could result in complex behaviour such as reacting to triggers or controlling data flows [54], [55] and allow the system to scale as demand increases. One such example of a workflow might be a collection of simulations that model the behaviour of some system and provide decision support or *what-if* analysis [10].

Figure 2 shows a detailed view of the layers of the reference architecture demonstrating this. Here independent systems in separate domains can build upon each other by utilising services provided. As an example here, a smart grid is utilising IoT devices and Software as a Service (SaaS) on a cloud platform with Infrastructure as a Service (IaaS) and Platform as a Service (PaaS). The *things* generate data that is processed at the edge of the cloud before being handled by the SaaS. Utilising the services provided, workflows can be constructed for use internally or presented as another service (i.e. Workflow as a Service (WFaaS)). These services and an API can be exposed to the wider city systems where they can be combined into workflows used by other hard infrastructure systems such as transport or smaller application domains. As these services are utilised in more safety critical systems both service and workflow level Quality of Service (QoS) will become vital [56], [57].

IV. Conclusion and Further Work

The interest in smart cities is growing and the need for ever more complex and intelligent systems is fuelling this growth. The next generation of IoT or connected systems being proposed are, at the moment, independent. These systems take time to build and therefore cannot instantly replace the existing infrastructure. They also require many similar functions. In this paper we proposed a reference architecture for the smart city based around SOA concepts; integrating IoT, Cloud and Edge technologies with existing city infrastructure. We proposed a service-oriented approach tp the development of new systems which can augment the existing systems in the city at all levels (figure 1). A detailed view of one such example was provided using an abstract smart-grid as a case study.

The benefits of the service-oriented approach are the ability for services to be continually evolved and added organically to the smart city. These services do not necessarily need to be only based on infrastructure and could be provided by for-profit autonomous systems as another revenue stream. For example, autonomous vehicles could provide local mapping data as a service to be utilised by other robotics platforms. There could also be multiple suppliers of robotic maintenance platforms being provided as services which may in turn utilise Cloud services for planning and coordination.

Though the presented reference architecture should allow systems to scale to the sizes required by a city, there are still many open research problems if the service-oriented approach is adopted. As systems move towards automation, there is a point at which the human components of the system must interact with machines. Therefore, there is need to understand human to machine service attributes such as service definitions and QoS. Additionally, redundancy and security of these systems will be vital to the stable operation of the smart city. If there is an interdependency between multiple systems then without some form of redundancy, whether explicit of automated, the whole city may become vulnerable to a disruption of a single system. Additionally, the network and computing infrastructure of the city becomes an even more vital component. Given the number of devices and services operating in a full implementation of a smart city there must be an ubiquitous, high-speed, wireless network supporting a large computing infrastructure. Both the network and computing infrastructure needs to be able to transmit and process the massive amount of data being generated by the city [1]. There is potential for information of interest to be lost in the noise of many data streams due to the curse of dimensionality. Therefore intelligent, automated data analytic methods are required in addition to the physical platforms.

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