Towards the Internet of Cities: A Research Roadmap for Next-Generation Smart Cities

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ABSTRACT

In this paper we outline the long-term vision for an Internet of Cities Infrastructure, an interdisciplinary effort towards creating the scientific underpinnings for designing, developing, and managing next-generation smart city applications. Due to the large number of involved stakeholders and their possibly conflicting requirements, along with limited available knowledge and data, effective and efficient creation and subsequent operation of smart city applications is currently not possible. By holistically approaching the challenges of creating and operating such applications, we will create methodologies, frameworks, and approaches to enable the Internet of Cities, a global network of smart cities and their applications that securely and collaboratively work together to improve the quality of life of their citizens, as well as greatly improve cost and energy efficiency of city operation and infrastructure.

Keywords

Smart City; Internet of Cities; Smart City Infrastructure

1. INTRODUCTION

The recent advent of the Smart City paradigm has led to plethora of new research initiatives around the globe. It started with the IBM Smarter Planet Initiative[1], quickly followed by the MIT City Science program[2] and Trinity's Smart & Sustainable Cities initiative[3], all addressing vital aspects of this vibrant field. However, most of these initiatives focus on a closed set of topics, which leads to a rather narrow, presence-centric view on the domain. In order to enable a truly holistic interdisciplinary and future proof approach, it is vital to address the domain of smart cities on a higher level of abstraction.

[1]http://www.ibm.com/smarterplanet/us/en/
[2]http://cities.media.mit.edu/about/initiative
[3]https://www.tcd.ie/research/themes/smart-sustainable-cities/

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In this article we draw a map for a different path enabling a holistic interdisciplinary view overcoming not only cognitive compartmentalization but also paving the path for an Internet of Cities. We draw this map based on recent research experience, as well as lessons learned during URBEM[4], a smart city initiative focusing on the city of Vienna[4]. URBEM focuses on enabling the path to a sustainable, supply-secure, affordable and livable smart city by providing holistic interdisciplinary views on the city based on real world scenarios. The city of Vienna itself poses an optimal research subject, being not only consecutively awarded one of the most livable cities in the world by Mercer and the Economist, but also being a pioneer of the smart city movement. Combined this provides us with an excellent foundation for outlining a research roadmap for the next generation of smart cities.

2. SMART CITY REALITY CHECK

Cities are ever-evolving, complex cyber physical systems of systems covering a magnitude of different areas. The initial concept of a smart city started with cities utilizing communication technologies to deliver services to their citizens and evolved to using information technology to be smarter and more efficient about the utilization of their resources. Initially, resources were limited to fields that were tangible, mainly energy and mobility systems. In recent years, however, not only what can be done with information technology has changed significantly, but also the resources and areas addressable by a smart city have broadened significantly. They now cover areas like smart buildings, smart traffic systems and roads, autonomous driving, energy hubs, electric car utilization, water/waste and pollution management as well as concepts like urban farming. This not only demonstrates the diversity of relevant, previously untapped areas, but also that limiting research to specific topics poses the risk of being unable to cover these novel directions.

Previous research [6] presents a smarter cities technology innovation framework, which introduces a high level closed loop capable of tackling several of the challenges important for smart cities. Even though the loop itself provides a reasonable reactive feedback mechanism covering the most important abstract concepts, we refine it to specifically outline several real world factors. Specifically we introduce the concept of a Multi-domain Expert Network to cover the ever-changing novel areas, as well as the explicit notion of industry/governance stakeholders and citizens as the active

[4]http://urbem.tuwien.ac.at/

elements impacting and influencing the system city. Figure 1 introduces this improved, ideal Smart City loop. The city itself emits massive amounts of data from a plethora of sources including IoT networks, documents and citizens. This diverse static and dynamic data needs to be stored and managed, to provide the fundament for the next step. The multi-domain expert network is a dynamic interaction of different domain experts, providing analytics and models about important aspects of the city, enabling a holistic view. This holistic view provides the decision support relevant for industry and governance stakeholders as well as citizens to impact and influence the city. We consider this loop a vital baseline for realizing a holistic, future proof and evolutionary smart city.

