Collective Awareness and Action in Urban Superorganisms

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***Abstract*— Future urban scenarios will be characterized by the close integration of ITC devices and humans. Citizens using their own capabilities integrated with ITC technologies could collaboratively constitute a large-scale socio-technical superorganism to support collective urban awareness and activities. This position paper, with the help of a representative case study, identifies the key challenges for future urban superorganisms and proposes a two-tier architecture to support their development.**

***Index Terms*— Cyber–Physical Convergence, Pervasive Computing, Self-Organization, Middleware.**

I. Introduction

In a few years all urban places will be enriched with sensors, actuators and computational resources capable of interacting with users' devices [Con12]. Citizens, on the other hand, will have the possibility of being continuously connected on a situation-aware and socially-aware way with each other and with the objects/entities around, e.g., via some advanced situation-aware social networking infrastructure .

The above two factors will eventually contribute to define a dense ecosystem whose individual components (i.e. citizens, devices, software services, sensors and actuators), thanks to the possibility of being continuously connected on a socially aware infrastructure, will be able to act as a substrate for the deployment of innovative pervasive computing services. Such services can contribute towards the smart city vision along several dimensions, from urban mobility, to environmental sustainability and participatory governance [Sma07,Keh11].

All the ITC solutions in these dimensions will have impact on our way of living in the urban environments. Nevertheless, most importantly, they will change the very nature of our urban environments, turning them into sort of *socio-technical urban superorganisms* [Hol09, Zam12].

Future pervasive urban services, rather than being limited at sensing what happens in the city (as most of current approaches do) will enable the complimentary sensing, computing, and actuating capabilities of humans and ICT devices. The dynamics of such collaborative interactions will promote large-scale (i.e., collective) adaptive capabilities of perception, awareness, and action. That is, the overall urban environment will act as a single "superorganism" made up of many individual organisms, capable of directing its global behaviour towards the achievement of specific urban-level goals.

However, engineering collaborative and coordinated services capable of harnessing human and ICT capabilities at a very large scale, challenges current engineering practices and middleware (or social networking) architectures. In this context, the contribution of this position paper is twofold:

- It sketches the key concepts of urban superorganisms and outlines the key research challenges to be faced to enable their deployment.
- It proposes a two-tier middleware architecture capable of tackling the identified challenges. A specific attention is put to the awareness module of the architecture.

The paper is organized as follows. Section II presents our global vision and also introduces a case study to ground the discussion. Section III discusses key research challenges. Section IV proposes a general-purpose architecture and details the awareness module. Section V concludes.

II. The vision of urban superorganism

People are increasingly equipped with smart phones with powerful capacities in terms of battery life, sensing, computational power and connectivity. At the same time, autonomous ITC devices (sensor networks, security cameras, robots, etc.) are likely to pervade cities in the near future. Thus, the future urban environment is becoming a sort of very dense digital ecosystem.

A. Human vs ICT devices capabilities

The "components" that are going to pervade future urban environments are characterized by heterogeneous and complementary sensing, computing, and actuating capabilities, that can possibly cooperate in a finalized way.

The capabilities in sensing from ITC side are provided by *(i)* mobile phones equipped with GPSs, accelerometers, cameras and magnetometers; *(ii)* sensors networks and smart objects that follow the Internet of Things paradigm; *(iii)* tags that exploit the near field communication technology (NFC, RFID and Bluetooth). From the human side, the five senses of humans, which in many situations can supply and be more accurate than ICT sensors, can be put at work for the community, due to the possibility of continuous access to social networks. In addition, users can make available via

social networks any other with any other factual information, thus acting as sorts of social sensors [Ros11].

The capabilities in actuating from ITC side are provided by *(i)* traffic controllers supporting pervasive solutions in the mobility dimension; *(ii)* public displays that will be exploited to promote adaptable and interactive citizens experiences; *(iii)* all kinds of actuators related to critical infrastructures (water distribution, energy grid, etc.). From the human side the key actuating element involved is the human body, which is a very flexible and general-purpose one, and can perform a variety of actions related to moving itself or moving items around or changing the properties of some physical entities. In other words, citizens could accomplish physical actions, by realizing a real impact on the urban environment.

