Towards a Cyber, Physical and Social Sensing Integration Framework for Smart City Services

Abstract—The emergence of Web 3.0, especially increasing adoption and integration of Internet of Things devices with social media and location services, have created an unprecedented opportunity to improve city services. While physical and cyber sensing-driven information systems enable public organizations to collect, monitor and analyze their services, the social sensing with location services-driven information infrastructure can provide them a complementary ability to dynamically listen to public over time. It can, thus, systematically and continually improve their services through personalized, region-specific subjective feedback profiling. However, challenges remain in understanding common information representation, sense-making and spatio-temporal integration across the sensing types. In this paper, we propose a novel framework for addressing such challenges using a novel analytics architecture. We propose to systematically integrate data from the three kinds of sensing: cyber, physical and social, and generate spatio-temporal profiles of analytical services for organizations and individuals. We demonstrate the value of the proposed analytical architecture using scenarios of diverse events such as natural disasters, mass activism, and city recreation activities.

INTRODUCTION

Rise of Internet of Things (IoT) in recent years has created a novel opportunity to envision and enhance information infrastructure across almost all industrial domains. In the similar momentum, it holds a potential to improve and enhance a range of city services. The time to tap into this potential is both ripe and urgent. However, a number of technical and socio-economic challenges exist. In the remainder of this section we present a number of real-world scenarios to highlight the range of possibilities and also the challenges. These insights lead us to describe the opportunities and solutions that are required.

Motivating Scenarios

In the following we describe different scenarios that highlight how social sensing can be useful in providing and/or enhancing a variety of smart city services. We use these examples to also highlight the technical and socio-economic challenges.

Scenario 1: Protest Marches: In late January 2017, we witnessed a world-wide coordinated effort in organizing marches that aimed primarily at highlighting women’s issues but also many other issues including race, immigration and gender. Most major cities in the USA had hundreds of thousands of participants. Situations such as these are a rich source of socially sensed information. For example, during these marches, participants were uploading their experiences to social engineering sites like Snapchat, Twitter, Facebook and Instagram. Much of this information provided invaluable insights into the key issues that the participants were highlighting. Despite the very large size of the crowds, fortunately there were no untoward incidents such as riots or stampedes. Yet, there are certainly critical safety issues that are of concern where law enforcement may need to obtain real-time information. For instance, the University of California, Berkeley campus experienced rioting and loss of property during what was supposed to be a peaceful protest against a scheduled speaker.

The safety issues are paramount. For instance, even a small amount of incitement in some section of the crowd may lead to riots and stampede as was seen at the UC Berkeley campus, which in turn was the result of an entirely different set of protesters mixing with peaceful protesters. Thus, it is critical for law enforcement to sense the social information being relayed from which appropriate insights could be derived, and steps can be taken proactively to minimize human injuries or even casualties and loss of property. Clearly, such a scenario is specific to a certain region though it is possible that trends in one region may impact others. In either case, the need for real-time, edge-based distributed analytics and correlation, and decision making to complete the feedback loop is needed. For this, it is critical that the communication infrastructure is capable of supporting real-time dissemination of information at greater scale, and support in-network real-time stream processing with decision support.

Scenario 2: Natural Calamities: Recent heavy snow and rainfall on the US west coast, or the ice storms in the upper mid-western US, or the tornado-driven weather in the southeastern US highlight the need for marshaling rescue efforts in the right place at the right time. This need was also experienced by one of the authors during the 2010 floods in Nashville, TN, USA. During that time, due to massive flooding, most road and communication networks were nonoperational. However, there were still some pockets of wireless communications capabilities available, which needed to be tapped into in order to speed up rescue and recovery efforts. The technology has improved in the past six years and we assume that despite calamities, there may be a higher chance of wireless communications that survive the disasters.
At the application layer, both the traditional sources like news, and new sources like socially sensed information may provide vital clues on survivors or those in desperate help, such as people who may need to be airlifted from flooded houses or those who need immediate medical relief [14]. Furthermore, there may be a need for response coordination among multiple teams each of which could be driven by individual and disparate silos of information systems, some of which may even provide contradictory information.

Up until now, a limited attention was paid to aligning the processing of heterogeneous types of content on social media, and open web data (e.g., news) with the information needs of first responders communication channels. With the evolution in communication technologies over time, however, we observe that the information types and sources to collect situational awareness information have increased significantly. Tapping into this potential is both urgent and timely to improve decision support for responders [17]. By combining information streams from such unconventional sources with conventional sources by spatio-temporal profiles, we posit to fill the gap between what is available to consume in silos, and what could be operationally useful – the integrated information.

