Towards the Live City – Paving the Way to Real-time Urbanism

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***Abstract*—In contrast to projections, which stated that the wide-spread distribution of high-speed Internet connections would render geographical distance irrelevant, cities have recently gained importance in academic research. Yet, real-time monitoring of urban processes is widely unexplored. We present the concept of a *Live City*, in which the city is regarded as an actuated near real-time control system creating a feedback loop between the citizens, environmental monitoring systems, the city management and ubiquitous information services. After clarifying the term 'live' – as opposed to common understanding of 'real-time' – we identify four main barriers towards the implementation of the *Live City*: methodological issues, technical/technological problems, lacking quantification of economic revenues, and finally privacy and legislative questions. In this paper, we discuss those challenges and point out potential future research pathways towards the realisation of a *Live City* – ranging from sensor network developments, real-time quality assurance and new user interface paradigms to world-wide legislation measures, a standardised urban operating system and the idea of a 'tuned' city.**

Keywords-live city; ubiquitous sensor networks; real-time city; urban services; real-time information services.

I. INTRODUCTION

Based on the fast rise of digital communication technologies [1], projections stated that the wide-spread distribution of high-speed internet connections will render geographical distance irrelevant [2],[3], and that cities are not more than mere artefacts of the industrial age [4]. As a side effect, cities were presumed to drastically decrease in importance as physical and social connections, and would play an increasingly ancillary role in socio-technical research.

In reality, the world developed completely differently – cities are back in the centre of research. In fact, a United Nations (UN) report, which has been released before the World Population Day in 2007, states that for the first time in history, more people now live in cities than rural areas [5]. Thus, cities in their multi-layered complexity in terms of social interactions, living space provision, infrastructure development and other crucial human factors of everyday life have re-gained importance in scientific research. This arises from the fact – amongst others – that major developments of scientific and technological innovation took place in the urban context [6],[7].

However, in research on urban areas, especially real-time monitoring of urban processes and target-oriented deployment of digital services, are still widely unexplored. These research fields have recently received a lot of attention due to the fast rise of inexpensive pervasive sensor technologies, which made ubiquitous sensing feasible and enrich research on cities with uncharted up-to-date information layers through connecting the physical to the virtual world, as shown in Fig. 1.

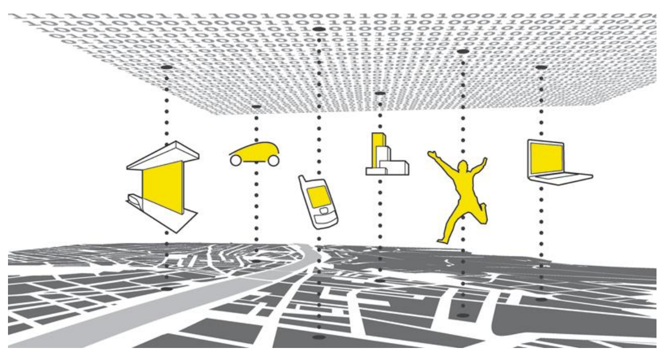

Figure 1. *Live City* – Connecting Physical and Virtual Worlds. [8]

One driver towards this vision is the diminishing digital divide on a global scale. While the digital divide within countries is still strongly affecting the degree of access to information and knowledge, the global digital divide is decreasing due to the fast rise of Information and Communications Technology (ICT) markets in China, India, South-East Asia, South America and Africa. Mobile phone penetration (mobile subscriptions per 100 inhabitants) has been at 76.2% of the world's population in 2010, where it is at 94.1% in the Americas and at 131.5% in Commonwealth of Independent States (CIS) [9]. The two fastest growing mobile phone markets China and India currently face a penetration rate of 64% and 70%, which makes a total number of 1.69 billion subscribers in those two countries alone.

This development builds the basis for the installation of urban real-time services. In a recent report on Digital Urban Renewal [10], the author states that major demand-side drivers for digital urban projects are the increasing focus on sustainability and emissions reduction, continued pressure on the urban transport infrastructure, and increasing pressures on citizen services due to demographic shifts, amongst others. On the supply side, several drivers have been identified including the ongoing evolution of the Internet as an underlying framework for services, new connectivity technologies, sensor networks and augmented reality.

All these comprehensive ideas supporting the paradigm of assessing, analysing and influencing urban environments in (near) real time (s. Section III for a disambiguation of 'real-time' and 'live') require a number of cognitive concepts, spatio-temporal algorithms and technological developments to be feasible.

However, we are still facing a lack of experience in assessing urban dynamics in real time. One reason is that ambient and continuous monitoring is an enormous challenge, and this is particularly true in the urban context, which poses very specific challenges. These comprise well-known technological questions, but also significant economical, social and political ones, which are rapidly gaining importance. This applies to a wide range of recent developments connected to live cities such as the Internet of things, pervasive sensing or ubiquitous urban monitoring.

Over the last few years, researchers and practitioners have also dealt with the apparent disconnect between the technical capabilities developed by researchers and technology firms in the broad context of smart cities and the actual adoption rates in cities. It can be argued that this follows the normal pattern of innovation adoption, and that in Geoffrey's Moore language the technologies have not yet "crossed the chasm" of adoption. However, a few patterns seem to emerge in urban environments, stressing the social and organisational nature innovation in addition to the technology aspects.

An important aspect to mention is that real-time and smart cities are nowadays often associated and developed under the umbrella of energy-related questions and applications, such as the Strategic Energy Technology initiative [11] by the European Commission. This paper tries to present a more holistic and comprehensive definition of a *Live City*. We see the city as a multi-layered construct containing multiple dimensions of social, technological and physical interconnections, i.e., as an actuated multi-dimensional conglomerate of heterogeneous processes, in which the citizens are the central component.

Towards the realisation of a *Live City*, we are currently experiencing a fast progressing technology development, which is not only moving ahead quickly, but which is moving ahead of society. This development can be compared with a stream moving at high speed, on which we are paddling to remain on the same spot or at least not to drift off too fast. The question, which we have to tackle in this regard, is where our goal for the future lies: down-stream, somewhere near our current spot, or even up-stream?

In this paper, we try to illustrate possible pathways to answering this multi-dimensional question. We incorporate societal, technical, political, privacy and economic issues into our rationale. We are well aware of shortcomings in terms of completeness and technical thoroughness. The paper shall be considered a first leap towards a *Live City* 'Installation Guide'.