The capabilities in computing from the ICT side makes it possible to collect and digest very large amounts of urban data in a short time, and to perform some limited pattern analysis on such data. From the human side, on the other hand, the capability of recognizing complex situations and patterns (so called "human computation" [Yue09]), which machines can hardly tackle.

In summary, novel means of pervasive interactions in the urban environment could be designed to exploit the complementary capabilities of individuals in a collective and adaptive way.

B. Urban superorganisms and collective awareness

The very large number of inter-connected individuals that can be found in urban environments, whether humans or ICT ones, can potentially be exploited to create what has been defined as a "superorganism" [Hol09]. In particular, as sketched in Figure 1, closing the sensing, computing and thinking, and actuating capabilities in a loop, and making such activities collective ones, can promote the realization of finalized and coherent collective behaviours, as it is observed in many natural situations, e.g., in ant colonies.

A single ant has very limited and local sensing and actuating capabilities, and little or no cognitive abilities. Yet, ants can indirectly coordinate their movements and activities, via spreading and sensing of pheromones in the environment, so as to exhibit, as a colony, very powerful capabilities of sensing (finding food in the environment), computing (finding the shortest path from food back to nest), and action (carrying large amounts of food in the nest). These capabilities make the whole colony seemingly intelligent and certainly adaptive in its foraging activities [Bon98].

Future collectives of socio-technical entities (i.e., citizens and ICT devices) will be likely continuously – and possibly invisibly – involved in distributed and participatory sensing campaigns. The results of such *collective sensing* activities will then promote a sort of participatory perception that can enable *collective awareness* (by computing, by thinking, and by communicating) of urban facts and issues, and urban dynamics. Based on such shared understanding, it will be possible to plan for specific *collective actions* aimed at fixing problems or adaptively steering urban dynamics.

Previous works in opportunistic and participatory sensing

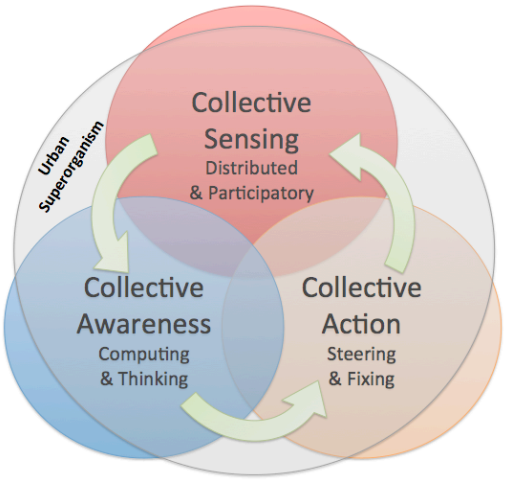

Figure 1. Sensing, awareness, and action, can be collectively put at work in future urban superorganisms.

have tried to involve users by making use of their devices as sensors [Kan12, Ram10]. On the opposite side, other works try to detect events or situations by observing users activities on online social networks [Sak10]. However, these works lack of a general and unified vision and do not completely deal with the complexity of the global scenario. Indeed, they do not explore all the possible convergences of humans and ITC devices. Moreover, they do not fully make use of the very large number of inter-connected individuals and their complementary capabilities to realize a collective awareness.

Recent research efforts in the field of self-adaptive and self-organizing systems have focused on defining a catalogue of bio-inspired mechanisms [Mar12], with the intent to overcome the limit of ad-hoc implementations that prevent their systemically reuse. Thus, the basic idea is that of providing the *bio-inspired self-organizing pattern modules* with a set of reusable patterns that could be used to ease engineering of artificial and collective behaviors of urban superorganisms. It is probable that the complementary capabilities of humans and ICT devices and the ability to coordinate and organize them could overcome current approaches and promote collective awareness and complex behaviors. In line with [Mar12], we think that bio-inspired algorithms could be helpful to achieve complex and coordinated behaviors.