Scenario 3: Recreation: As the urban sprawl increases, people are increasingly facing traffic issues as well as many other issues including quality of public schools, trash pickup, quality of water and electricity supply, etc. There is a great need to improve public awareness towards various social issues such as recycling, or effectively utilizing car pooling and public transport. At the same time, city planners need to have more in-depth understanding of the needs of different parts of the city, and how best to address these needs. Addressing these challenges holistically once again requires correlating physical sensor data with socially sensed information. Moreover, examples of this kind reveal the need for completing the loop at multiple spatio-temporal scales. For instance, real-time traffic congestion alert or estimated arrival of buses requires a real-time closing-the-loop. On the other hand, issues such as public schools or planning new bus routes have much larger time scales.

Research Needs and Proposed Solutions

To address these scenarios in an informed manner, we identify fundamental research opportunities that lie directly at the intersection of social, cyber and physical sensing infrastructure. For example, the motivating scenarios highlighted a number of technical needs and illustrated a number of challenges. Addressing these challenges and urgent needs requires new research along a trio of dimensions: (i) sensing, and integrating information from heterogeneous sources of information streams at different spatio-temporal scales, (ii) the architectural foundations to support these needs which can result in reusable and extensible platforms that are deployable seamlessly and rapidly, and (iii) new applications that can leverage these platforms to provide new services. The rest of this paper presents our vision and proposed ideas along these three dimensions.

Research Thrust 1: Sensing and Integrating Heterogeneous Information Streams

Given the growing adoption of IoT sensors (physical sensing) in addition to current trends of social media (citizen sensing), and open, linked data on the Web (cyber sensing) in our daily lives, there is a variety of information streams to exploit in smart cities context. The primary goal of sensing complementary, sometimes redundant, information streams is to improve the effectiveness of understanding and enhancing the overview of contextual awareness to the end users in a given application context. For instance, diverse streams of information from social media, and other web sources of news and blogs about a dynamic disaster event can be complemented by environmental sensor observations at the affected location over time, and thus, provide a better common operating picture for disaster response agencies by location and time.

For sensing across the three layers of social, cyber and physical sensing, we propose to divide the heterogeneous information streams, say in a smart city services context, by source type as conventional and unconventional source-based. Conventional sources may include application-oriented practices from the past while the unconventional sources may include practices from novel use of advanced technology at any of the layer. For instance, in the application context of city emergency services, 911 calls-based communication by trusted internal responder networks constitute a conventional source, while the unconventional sources can include social media or weblogs that arise from recent advancements in information technology. The conventional source-driven stream may include information for monitoring the sensor-based observations of physical objects, such as a bridge, with a highly structured metadata of information. On the other hand the unconventional source-driven streams may include information in real-time from social media and news or blogs on the Web about the bridge health in highly unstructured content of commentary. However, in both of these cases, the key commonality is the spatio-temporal context of information provided with a varying degrees of structure.

To integrate information across the three sensing layers, we first propose to align information collection and processing from the unconventional and conventional sources at each sensing layer by organizing information via fundamental contextual attributes of space and time. We then integrate information from diverse sources to create spatio-temporal profiles of analytical objects of interests for specific city services applications (e.g., ambulance and fire trucks in
While it may seem straightforward to use all available assets for every new application that is designed and deployed. Therefore, we need a social computing platform that can exploit available devices in a city securely and privately and combine it with available cloud computing resources. The social computing platform is similar in structure to peer-to-peer mobile resource sharing networks. While Peer-to-Peer (P2P) resource sharing has existed for some time, ubiquity in mobile networks has not been achieved. This is in large part due to the fact that mobile networks are heterogeneous, having many different features and device capabilities. There are several challenges including discovery (finding the available near-by nodes), selection (selecting a subset of near-by nodes appropriate for a particular task), quality assessment (metrics for determining quality of service (QoS)), and replacement (replacing nodes with poor QoS).

To enable this extensible architecture that supports a P2P model where peers can opportunistically join and leave, we require a component-based approach so that the desired application functionality can be composed dynamically out of basic building blocks and deployed according to resource availabilities and mission requirements. As long as the building blocks support the expected interfaces, their implementations can be supplied by any third party. A component-based architecture also lends itself to ease of migration since functionality can simply be disassembled at runtime in one location, and composed and deployed in another location as shown in our prior work [13], [6]. From our experience with prior projects [1], [3], [8], we believe that the dynamic component placement and execution approach suggested here will require us to address a range of requirements described next.