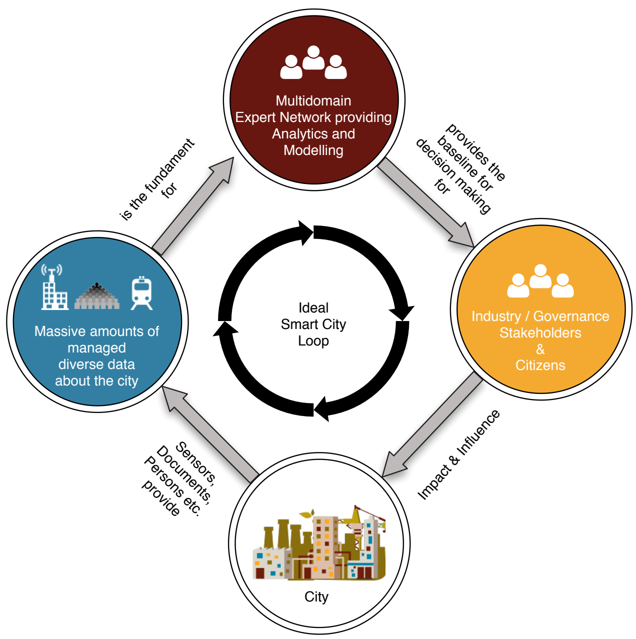

Figure 1: An Ideal Smart City Loop.

The effects of this loop not only enable cities on their path to become smart, they also open up a wealth of new opportunities to discover uncharted territory and utilize unexpected synergy effects. The novel connectedness of information, domain experts and stakeholders allows unanticipated forms of interaction and exchange. Experts gain new insights using previously unattainable data, enabling them to understand and grasp the city in unimagined ways. This new understanding however is not just limited to their domain, but allows them to suddenly see connections to other domains in which their models and ideas can flourish. This open connectivity of experts, stakeholders and citizens enables an open exchange beyond domain borders, empowering a truly interdisciplinary approach without limits. This turns the city into an organic, dynamic and adaptive network of capabilities shedding itself from the dangers of compartmentalization. In order for a smart city to truly thrive, it is of essential importance that it becomes an interconnected entity not limited by geographical borders. What shows great potential in an intra city context becomes truly limitless in an inter city universe. Smart Cities exchanging their capabilities in an organic elastic manner, being able to address whatever challenge and opportunity they face with the expertise, data and knowledge of a global network will enable cities to become the global smart haven of innovation they can be.

3. RESEARCH CHALLENGES

To enable the previously introduced Ideal Smart City Loop we need to create the scientific underpinnings for future Internet of Cities Infrastructures (IoCI). To ensure this, a comprehensive set of methodologies, models, and tools for design, development, management, and evolution of next-generation smart city applications is needed. Such work needs to follow a first principles approach to tackle the grand challenges of future smart cities through close integration of researchers and stakeholders from different domains to create an open, holistic, and interdisciplinary research platform. Research in the IoCI needs to be aligned along three main pillars, as shown in Figure 2: *methodology*, *modeling*, and *middleware*.

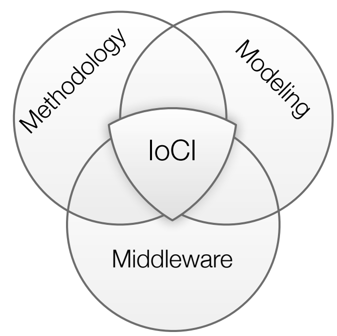

Figure 2: The three main pillars of the IoCI and their relationships.

3.1 Modeling

Current efforts towards creating smart city applications face significant challenges due to a lack of available real-world infrastructure to create and verify applications in terms of functionality, non-functional properties, or regulatory requirements. Current solutions either rely on small-scale testbeds [7] or proprietary, custom-designed simulations to emulate real-world environments (e.g., Anylogic[5]). However, such solutions are far from ideal, as changes in real-world environments need to be manually replicated in lab testbeds or simulations, and the migration of applications from test infrastructure to real-world deployments must be carefully planned and manually carried out for each new application version. Furthermore, smart city applications under development partially rely on data that is already available in the physical environment, and hence would benefit from using real-world data instead of simulations if possible.