In our opinion, it will be possible for the socio-technical collective of humans and devices to put in place a variety of finalized collective behaviours, expressing various forms of "urban awareness and intelligence", and promising to dramatically change the way we move, live, and work, in our urban environments.

C. Case study scenario

Let us now introduce a case study scenario related to the governance dimension in smart cities to exemplify the above concepts. In particular, let us consider a post-earthquake scenario. There, one could think at dynamically selecting and coordinating autonomous devices and groups of citizens or rescuers to perform – among many thinkable activities – a collective report of damages of the structures of buildings.

Needless to say, dynamically reconstructing a collective awareness of the current state of things in a moment in which nothing is any longer as reported in maps and individual memories, can be of dramatic importance.

More specifically, by steering and coordinating the movements and positions of heterogeneous mobile individuals (e.g., humans but also robots and CCTV cameras) one can dynamically plan for which portions of the city to map and in which order, also to account for the possibility to realize a 3D reconstruction (i.e., by making sure to have pictures of the same damages buildings from different well-defined locations) [Zak10]. This kind of coordination towards reconstructing a collective awareness of the state of the city could also make profitably use of the complimentary sensing and *understanding* capabilities of humans and ICT devices to make sure, for example, that all the images are properly tagged with information generated by devices and further enriched by humans, due to their higher classification capabilities.

III. Challenges for Superorganism Architectures

We identified many challenges towards the realization of a situation-aware and socially-aware infrastructure to support novel urban superorganisms features, i.e., to support innovative services needing collective coordination, awareness and adaptation.

Support for heterogeneity and interoperability

Whether they are humans equipped with a mobile phone or autonomous ITC devices, the software architecture has to be able to realize an abstraction layer in order to achieve the same goal on different individuals, by adapting and exploiting their heterogeneous and complementary SAC *(Sensing Actuating Computing)* capabilities.

Think at the complex collective task as that of taking multiple photos of a predefined building for a 3D reconstruction. Individuals could accomplish the coordinated sensing action in different ways; e.g. to take a photo *(i)* a remote camera could move along three axes; *(ii)* a drone could fly to the area of interest; *(iii)* a citizen could reach the predefined location supported by his mobile phone.

The challenge is to realize an abstraction layer able to continuously observe the superorganism status and plan strategies to reach specific goals by making use of heterogeneous individuals with evolving SAC capabilities.

Support for dynamic re-configurability

As emerged by the heterogeneity challenge, the software architecture should show a certain degree of flexibility. Thus, the ability to dynamically execute heterogeneous code with heterogeneous SAC capabilities is a key challenge to be tackled. For instance, in the case of a task executed by a citizen, the architecture has to support a service that requires the user interaction and thus has a user interface; while, in the case of the same task executed in a remote camera or a drone, the latter has to support services exploiting the SAC capabilities unsupervised devices.

Furthermore, dynamic service composition and re-configuration is needed. The design of an architecture dealing with these challenges will make applications interoperable and able to self-reconfigure and self-optimize depending on the execution context.

High degree of awareness

A prerequisite in this challenging scenario is a high degree of awareness. The high-level awareness acquired by the individuals through sensors should be used to infer complex situations and create a sort of collective awareness of the surrounding physical and social environment. The challenge here is to realize a software infrastructure that is able to:

- Opportunistically sense and recognize many heterogeneous kind of situations.
- Self-reconfigure the awareness subsystem itself. The reconfiguration should be based on the partial awareness acquired by the infrastructure and is aimed to *(i)* improve the recognition accuracy by optimizing the classification modules and to *(ii)* preserve computational resources.
- Exploit the awareness of other individuals of the superorganism to infer complex situations and behavior in the urban environment that involve groups of individuals.

All these challenges have to be solved to support for instance, scenarios where the individuals sensing capabilities have to be exploited to acquire detailed environmental information.

High degree of interconnection

As emerged by the case study, individuals have to be connected and able to exchange messages for both *(i)* supporting collective and finalized behaviors, e.g. the coordination effort required to steer individuals to take photos of a building with different perspectives; and *(ii)* gathering individual awareness to infer complex situations that involve the superorganism rather than specific individuals. It is worth noticing how this requirement calls for innovative data fusion techniques. In fact, at both the individual and superorganism levels multiple data streams of information sources have to processed and put together to build up a coherent picture of operating conditions.