This paper is organised as follows: after this introduction we illustrate a few examples on existing approaches towards *Live Cites* in Section II before giving a disambiguation of the term 'live' in Section III. Section IV discusses challenges in current research on the *Live City* and Section V illustrates potential future research avenues, before Section VI summarises conclusions from the paper.

II. State-of-the-art – Real-time and Live Cities

One of the first implementations of a 'real-time city' has been done by the MIT SENSEable City Lab [8]. This research group has considerably coined the term '**real-time city**', particularly through visualising the city as a real-time and pulsating entity. In further research initiatives, the SENSEable City Lab investigated human mobility patterns, the usage of pervasive sensors to assess urban dynamics, event-based anomaly detection in ICT infrastructures, and correlations between ICT usage and socio-cultural developments. The major shortcoming in this research is that no generic long-term goals are addressed apart from singular implementations in selected cities.

A new and innovative idea in the context of assessing urban dynamics in real time is the concept of **Living Labs**. According to [12], a Living Lab is a 'real-life test and experimentation environment where users and producers co-create innovations'. Living Labs are strongly driven by the European Commission, which characterises them as Public-Private-People Partnerships (PPPP) for user-driven open innovation. A Living Lab is basically composed of four main components: co-creation (co-design by users and producers), exploration (discovering emerging usages, behaviours and market opportunities), experimentation (implementing live scenarios) and evaluation (assessment of concepts, products and services). Even though the concept of Living Labs has rapidly gained attention over the last decade, it has not been holistically explored in terms of general research challenges and concrete future points of action.

Also, much research is performed in the area of **smart cities** (in particular in South Korea also the term 'ubiquitous cities' is popular). For instance, IBM has implemented a number of urban services in the course of their 'Smarter Planet' programme [13]. Within this initiative research is performed together with cities all over the world to implement applications in the areas of city management, citizen services, business opportunities, transport, water supply, communication and energy. The goal is to seize opportunities and build sustainable prosperity, by making cities 'smarter'. Despite the seminal nature and the broad awareness for the concept, smart cities are currently mostly understood in terms of energy-related questions (particularly in the European Union), i.e., nearly no trans-disciplinary approaches have been developed.

A sensor-driven approach to ubiquitous urban monitoring is presented in [14] and in [15]. The authors present a measurement infrastructure for **pervasive monitoring** applications using ubiquitous embedded sensing technologies with a focus on urban applications. The system has been conceived in such a modular way that the base platform can be used within a variety of sensor web application fields such as environmental monitoring, biometric parameter surveillance, critical infrastructure protection or energy network observation. Several show cases have been implemented and validated in the areas of urban air quality monitoring, public health, radiation safety, and exposure modelling. Yet, these approaches mainly focus on technical and methodological developments and do not account for wider challenges such as societal, political and legislative aspects.

III. A Disambiguation of the Term 'Live'

The term '*Live City*' originates from the modification of the expression 'Real-time City' as definitions and usages of the latter expression are vague and vary on a quite broad scale.

Anthony Townsend presents a highly mobile phone centric definition of a real-time city by stating that 'the cellular telephone […] will undoubtedly lead to fundamental transformations in individuals' perceptions of self and the world, and consequently the way they collectively construct that world' [16]. The author sees the real-time city as a potential platform for dedicated advertising and states that 'accessibility becomes more important than mobility'. This implies that it will be more critical to access urban services rather than moving around physically. This in turn means that the digital (i.e., mobile phone) infrastructure will be more important than the physical (i.e., transport) infrastructure.

A possible definition of *urban informatics* – a term closely related the real-time city – is 'the collection, classification, storage, retrieval, and dissemination of recorded knowledge of, relating to, characteristic of, or constituting a city' [17]. This definition gives a more holistic, but rather general view on the term 'real-time city', which centers around information and knowledge while cultural, social, political and privacy aspects remain greatly untouched.

Apart from these definitions, the term is generally understood as providing spatial information about the city in a timely manner without necessarily accounting for a feedback loop or dynamic processes.

In these interpretations of the expression 'real-time', it has been strongly mitigated. The term 'real-time' originated in the field of computer science, where it initially described a process, which is completed 'without any delay'. This broad view was then divided into hard and soft real-time demands. Soft real-time basically defines that deadlines are important, but the whole system will still function correctly if deadlines are occasionally missed. The latter is not true for hard real-time systems. Another term to express non-rigorous temporal requirements is 'near real-time', which describes a delay introduced into real-time applications, e.g., by automated data processing or data transmission [18]. Hence, the term accounts for the delay between the occurrence of an event and the subsequent use of the processed data.

These definitions of the term 'real-time' have been set up for the domain of computer science. Thus, it is important to evaluate and re-define the expression in the context of urban geography. Naturally, strict real-time requirements are a central aspect in monitoring applications, whereby these demands are highly application-specific and can vary significantly. Therefore, they are not a fundamental goal in the field of urban geography, as the term 'real-time' is primarily defined by an 'exact point in time', which is the same for all data sources to create a significant measurement outcome. Secondarily, the term defines the possibility to start a synchronous communication at a certain time, which might often be important for geographical monitoring applications, e.g., to enable the generation of an exact development graph for temporal pollutant dispersion over a defined period of time in precise intervals.

Additionally to the suggestion of assessability of the environment in the 'now', the expression '*Live City*' also implies a feedback loop. The term 'city' does not only define the description of location-aware parameters, but also entails the exploration of causal patterns in these data. In the context of geo-sensor network and monitoring applications, this in turn means that the urban environment is not only analysed remotely by examining quasi-static data, but the procedure of sensing and processing live data offers the possibility of modifying the urban context in an ad-hoc fashion.

In conclusion, it can be stated that the strict term 'real-time' can be interpreted as 'at present' for urban monitoring applications, in the sense that the aim is to assess the environment 'now', not a historical and perhaps outdated representation. However, these topicality requirements can vary depending on the application context. For instance, an update on traffic conditions does not have to exceed a delay of a couple of minutes when this information is used for navigation instructions, whereas a 30 minute update interval can well be sufficient for short-term trip planning.