Within the IoCI, this challenge will be addressed by embracing the need for modeling and simulating parts of an application's environment, as well as integrating real-world data from the physical environment at different stages during its lifecycle at the core of our research efforts. We will create the scientific basis for an open modeling environment that allows researchers and practitioners to create dynamic, tailored environment simulations that seamlessly

[5]http://www.anylogic.com

integrate real-world data into simulations. Furthermore, our model will allow for elastic, hybrid simulations that allow for transparent adjustment between operating within simulated and real-world infrastructure for different parts of applications. Such hybrid simulations will enable transparent and repeatable validation of application functionality against real-world infrastructure with as little risk as possible. Furthermore, simulation models can operate in parallel to real-world infrastructure to verify and improve simulated environments for future use. By creating an open modeling infrastructure, researchers and vendors will be able to integrate their simulation and modeling tools to verify their approaches and tools against an extensive and proven catalog of validation scenarios. Furthermore, the modeling environment will be deeply integrated in to the IoCI methodology.

3.2 Methodology

The second major focus of the IoCI will be on devising a comprehensive methodology to assist stakeholders in designing, developing, and evolving reusable and maintainable smart city applications. We will base our research on MADCAT [5], an iterative software engineering methodology for cloud applications with an explicit focus on artifact traceability, reuse, and improved stakeholder communication. Building on efforts of closely integrating stakeholders from different domains into the process of creating smart city applications (e.g., [9]), we will create a holistic methodology for engineering smart city applications that explicitly enables the design and development of reusable and independently maintainable application components in close cooperation with expert stakeholders. The methodology will allow for a capability-oriented approach for capturing and packaging required functionality in distinct, reusable *units* that can be shared and integrated in multiple applications. Such units define their expected environment via clearly specified interfaces, allowing for the seamless integration of modeling and simulation environments, as well as real-world infrastructure, providing a clear abstraction between the system under development and its execution environments, such as testing, staging, and production, each with differing degrees of simulated environment assets.

3.3 Middleware

To reliably operate and manage future smart city applications, the third pillar of the IoCI is a comprehensive middleware toolset that will allow operators to seamlessly deploy and execute complex applications in an autonomic, repeatable, and observable way. In order to do so, we will separate the middleware tools in three different layers that build upon each other. On the lowest layer (*infrastructure layer*), building the foundation, the middleware needs to manage and monitor the available smart city infrastructure, consisting of stand-alone servers, cloud environments and edge infrastructures. Due to the huge heterogeneity in terms of e.g., provided management interfaces, provisioning, maintaining and operating smart city infrastructures is a challenging task. Therefore, in the infrastructure layer we need a comprehensive toolset that allows operators to expose, manage, and monitor the underlying infrastructure in an uniform and extensible way. Based on the infrastructure layer, the middleware has to provide a *runtime layer* for smart city applications that allows and supports the following key aspects. First, the runtime layer needs to support elastic application deployment considering the targeted infrastructure, expected number of users and required data volume. Second, the runtime layer has to provide a runtime environment for executing smart city applications that allows to seamlessly scale applications across various infrastructures. Third, to deal with the magnitude of data formats and immense data volume the runtime layer has to provide efficient and scalable data management, consisting of data mediation, transformation, processing and storage. Finally, since various smart city applications can be executed simultaneously, the runtime layer needs to provide both adaptable data and application isolation levels, that allow multiple tenants to operate simultaneously without interfering each other. The final layer (*integration layer*) of our middleware toolset is then responsible for integrating novel smart city application development methodologies, models, and simulations. The integration layer supports different application development and deployment stages (e.g., simulation, testing, production, and rollout), which provides operators and developers different application runtime environments by accessing either simulated or real infrastructures. Additionally, the integration layer exposes interfaces to retrieve data that is collected during the execution of applications and the management of the underlying infrastructure, in order to e.g., feed simulations, extract usage patterns, or generate models.

4. TOWARDS THE INTERNET OF CITIES

The challenges mentioned above must be addressed in order to enable the Smart City Loop and to pave the way for an Internet of Cities. In this section, we outline four central components of future Internet of Cities infrastructures, based on a holistic analysis of the three pillars methodology, modeling, and middleware.