Strategies for dynamic selection

One should evaluate which individuals are more suitable to be involved by taking in account different constraints. For instance, in the case study, many robots and humans could be available at the same time to take pictures. Strategies taking into account different constraints (e.g. geographical areas, individuals status, SAC capabilities) are needed to pick up the most affine individuals for the desired behavior. These strategies could be based both on explicit interactions (e.g., sending a message to an individual) or implicit interactions (e.g., subsampling the whole population of individuals satisfying specific constraints).

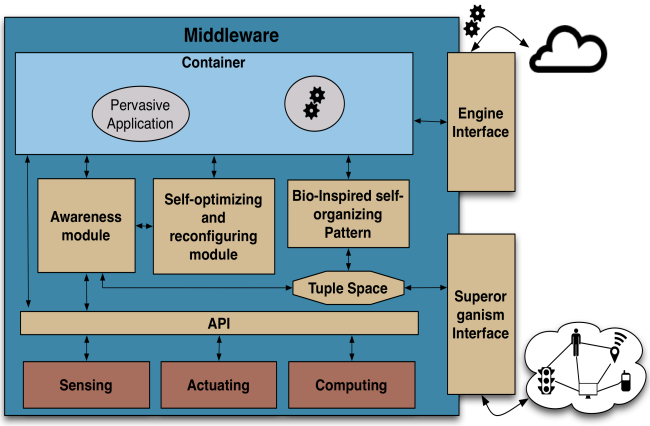

Figure 2. Architecture for individuals in the superorganism

Mixing bottom-up and top-down design approaches

Designing with a top-down approach means that all the requirements of a software architecture have to be taken in account a priori; systems engineered in this way have a predictable and measurable behavior but are not capable to cope with dynamic execution-context; while systems designed with a bottom-up approach are more robust and suitable for a pervasive environment but predicting their behavior and controlling them "by design" is not an easy task. In the design of architectures for urban superorganisms, both of the two approaches are needed and finding and tuning the optimal trade off between them is a key challenge to be tackled [Can12].

A first case identified is that of the coordination between individuals, as emerged by the use case. We claim that the resulting superorganism should rely on self-organization in order to take advantage of collective behaviors, by taking inspiration from natural metaphors. However, we claim also that emergent behaviors have to be controllable "by design" and thus understanding the trade-off of the two approaches and to what extent they can co-exist is a key challenge to be tackled to design controllable collective behaviors.

IV. An Architectural Proposal

By taking in account the challenges emerged in the previous section, we propose a two-tier middleware architecture. The former, deployed on individuals, is able to support the resulting superorganism; the latter hosts the centralized control engines, which are able to actuate urban superorganisms through the dynamic injection of pervasive services.

Individual Perspective

Our primary goal is to develop a middleware, on top of individuals, enabling urban superorganism features. According to the challenges described in the previous section, the middleware is characterized by a layered architecture, as depicted in Fig. 2. The first layer is an abstraction layer that exposes APIs to access to the SAC functionalities (sensors, actuators and computational capabilities) provided by individuals. To deal with their heterogeneity, it exposes only the APIs supported by the current individual.