To account for this non-rigorous requirement, the term '*Live City*' seems better suited than 'Real-time City'. In this reflection, 'near real-time' appears to be closest to 'live', as it does not impose rigid deadlines and the expression itself suggests dynamic adaptation of a time period according to different usage contexts.

IV. Challenges in Current Research on the Live City

The urban context poses many challenges to pervasive monitoring and sensing systems. Particular issues arise for the deployment of near real-time information services in the city. These range from physical sensor mounting to social and privacy implications. Furthermore, the sensitive urban political landscape has to be accounted for, which might cause unforeseen challenges. Naturally, technical challenges play a key role in the establishment of *Live Cities.*

A. Technological and Technical Issues

The first essential technological challenge is the integration of different data sources owned by governmental institutions, public bodies, energy providers and private sensor network operators. This problem can potentially be tackled with self-contained and well-conceived data encapsulation standards – independent of specific applications – and enforced by legal entities, as discussed in sub-chapter V.B. However, the adaptation of existing sensors to new interoperability standards is costly for data owners and network operators in the short term, and so increased awareness of the benefits of open standards is required.

From a technical viewpoint, unresolved research challenges for ubiquitous urban monitoring infrastructures are manifold. These challenges range from finding a uniform representation method for measurement values, optimising data routing algorithms in multi-hop networks, data fusion, and developing optimal data visualisation and presentation methods. The latter issue is an essential aspect in real-time decision support systems, as different user groups might need different views on the underlying information. For example, in case of emergency local authorities might want a socio-economic picture of the affected areas, while first-response forces are interested in topography and people's current locations, and the public might want general information about the predicted development of a disaster.

In addition, there are a number of well-known technical issues in the establishment of urban monitoring systems (energy supply, sensor mote size, robustness, routing, ad-hoc network connections, reliability, connectivity, self-healing mechanisms, etc.). These have to be addressed as the case arises depending on specific requirements of the end application. Thus, they are not part of the presented research.

Furthermore, highly unpredictable challenges exist arising from the openly accessible, dynamic and variable urban environment, such as severe weather conditions, malfunctioning hardware, connectivity, or even theft and vandalism. These general and mostly technical issues are well elaborated and shall not be discussed within this paper.

B. Various Stakeholders

Other issues for the installation of a *Live City* are thematic challenges and socio-political concerns, which are rapidly gaining importance. The feedback loop depicted in Fig. 2 is a key factor in designing urban monitoring systems. In practice, various kinds of stakeholders have to be considered including citizens, information providers, research institutions, politicians, the city management, or other influential interest groups. This cycle involves all steps of the deployment process from planning, deployment, customised information provision, and feedback from the citizens and other interest groups [19].

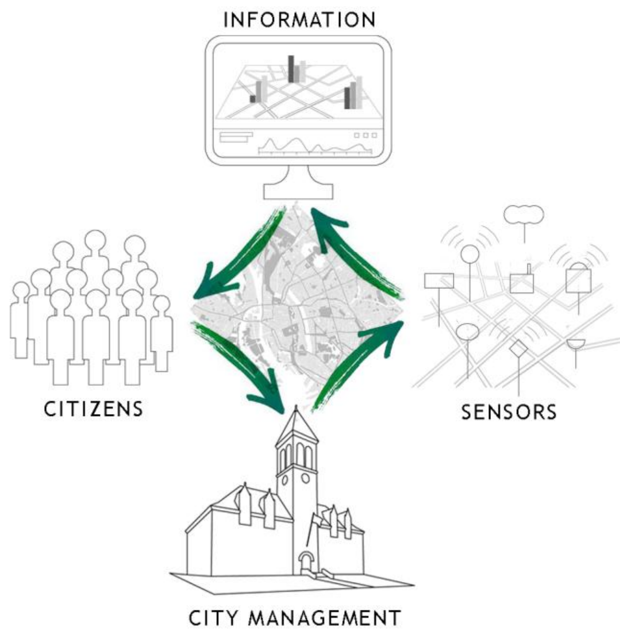

Figure 2. Feedback Loop Enabling the *Live City*.

Regarding the cycle depicted in Fig. 2, a common pattern refers to the network of actors that constitute the city from the decision-making point of view. While for simplicity we may indicate "city management" as the entity that supervises investments and decisions, in practice the end result of city innovations is the consequence of decisions made by a network of public and private actors, each one with a separate agenda and specific political or commercial objectives. The synchronisation, or lack thereof, between these actors frequently determines speed, depth and extent of adoption of new technologies, and the impact that technology ultimately has on the city. The process of public-private partnerships (PPP) and the governance of technology innovation in urban environments are frequently secondary concerns of technology vendors and scientists.

Another important methodological peculiarity of the urban context is that there are large variations within continuous physical phenomena over small spatial and temporal scales. For instance, due to topographical, physical or radiometric irregularities, pollutant concentration can differ considerably, even on opposite sides of the street. This variability tends to make individual point measurements less likely to be representative of the system as a whole. The consequence of this dilemma is an evolving argument for environmental regulations based on comprehensive monitoring data rather than mathematical modelling, and this demand is likely to grow.

C. The Value of Sensing Collective Behaviour versus Privacy Implications

Although we experience quickly increasing awareness of the opportunities of digital mobile communication, the question arises how we can engage people to contribute actively being 'human data sources' and involve themselves into re-designing urban processes. This is necessary in order to leverage collective information in areas such as environmental monitoring, emergency management, traffic monitoring, or e-tourism. One example, in which this kind of volunteered data was of invaluable importance, were the earthquake and the subsequent tsunami in Japan in March 2011. In this case, the *Tweet-o-Meter* [20] application has been used to find anomalies in Twitter activity. Right after the earthquake, people started to post status reports, video streams, and conditions of destroyed houses and cities, which could be interpreted in near real time as an indicator for an extraordinary event. Furthermore, information could be semantically extracted from personal comments and posts. In this context, an important but yet poorly research issue is the use of incentive schemes to encourage people to contribute their data. Current approaches mostly comprise 'feedback' and 'gamification', but their practical suitability has not been fully proven yet.

Early implementations and deployments also show the impact of new sources of evidence on the way organisations operate. As an example, police forces can greatly benefit from real-time feeds of urban information showing anomalies in the collective city behaviour that may underline safety risks or attention areas. While this is increasingly feasible through data mining of real-time data feeds, the challenge for law enforcement is how to react to this information, which questions the normal planning and operational practices.