4.1 Urban-Scale Data Management

Urban-scale data management addresses the emerging challenges of managing the magnitude of diverse data emitted by the city. The advent of pervasive sensor platforms and the rise of the Internet of Things have led to a plethora of novel devices and entities emitting data in and about the city. Millions of new sensors and devices in buildings, grids, and transportation systems, but also around the citizens of the city in the form of smartphones, navigation systems or fitness trackers are flooding the ether. They all might hold viable information that could, in the right form accessed by the right persons, hold vital information for the city. Despite these new high volume diverse and dynamic data providers there is also a multitude of static data about the city stored in a variety of different formats and legacy systems. This not only calls for novel storage mechanisms that can handle this huge amount of diverse data, but also for the ability to link this data together in order to create the foundation for a holistic view based on the methodology discussed above. Even more important than the ability to hold this data is the ability to enable an efficient and effective management middleware that can retrieve the desired information in an approachable form. Beyond this, urban-scale data management calls for new ways to think about the collected data itself, such as how to use data from other cities in models and analytics (e.g., [3, 2]), seamlessly integrated with simulated data extracted from environment models. If, for example, city A holds relevant data about traffic patterns, which transformation, cleansing, and enrichment steps are necessary to use this data in city B? Also, how do we draw attention to data that might hold important insights but is currently invisible in the big data haystack? It is crucial to re-evaluate the way we approach reasoning about data and to consider it in an intrinsically interconnected way [8, 1] in order to enable data management on an urban scale.

4.2 Multi-Domain Expert Networks

An important factor to enable future proof cities is the capability to incorporate novel areas of interest and to react to new challenges. Given the highly dynamic fashion of the complex adaptive system city this is only possible by enabling a system of elastic adaptation based on the methodology discussed above. One central element of this is the ability to add domain experts and connect them and their models in a dynamic, on demand fashion. This calls for novel interaction models to enable an organic workflow that respects the opportunities of urban-scale data management. Such mechanisms further need to closely integrate interdisciplinary, multi-domain analytics [10] to process and reason on massive amounts of diverse data, handle heterogeneous formats, and provide legacy system support to enable the dynamic interaction of domain experts. Also, the notion of expertise needs to adapt since solutions might be found in previously unimagined realms. Today's metropolises hold the power of millions of smart people all enabled by the newest technologies. In order for a city to truly become smart it needs to create mechanisms that enable its citizens. This calls for citizen engagement and participation mechanisms as well as novel rewarding tools to incorporate them as a vital element of said expert networks.

4.3 Urban-Scale Elastic Infrastructure

To enable the aforementioned capabilities and to provide the fundament for an Internet of Cities we need a middleware fabric that can efficiently and effectively tackle these challenges. This calls for organic elastic infrastructures providing the building blocks for a truly dynamic network of capabilities. Such an infrastructure needs to be able to support the aspects of IoT provisioning and large scale deployment (e.g., [11, 4]) as well as IoT management and governance. It needs to be able to enable software-defined systems as well as to provide the resources for intensive computations. It is crucial to provide these resources where and when they are needed in a truly global demand-specific manner. In this sense elasticity does not only mean adding or removing resources, it should mean that an infrastructure can "elastically" respond to changes. These changes span configurations, deployment topologies, as well as requirements and are the foundation for continuous evolution of smart city applications. Beyond this, these infrastructures need to support the emerging structures of smart cities, ranging from smart grids and smart meters to dynamic traffic and transport systems and many more.

4.4 From Smart City to the Internet of Cities

In order to truly enable smart cities they must not to be limited by geographical borders. The next generation of smart cities needs to be an interconnected network of capabilities not only exchanging vital data but also learning from each other. These capabilities need to be able to move freely within clouds towards the cities that need them when they need them. This not only calls for means of easy connectivity, but also for simple and reliable exchange standards that respect concerns (e.g., [9]) like security, compliance, and costs. This however is not just about applying known techniques on existing entities, it is about enabling a new notion of dynamic interconnectedness leading towards an Internet of capabilities. These capabilities would reach beyond simple consumable services, but be truly self-sufficient containers that gain the ability not only to freely move between cities, but also to organize themselves in an efficient manner.

5. CONCLUSION

In order to design, develop, and manage next-generation smart city applications, in this paper we propose a long-term vision for an Internet of Cities Infrastructure. The Internet of Cities Infrastructure is an interdisciplinary effort to create the scientific underpinnings that are needed for building and operating applications for future smart cities. Currently, effective and efficient development and subsequent operation of smart city applications is not possible, due to the increasing number of involved stakeholders, conflicting requirements, fragmented available knowledge, and an abundance of sensory and environmental data. In order to address the identified challenges, we provide a holistic approach to implement an ideal smart city loop by creating methodologies, frameworks, and approaches that will form the basis of an Internet of Cities. This Internet of Cities establishes a global network of smart cities that securely collaborate in order to improve cost and energy efficiency of city operation and infrastructure, as well as enhance the quality of life of its citizens.

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