In our envisioned solution there is no permanently deployed and operational system. On the contrary, only when individual users sign into their transit hub instance will that volunteer node join the available cluster. Therefore, the system is formed through a dynamic orchestration of individual app instances across multiple geographical areas. This new requirement calls for a P2P model of dynamically discoverable providers that can be composed to form an end-to-end system. Since each provider provides specific and unique capabilities, the P2P model is made up of asymmetric peers, i.e., heterogeneous peers. What this entails is that when composing larger systems out of building blocks, there is a need for the components to be discoverable, and supporting open interfaces and standard protocols. However, we can make an observation that instead of discovering unknown peers, the problem can be made manageable by the assumption that we are discovering instances of the application provided by us. Another point to note is that the problem of multiple peers having to discover each other is a problem faced in wireless software defined networking as well [7].

The another problem of resource management and discovery...
are intricately interconnected. To solve them both we require timely information on resource availabilities and their utilization. In prior work we have demonstrated how the OMG Data Distribution Service (DDS) publish-subscribe middleware can be used for highly scalable, reliable and real-time resource monitoring [9]. Once, the resources are known, we must be able to orchestrate the deployment of components (operations with states) to various nodes. To address this problem, we will endeavor to design a choreographed deployment, which will take the graph of computations to be performed (workflow) and place them on different computing nodes, always preferring the volunteer nodes. Such deployment architecture would not feature centralized cluster level services to manage deployments; instead distributed deployment agents, representing either individual computing nodes or groups of nodes clustered together based on location. We expect this clustering to happen dynamically using a cloud based service that will group computing nodes based on their geographical location (done anonymously by assigning random ids and websocket to the nodes). The cloud service will not store any long term information about these clusters.

In a choreographed deployment architecture, an agent (in this case a node requesting computation) wishing to deploy a distributed application would publish deployment-related meta-data into a distributed data space. Such meta-data might include topological descriptions of distributed applications, capabilities and requirements of available services/hardware, and current system goals. In prior work [8], [12], [10], we have shown how goal-based descriptions can be useful in dynamic reconfiguration of the system, which enables quantifying the degrees of freedom in the system design space. Individual component instance (an operation stage of a workflow) meta-data published in this space would include 1) hardware requirements, 2) co-location constraints (other components that must or must not be on the same node), 3) services required by the component, and 4) services provided by the component.

Individual deployment agents that are able to satisfy the hardware and co-location constraints of components take ownership of that component instance and deploy it, publishing any provided service references into the distributed data space. As required services are deployed by other agents (and consequently have references published), the deployment agent will establish connections and activate the component—in this way, individual deployment agents act independently to perform the same deployment activity as an orchestrated deployment.

**Research Thrust 3: Opportunities for Novel Applications**

We believe that applications that leverage the social computing platforms may be classified into:

- **Individual-centered**, such as personalized services
- **Organization-centered**, such as analytical dashboards
- **Connected community centered**, i.e., across organizations or a connected community, such as city services surveillance.

Although we do not have any applications that have been developed yet for such a computing environment, we describe the contours of a potential application that can help in homeland security. Consider the two terrorism-related incidents of September 17, 2016 involving bombs exploding in trash cans that occurred in the Chelsea area of New York City and in the adjoining state of New Jersey that left at least twenty nine people injured. One other device did not detonate. Surveillance videos captured by nearby cameras provided vital clues to investigators to understand the nature of the bombing and apprehend the suspect. The short duration of time within which law enforcement were able to pinpoint the source of the problem can be attributed in large parts to the already deployed assets, such as security cameras and their associated computing capability that provided vital clues.

We believe that in the near future, with increasing availability and use of smart devices by humans, such as Sony’s SmartEyeGlass, it is possible that socially sensed information, e.g., images captured and relayed through smart glasses, which are controlled by the humans operating the glasses via mobile phone apps, can be spatio-temporally combined with information from existing assets, such as surveillance cameras to more rapidly identify and thwart any such terrorism activities. Other more civilian and safety related applications are also feasible, e.g., reporting icy roads or flash floods.

Today there are very less number of “apps” available for such smart devices, and thus, there exists a rich set of opportunities for mobile app design and development that can leverage the proposed social computing platforms.

**Conclusions**

In this paper, we have outlined a vision of the fundamental research directions needed to realize the emerging paradigm of social sensing in smart city services context, and information processing that integrates cyber, physical and social sensing. We used a variety of motivating scenarios to highlight the key technical challenges, and proposed a trio of research directions to address those challenges.

**References**