Faced with real-time or even predictive safety alerts, should the police forces adopt a dynamic allocation of resources based on demand and supply mediated by technology or use this input as an extra source of evidence for existing management practices? How does this impact labour, skills, equipment or work shift? What are the legal or institutional implications? All city organisations are faced with similar questions, which emerge because technologies have enabled new information streams forcing them to reconsider established practices and operations. While it can be argued that this is the case for any organisation facing disrupting technologies, in urban settings the issue is compounded by the fact that many institutions face the same challenge simultaneously, and the degree to which organisations succeed or fail depends only in part on themselves.

This development raises the challenge to find the balance between providing pervasive real-time information while still preserving people's privacy. Strategies to address this stress field are described in sub-Section 0. In addition, it seems self-evident that the provided information has to be highly accurate, reliable and unambiguous. Thus, quality control and error prevention mechanisms including appropriate external calibration are even more important for monitoring networks in the city than in other, less connected, environments. The issue of quality control will be further discussed in sub-Section V.A.

In terms of privacy, the claim might arise that we need to be aware of our personal and private data *before* we share them. The essential question in this context, however, is *how* we can raise awareness of ways to deal with that matter. Terms and conditions of digital services and technology are mostly hardly understandable to non tech-experts. Thus, more simple and binding ways of communicating this kind of information have to be found.

Finally, some more unpredictable challenges posed by the dynamic and volatile physical environment in the city are radical weather conditions, malfunctioning hardware, restricted connectivity, or even theft and vandalism. Moreover, there are a number of rather obvious but non-trivial challenges to be addressed, such as optimal positioning of sensors, high spatial and temporal variability of measured parameters or rapid changes in the urban structure, which might cause considerable bias in the measurements.

V. Discussion: Future Research Avenues

From the challenges described in Section IV we can derive a number of essential research questions, which have to be tackled in the area of *Live Cities*. These can be divided into methodological aspects, technical and technological issues, questions on privacy and legislation, and the assessment of economic benefits, which arise through the installation of a *Live City*.

A. Methodological Research

Over the last years prospects were made that 'data would be the new oil' [21],[22]. It has been stated that - like oil - data cannot be used without first being refined. This means that raw data is just the basic ingredient for the final product of **contextual information** that can be used to support strategic and operational decisions. Thus, a central issue in terms of providing real-time information services is the analysis of data according to algorithmic requirements, representation of information on different scales, context-supported data processing, and user-tailored information provision aligned with the needs of different user groups.

In general, the deployment of a large number of sensors ensures more representative results together with an understanding of temporal and spatial variability. However, deploying sensor networks is costly, politically sensitive and requires much time. One way to overcome these issues is to 'sense people' and their immediate surroundings using everyday devices such as mobile phones or digital cameras, as proposed by Goodchild [23]. These can replace – or at least complement – the extensive deployment of specialised city-wide sensor networks. The basic trade-off of this people-centric approach is between cost efficiency and real-time fidelity. The idea of using **existing devices to sense the city** is crucial, but it requires more research on sensing accuracy, data accessibility and privacy, location precision, and interoperability in terms of data and exchange formats.

In terms of geo-data sources, Volunteered Geographic Information (VGI) plays a key role in realising the idea of a *Live City*. We are already experiencing an overwhelming willingness of citizens to contribute their personal observations ranging from opinions posted on Facebook to Tweets about local events or commented photo uploads on Flickr. As mentioned in Section IV, this kind of **collective information** can potentially have a vital impact on operational real-time strategies in areas such as emergency management, dynamic traffic control or city management.

A central issue in VGI is the **representativeness of volunteered information** [23],[24]. We argue that defining or deriving consistent semantics in user-generated content possibly requires the combination of bottom-up and top-down approaches. In bottom-up approaches, user communities build their own semantic objects and connections between those by using their own personal taxonomies. In contrast, top-down approaches – mostly academically driven – try to define semantic rules and ontological connections in a generic way prior to and independently of the end application.

Only the combination of those using Linked Data concepts (rather than rigid and inflexible ontology approaches) can lead to **domain-independent and comprehensive semantic models**, which are needed to cover the whole breadth of topics, users and applications in the *Live City*. This requires standardisation on two levels – firstly on sensor data level (encodings for measurements) and secondly on phenomenon level (measurand encodings). In this regards, semantic search will be an essential concept to extract knowledge and information from user-generated data combined with sensor measurements.

An aspect, which is strongly connected to availability of data sources, is **openness of data**. As argued by Jonathan Raper [25], quality of decision-support is increasing with the quality and the quantity of available data sources. We are currently facing a situation that in most cases, too little data are available to support well-informed decisions in near real time. This raises the question how data owners such as companies in the environmental sector, energy providers or sensor network operators can be animated to open their data repositories for public use.

On the contrary, we might face a vast amount of data freely available in the near future, contributed by a variety of different data producers – mostly non-quality assured data stemming from private observations or sensor networks. This of course raises the question of trustworthiness of these data. Thus, **automated quality assurance** mechanisms have to be developed for uncertainty estimation, dynamic error detection, correction and prevention. In this research area,