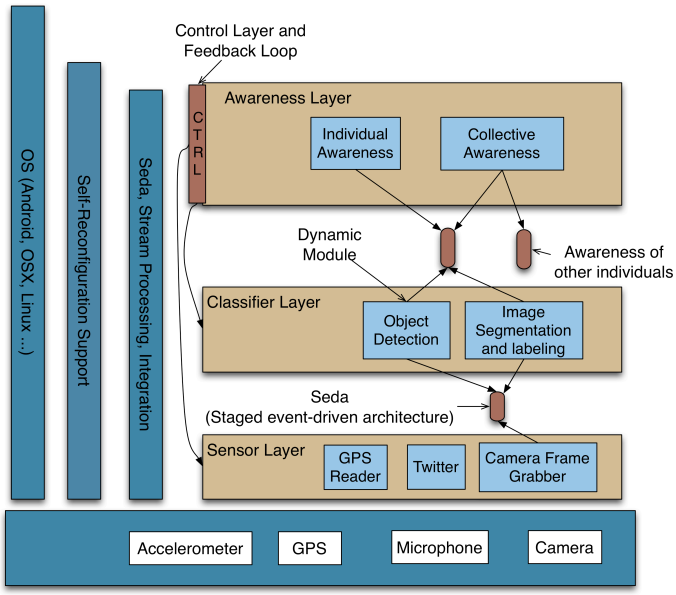

Figure 3. Awareness module internals

On top of this low-level layer our middleware provides support to *(i)* self-reconfiguration, *(ii)* inter-connection, and *(iii)* awareness.

To enable injected services to self-reconfigure and adapt to the current execution context. It is up to the self-optimizing and reconfiguring module to enable applications to self-reconfigure and thus deal with the re-configurability challenge, given applications specific strategies. In order to realize a reconfigurable application structure, the software model that best fulfills this requirement is the service-oriented component one (SoC) [Bel11].

To support emergent behaviors of superorganisms, the middleware embeds interconnected tuple spaces representing, in a distributed fashion, the current state of the environment on which individuals are sensing and acting. This module interacts with other individuals in the superorganism through the local tuple space, which uses the superorganism interface to exchange data and information between affine individuals.

Awareness is supported by the awareness module. It has been designed to provide both: *(i)* individual awareness (up-to-date information about individual physical and social context) [Bet10]; and *(ii)* collective-awareness (up-to-date information about the superorganism context).

As shown in Figure 3, it uses three conceptual layers to reach its goal, the sensor, the classifier and the awareness layer. Internally (see Figure 3), components of the sensor layer filter sensorial data stream coming from heterogeneous sensors; while components of the classifier layer classify them using general or specific purpose algorithms; finally, components of the awareness layer fuse classification labels to obtain a coherent overall picture of the situation.

Inspired by biologic mechanisms, we designed the awareness module to be able to autonomously self-

reconfigure. Particularly, by making use of its high level information, it is able to dynamically enable and disable specific data streams (and, thus, their corresponding sensors) and classification components for *(i)* improving the recognition accuracy by optimizing the classification modules, (ii) for adapting to evolving situations and for *(iii)* saving computational resources.

Finally, the role of this module is to support the execution of novel pervasive services that are dynamically injected through the *engine interface*; this feature could be implemented through a container-based approach [Gam05], which supports dynamic execution by providing a common environment with a set of reusable functionalities**.**

Superorganism perspective

According to the challenges identified in Section III, engines, which exploit urban superorganisms, have to rely on an autonomic architecture. Indeed, they are in charge of: *(i)* sensing specific aspects of the urban environment, whose individuals are dynamically selected; *(ii)* reacting to specific situations by following user-defined policies; and *(iii)* actuating urban superorganisms to optimize or to sense again, by realizing a closed control loop.

Finally, the control engines should coordinate with each other to share the acquired high-level awareness to support the achievement of complex global goals. Along this direction, a control engine has to behave like a virtual sensor to give the possibility to other engines to make use of its specific awareness. These features enable the possibility to realize a hierarchical inter-connected structure of engines able of sensing and actuating the whole superorganism in a fully distributed way.

V. Conclusions and Future works

As we have discussed in this paper, we believe that it will be possible to exploit socio-technical superorganisms to deliver complex collective urban-level services. In our opinion, innovative finalized collective behaviours expressing various forms of "urban awareness and intelligence" will take place, and dramatically change the way we move, live, and work, in our urban environments.

However, to reach this goal, many research challenges need to be addressed, and suitable middleware infrastructures have to be developed. At the time of writing, we are in the process of completing a first prototype implementation of the proposed architecture. In addition, our future work includes testing the infrastructure in controlled (campus-level) environment and, later on, start experiencing it on-the-wild with simple urban awareness services.

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