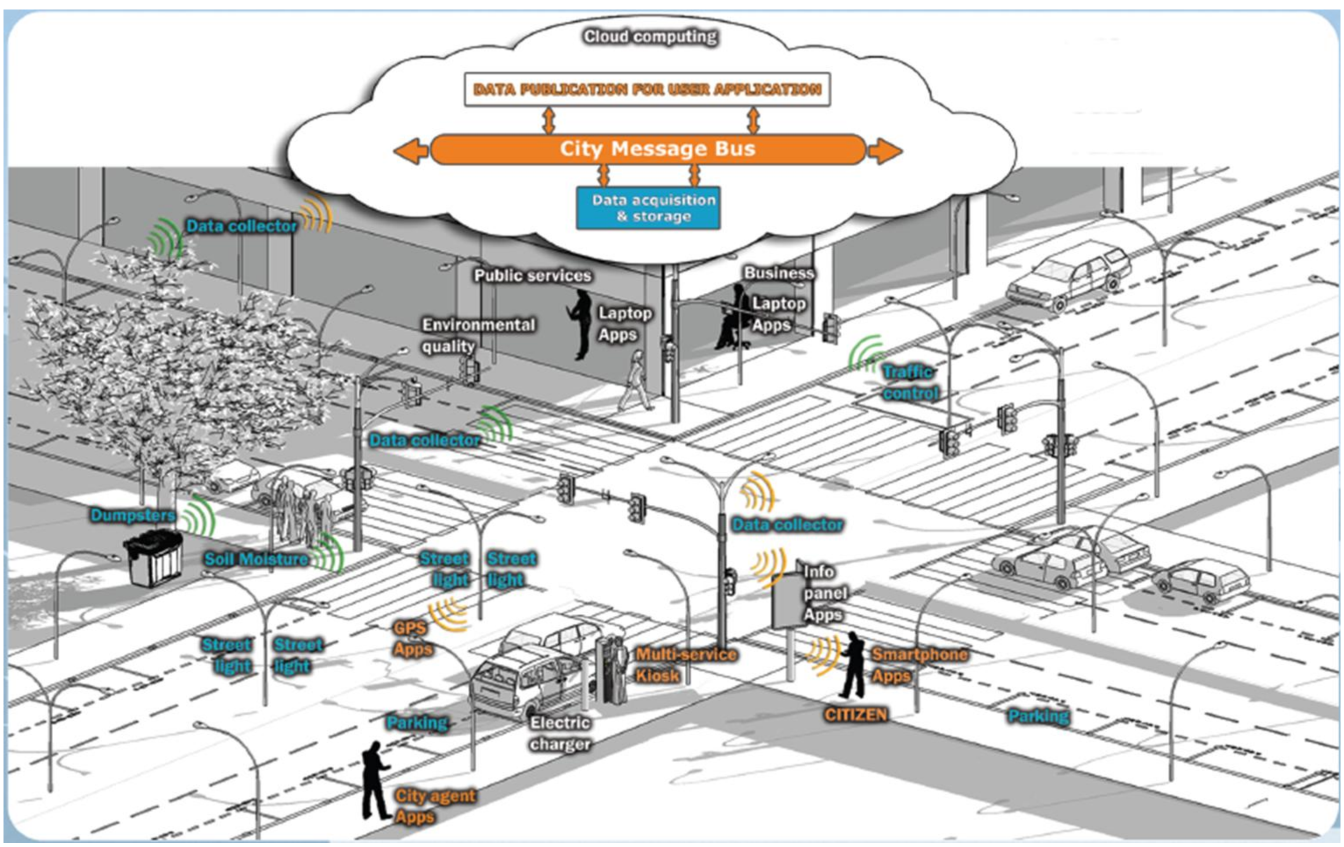

Figure 3. Urban Operating System.

we are currently seeing different approaches in development including Complex Event Processing (CEP) [14] for error detection, standardisation efforts for representing uncertainty in sensor data (e.g., Uncertainty Markup Language - UncertML) [26], or proprietary profiles to define validity ranges for particular observations. Only when these questions are solved, reliability and completeness of recommendations can be ensured.

Up to now quality analysis on VGI (e.g., [27],[28],[29]) focused on completeness as well as geometrical and semantic accuracy, but considered only few timeslots and neglected the (near) real time aspect of a *Live City*. Interestingly this kind of data can also be used to improve the data situation through intelligent algorithms as [30] shows.

Furthermore, measurements are only available in a quasi-continuous distribution due to the high **spatial and temporal variability** of ad-hoc data collection. Addressing this issue will require complex distribution models and efficient resource discovery mechanisms in order to ensure adaptability to rapidly changing conditions.

B. *Technical and Technological Research*

Practical experiences show that urban growth necessitates management with focus on efficiency and durability. The careful integration and managing of acquired information and ensuring a bigger and better interoperability of various services will ultimately drive successful management of the urban space. Consequently cities need an '**urban operating system**' which will endow them with new intelligence in coordinating and interconnecting all services. Those services comprise provision of real-time information on mobile devices facilitating smarter movement around the city, and the optimisation of services for city and contractor agents of public service to improve information exchange and to provide public access to open data in order to encourage citizen participation.

The urban operating system, illustrated in Fig. 3, consists of a setup of material and software architecture and allows for addressing the challenges mentioned in Section IV by taking into account constraints linked to outdated infrastructure:

- Acquisition of the information in real time
- Transportation of the information from public road network to information system
- Integration of systems deployed in the city (parking spaces, streetlights, traffic systems, waste management, etc.)
- Processing, dissemination, publication and storage of information in real time (real-time publication and dissemination, and provision of historical data for dynamic data mining processes)

In effect, the urban operating system acts as a connecting base layer, which enables the interplay of urban objects, public infrastructure and the citizens. Like this, people can benefit by gaining access to real-time information about the city (traffic conditions, air quality, social activities, public transport, health-related issues, etc.). This entails citizens to base their short-term decisions on real-world conditions, which are conveyed on demand in near real time.

This in turn requires the continuous assessment of urban processes, which requires the broad installation of sensor networks. The deployment of sensor networks implies a number of challenges, particularly in urban settings. Apart from technical research in the area of sensor networks regarding miniaturisation, energy supply, robustness, ad-hoc network connections, reliability, connectivity, self-healing mechanisms, etc., **standardisation and interoperability** are vital prerequisites for establishing pervasive and holistic monitoring systems. As current sensor network implementations are mostly built up in proprietary single-purpose systems, efforts to develop a uniform communication protocol will be needed [31]. One very promising approach in this field is the Sensor Web Enablement (SWE) initiative [32] by the Open Geospatial Consortium (OGC). SWE aims to make sensors discoverable, accessible and controllable over the Internet. SWE currently consists of seven standards and interoperability reports, including the Sensor Observation Service (SOS) for observation data retrieval, Observations and Measurements (O&M) for sensor data encoding, Sensor Markup Language (SensorML) for platform description and the Sensor Alert Service (SAS) for event-based data transmission. More details about SWE can be found on the

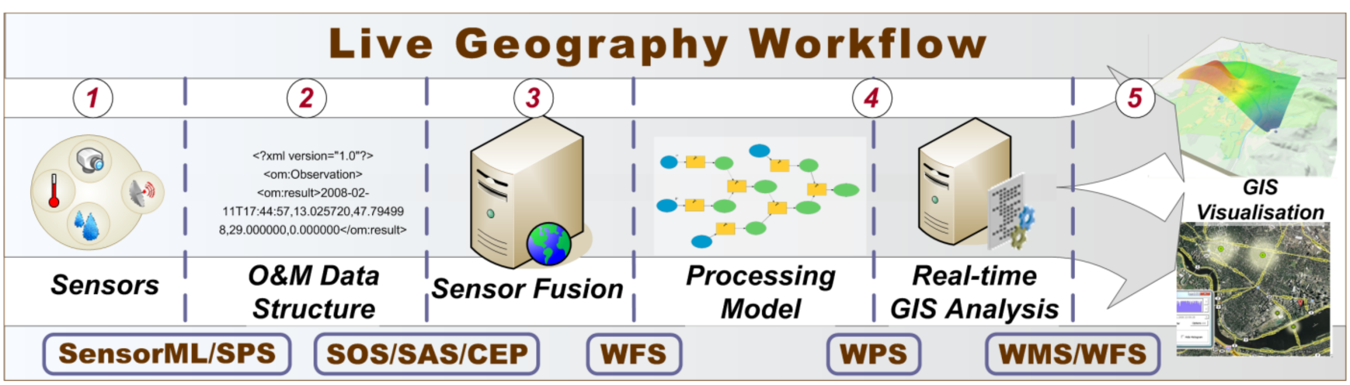

Figure 4. Live Geography – Standardised Geo-Sensor Data Analysis Architecture.

OGC web site[1].

In terms of integrating various kinds of real-time data such as sensor measurements, meteorological data, energy system states and human observations with existing sensor and analysis systems, the creation of a **standardised measurement infrastructure** using well-conceived data and service standards is a major technical challenge. An essential factor will be the integration of new developments with existing community projects such as Ushahidi or Twitter to create new possibilities for high-quality information. This will potentially result in increased situational awareness and enhanced Common Operational Pictures (COP). Furthermore, this development supports infrastructure-oriented approaches and directives such as Global Monitoring for Environment and Security (GMES), Infrastructure for Spatial Information in Europe (INSPIRE) and the Shared Environmental Information Space (SEIS). The *Live Geography* infrastructure [31] is a first step towards the realisation of a generic workflow-oriented geo-sensor data analysis architecture. As shown in Fig. 4, the Live Geography workflow covers all essential parts including standardised sensors, sensor fusion, web-based data processing and geo-data visualisation, and is generic enough to integrate all data sources relevant to Live City applications.

Here, an important future research area is the development of generic and portable **sensor fusion** algorithms, which are a vital prerequisite to combine data stemming from different heterogeneous sensor networks. Sensor fusion basically stands for the harmonisation of data in terms of units of measure, time zones, measurement models and observation semantics. To be compliant with the requirements of a *'Live' City*, the fusion process has to happen in near real time. [33] presents an approach for on-the-fly integration of measurements coming from different SOS instances using the free open-source server GeoServer[2]. The system harmonises measurements in real time and provides them on the fly via standardised OGC web service interfaces such as the Web Feature Service (WFS) and the Web Map Service (WMS). Although this implementation is still improvable in terms of fusion capabilities, it demonstrates a seminal approach towards sensor fusion.

The next step in a *Live City* workflow is geo-analysis of real-time data sources, i.e., the **refinement of raw data** towards user group-specific information, which can then be used for short-term decision support. This analysis process can be implemented by the OGC Web Processing Service (WPS) in a standardised way in general. But the WPS architecture is very generic in its current version so that the developments of further specialised (domain-specific) application profiles are necessary as is argued in [34],[35] and [36]. The power of using WPS for implementing more complex analysis functionality for urban models has for instance been shown in [37].

Another methodological issue in terms of communication technology is the availability of **ubiquitous communication media**. Today, we presume a fully functioning Internet to transmit information. However, in case of emergency, this layer is potentially not available, as we experienced for instance during hurricane Katrina in 2005 in New Orleans. Thus, we have to find alternate possibilities to communicate critical information independently of existing infrastructures. Possible solutions comprise long-range ad-hoc networks or the construction of a robust communication core network, which can withstand external influences such as tsunamis, earthquakes, storms, avalanches or even vandalism.

The *Live City* concept naturally implies the **provision of user-tailored information in near real time**. However, we have to consider that fulfilling this requirement is not always possible, for instance if data analysis algorithms are very complex and laborious, or if base data are only updated in certain intervals. Despite these restrictions we have to find algorithmic methods to accurately predict developments in our environment even in case of reduced data availability. This can for instance happen through the integration of well-calibrated models and spatio-temporal interpolation algorithms. This approach can naturally only mitigate the drawback of imprecise information, but not eliminate it.

A tightly related research challenge is the creation of **ubiquitous user interfaces**. Here, we tend to think about visionary devices and gadgets, but even today we have the need to develop solutions for some application domains like *Live Cities*, where an extremely wide range of legacy user interfaces is being used at different places, but still requiring a stringent link amongst each other. This means that people need to share the same information and be aware of other users of the system – in particular their location. The roles of these users are highly dynamic and change with time and space – so do the user interfaces they need to interact with up-to-date shared knowledge and each other.

A wide range of users exists within the *Live City* – from the general public, management centres, governmental institutions and urban planners to researchers and specialised maintenance staff. All of them need to access and interact with geospatial information in an truly ubiquitous way, i.e., simultaneously at different places with different devices: in the management central on interactive large screen wall displays, outdoor with tablet computers or smartphones, or potentially with new **augmented reality** devices – in particular as hands need to stay free for more authentic and pure experiences of the city.

Even wearable computing appliances start to play a central role and have to be considered for special. In this context, a highly interesting aspect is that we do not only have alphanumeric data to be presented, but the users need to interact with highly **interactive spatiotemporal information** (2D+t and 3D+t) on this broad range of devices – but in all cases users need to access similar functionality and information in an ad-hoc fashion. Some of this information is public or shared, some is restricted to distinct users or user roles. Still, there is a need of consistency – at least on the mental level for the interaction and visualisation metaphors used. This consistency is required because people might get confused and make errors if they need to switch

[1] http://www.opengeospatial.org

[2] http://www.geoserver.org

too often between different paradigms – something that needs to be minimised extremely in real-time applications.

Another interface-related problem is that *Live City* applications can often not rely on the wireless network – as mentioned above. In consequence, there is a need for supporting both autonomous and **collaborative decision-making and interaction**. This makes user interface design for different user groups a particular challenge. Currently we have to deal with a wide range of these challenges in the case of city management systems using today's technology (also to guarantee robustness of the application), but it is clear that new ubiquitous UI devices, metaphors and paradigms have a large potential in this area.

This also includes the provision of **real-time data and information in 3D**, as illustrated in Fig. 5. Integrating up-to-date sensor data, such as environmental, traffic-related or safety-relevant data can significantly improve the value of urban information systems. This requires the visualisation of 3D city and landscape models and the interactive navigation through the scene, which again raises a number of research challenges such as representation of 3D data on small screens, optimised information reduction, guaranteeing highest-possible representativeness of the data, creating urban dispersion models or sufficient update cycles.

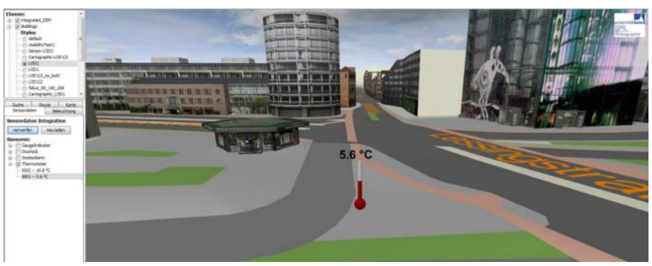

Figure 5. Integration of Sensor Data in 3D Environments. [38]

C. *Privacy and Legislation Measures*

Particularly in the area of user interaction and public participation procedures, a crucial question in the context of *Live Cities* is how we can **preserve people's privacy** dealing with ubiquitous information and partly personal data. One possible solution to address this issue is to make use of new Collective Sensing approaches. This methodology tries not to exploit a single person's measurements and data, but analyses aggregated anonymised data coming from collective networks, such as Twitter, Flickr or the mobile phone network [39]. Like this, we can gain a coarse picture of the situation in our environment without involving personal details of single persons. In case of tracking applications or services, in which personal data are involved, people have to have an opt-in/opt-out possibility. This means that users can decide themselves whether they want to use the application – and also withdraw their consent - being aware of the type and amount of data that is collected and transmitted.

Another central issue in deploying monitoring systems in the city is the personal impact of fine-grained urban sensing, as terms like 'air quality' or 'pollutant dispersion' are only surrogates for a much wider and more **direct influence** on people, such as life expectation, respiratory diseases or quality of life. This raises the demand of finding the right level of information provision. More accurate, finer-grained or more complete information might in many cases not necessarily be worthwhile having, as this could allow for drawing conclusions on a very small scale, in extreme cases even on the individual. This again could entail a dramatic impact in a very wide range of areas like health care, the insurance sector, housing markets or urban planning and management.

A central question in this context is: can we actually achieve a system, in which transactions are not tracked or traced? Thinking about mobile phone calls, credit card payments or automated toll collection, each of the underlying systems has to have some kind of logging functionality in order to file payments and generated automated reports. In these cases it is probably just not possible prevent storage – at least for a short time. Thus, **legal frameworks** have to be developed on national, trans-national and global levels. The largest limiting factor in this regard is the varying interpretation of 'privacy' in different parts of the world. For instance, privacy can be traded like a good by its owner in the USA, whereas it is protected by law in the European Union. This means that supra-national legislation bodies and initiatives are called upon to set up appropriate world-wide regulations.

As shown in Fig. 6, legislation and governments play a highly different role in these two settings.

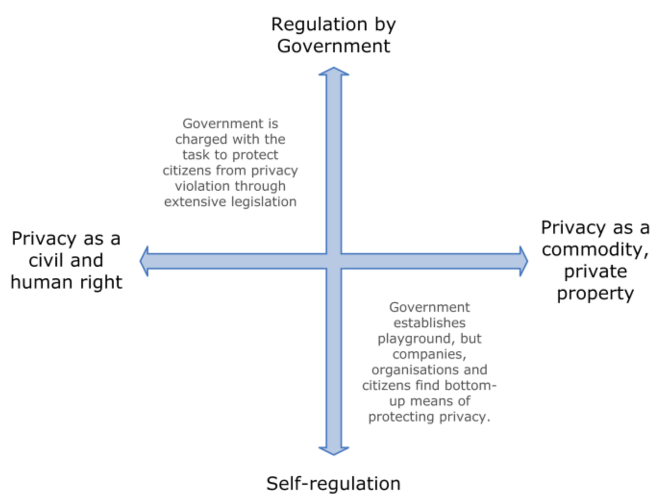

Figure 6. Different Understandings of Privacy.

This also includes the critical question of **data ownership** – who owns the data: the data producers (i.e., the citizens or a mobile phone network operator), the institutions that host a system to collect data, or the data providers? Furthermore, if sensitive data is analysed to produce anonymised information layers, who is responsible if decisions that are based on this information are wrong due to lacking quality of the base data? In conclusion, the issues of privacy, data ownership, accessibility, integrity and liability have to be tackled thoroughly all at once and not separately from each other.

In case of tracking applications or services, in which personal data are involved, people should have an **opt-in/opt-out** possibility. This means that users can decide themselves whether they want to use the application – and also withdraw their consent – being aware of the type and amount of data that is collected and transmitted.

D. *Assessing the Economic Value of Live Cities Services and Applications*

Finally, an important aspect is the assessment of the economic value of establishing a *Live City*. Concrete revenues have not yet been defined, which would compel this kind of investment. Thus, we need to find instruments to quantify financial benefits of ubiquitous information services, city-wide sensor networks and mobile applications collecting user-generated information on the current status of the city.

It is symptomatic that previous experiences demonstrate that the understanding of the network of decision makers, actors, institutional stakeholders and power entities is of paramount importance to introduce successful changes. In many situations it may be necessary to create **ad-hoc structures that facilitate urban innovation**, for instance incubators, private-public partnerships, special purpose vehicles, ad-hoc institutions and many more. As we increasingly understand the relationship between smart cities and institutional arrangements, research will be needed to formulate models that can be replicated across cities and cultures, and provide a more sustainable basis for innovation adoption in cities.

From a quantitative viewpoint, the economic value of *Live City* services and applications can be either defined in **concrete revenues or as an after effect of improved quality of life**. The Economist Intelligence Unit's liveability ranking [40] quantifies the challenges that might be presented to an individual's lifestyle in 140 cities worldwide. Each city is assigned a score for over 30 qualitative and quantitative factors across five broad categories: Stability, Healthcare, Culture and Environment, Education, Infrastructure.

These five categories basically sum up 'what people want'. Interestingly, each of these categories can to some extent be improved or optimised by applying the principals of a *Live City* as described in this paper. In turn, improving a city's quality of life leads to a contented work force and families, and in turn, to increased economic value.

Most cites have not been planned from the ground-up and grew organically. The technologies that have been developed in the few last years, like pervasive sensors to assess urban dynamics and especially mobile technologies, offer new opportunities to 'tune' and 'fine-tune' the urban processes within cities, just as any other process can be optimised.

These urban processes can be transportation related, to monitor and direct the daily traffic in real time, optimise parking spaces and navigation to available parking, or simply to help people with their daily tasks, finding jobs, finding housing, connecting people in spare time, showing where less people are for leisure-time activities or where many people are for night life. Tools that bring the feedback loop directly to people make it easy to **promote events and give people instruments** to rate the attractiveness of these happenings.

Mobile technologies and the available development ecosystems offer great **opportunities for young start-ups** to build GPS-enabled, crowd-sourced, location-based apps. Just one example is the Wikitude World Browser [41], amongst 500.000 other apps, which are tailored at individual needs. Igniting and funding a start-up scene can be the starting point for any government to build a connected *Live City*: start-ups create jobs and apps, which in turn, if tailored for locals, benefit the people in the city and improve the quality of life.

The improved economic **value of a 'tuned' city**, i.e., better traffic management, optimised parking services, better housing and job search, city services and applications that deliver location-based news, events and happenings can be enormous. On one hand there can be cost saving advantages, for instance in considerable fuel savings if available parking spaces are reserved on a first-come-first-served policy and the driver is routed to this parking space rather than having to circle looking for a parking space.

A further important element in adopting smart technologies for urban innovation is the need to facilitate experimentation. The growth of the Internet industry in the last decade has brought about a model of companies largely based on small-scale experimentation, controlled failure and rapid adaptation. The idea that an internet company can be "planned and executed" (the waterfall model) has been replaced by the idea that an internet company "grows" through trial and errors while finding what works and what doesn't, accepting that **strategy is constructed ex-post**, rather than ex-ante. This modus operandi is being considered in many other sectors, which recognize the benefit of adaptability in the face of rapid external change.

Most cities, on the contrary, still work on long planning horizons and waterfall planning models are the norm. While cities cannot be compared to software projects, there are many areas of urban development that do not require infrastructure planning and investment and could be candidates for some radical review. The fact that we can increasingly measure the city in real-time and feedback the results of urban modifications in near real-time makes it conceivable to adopt trial-and-error policies on a much larger scale. While there are examples available, there is a strong need to develop **management frameworks** that would support organisations in this effort.

On the revenue side Google has shown in the last few years that Internet advertisement actually works. Google matches the search terms people enter in their search engine with ads. This works so well that it grew to 30 billion revenue per year, operating a million servers worldwide, serving 1 billion search requests every day. One key to generating revenue in the field of *Live Cities* may be to apply what Google did with the Internet to the real world, offering information and search services that focus on time, location, context and people rather than on simply search terms.

VI. Conclusion

In opposition to projections, which stated that the wide-spread distribution of high-speed internet connections would render geographical distance irrelevant, cities have recently become the centre of interest in academic research. However, especially **real-time monitoring of urban processes** is widely unexplored and has recently received a lot of attention due to the fast rise of inexpensive pervasive sensor technologies, which made ubiquitous sensing feasible and enriches research on cities with uncharted up-to-date information layers.

Within this vision of a *Live City*, the city is not only regarded as a geographical area characterised by a dense accumulation of people or buildings, but more as a multi-layered construct containing multiple dimensions of social, technological and physical interconnections. Through this viewpoint of urban areas as an actuated **multi-dimensional conglomerates of dynamic processes**, the city itself can also be seen as a complex near real-time control system creating a feedback loop between the citizens, environmental monitoring systems, the city management and ubiquitous information services.

In the *Live City*, the everyday citizen is empowered to monitor the environment with sensor-enabled mobile devices. This feedback of ‘sensed’ or personally observed data, which is then analysed and provided to citizens as decision-supporting information, can change people’s behaviour in how they use the city and perceive their environment by supporting their short-term decisions in near real time. However, this requires promotion of the user appropriation of the information through awareness of limitations.

Basically, we identified four main barriers towards the implementation of the *Live City* concept: methodological issues, technical/technological problems, lacking quantification of the economic benefits, and finally privacy and legislative questions. We discussed these challenges and highlighted **future research avenues** in Sections IV and V.

We believe that promoting the *Live City* concept will trigger a profound rethinking process in collaboration and cooperation efforts between different authorities. Also, a people-centric view of measuring, sharing, and discussing urban environments might increase agencies’ and decision makers’ **understanding of a community’s claims** leading to proactive democracy in urban decision-making processes.

In terms of privacy and personal data collection, it is evident that everybody has to have the right to decide what kind of personal data is collected by whom, and for which purposes these data are used. In this context, people have to have an **opt-out possibility** to withdraw their consent to personal data collection. This is particularly important in the context of collective sensing, which tries not to exploit single people’s measurements and data, but analyses aggregated anonymised data coming from collective networks, such as Twitter, Flickr or the mobile phone network.

Regarding the vision of digital earth, as formulated by Al Gore [42], both negative and positive aspects have to be addressed: positive aspects like emergency support, traffic congestion prevention, or, generally speaking, holistic real-time situational awareness of our environment; but also potential negative developments such as unwanted directed advertising, unauthorised tracking or extensive data mining have to be considered.

As mentioned in the Introduction, we are experiencing a fast progressing technology development, which is already moving ahead of society. The deciding final question can be: If we compare this development with a stream moving at high speed, on which we are paddling to remain on the same spot or at least not to drift off too fast, where does our goal for the future lie: down-stream, somewhere near our current spot, or even up-stream? In the end, legislation bodies are called upon to set the legal stage for leveraging *Live City* technologies, exploit economic opportunities, but still preserve citizens’ privacy.

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