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Survey Paper

Engineering self-organizing urban superorganisms

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ABSTRACT

Progresses in ubiquitous, embedded, and social networking and computing make possible for people in urban areas to dynamically interact with each other and with ICT devices around. This can result in a system with a very large number of agents working together in an orchestrated and self-organizing way to achieve specific urban-level goals, i.e., as if they were a "superorganism". In this paper, we sketch the future vision of urban superorganisms and overview some emerging application areas heading towards the vision. Following, we identify the key challenges in engineering self-organizing multi-agent systems that can work as a superorganism, i.e., seamlessly involving ICT agents and human agents so to achieve some required urban level goals. Finally, we introduce the reference architecture for an infrastructure to support our future vision of self-organizing urban superorganisms.

1. Introduction

Progresses in mobile and ubiquitous computing are paving the way for innovative services to perceive detailed information about the surrounding world and interact with it (Conti et al., 2012). In addition, social networks are promoting innovative models and tools to engage people in situated collaboration activities (Rahwan et al., 2010).

In urban scenarios, these factors let us envision the possibility of integrating the complementary sensing, computing, and actuating capabilities of ICT agents and of humans agents, so as to realize a number of innovative services to increase both quality of life and urban sustainability (Zambonelli, 2012). The ultimate vision is that of a heterogeneous urban-scale multi-agent system (Jennings, 2001), whose individual agents can self-organize their collective activities to achieve specific urban-level goals, as if they were part of a single organism, i.e., what in biology is usually called a "superorganism" (Holldobler and Wilson, 2009).

In this paper, starting from the assessed biological perspective on superorganisms, we sketch the future vision of urban superorganisms, showing how ICT capabilities and human capabilities well complement each other. In particular, we discuss how, the urban superorganism *as a whole* will be able to: (i) combine a wide range of information sources (e.g., environmental data from sensor networks, mobility data and social network posts) to sense the current state of the city (Rosi et al., 2013) and of its individuals (Fortino et al., 2014); (ii) perform advanced reasoning on the data to identify patterns and situations, and plan actions (Aiello et al., 2011; Bettini et al., 2010; Pitt et al., 2013); and (iii) engage in large-scale coordinated tasks to achieve specific goals (e.g., optimize traffic flow in the city and make it more environmentally sustainable) (Harnie et al., 2014). Accordingly, we overview how such capabilities can be exploited to realize many innovative applications and services, pushing current smart cities' visions much forward (Kehoe et al., 2011).

Clearly, the road towards the full realization of the urban superorganism vision and of its associated applications is having plenty of challenging open research questions. These range from scientific questions (e.g., how can we enforce "by design" a specific self-organizing behavior?) to engineering (what coordination models and technologies better suit a large system of heterogeneous agents?) and social ones (how can we made people willing to act as part of the superorganism?). This paper will analyze some of these research challenges and eventually proposes a reference architecture for a middleware infrastructure aimed at tackling the above challenges and at supporting the deployment and execution of advanced superorganisms services.

The remainder of this paper is organized as follows. Section 2 details our vision on self-organizing urban superorganisms. Section 3 overviews innovative application areas for future urban superorganisms. Section 4 discusses key research challenges to be solved towards the realization of the vision. Section 5 proposes a general-purpose architecture addressing some of those challenges. Section 6 concludes.

2. The urban superorganism vision

In the near future, a very large number of inter-connected agents, whether human or ICT ones, can be potentially exploited to create

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what – in biology – has been usually defined a superorganism (Holldobler and Wilson, 2009). That is, a large ensemble of individual organisms capable of behaving in a collectively orchestrated way to serve the good of the ensemble itself. In particular, closing the sensing, computing, and actuating capabilities in a loop, and making such activities collaborative ones, it is possible to realize coherent collective behaviors, as it is observed in many natural situations, e.g., in ant colonies (Bonabeau et al., 1998).

2.1. From biological to urban superorganisms

A single ant has very limited, 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 collective behaviors.

This can occur because the pheromones mechanism induces coordinated activities that – by closing into a feedback loop – turns the limited individual capabilities of sensing, understanding and acting into collective ones. In fact (Bonabeau et al., 1998; Van Parunak, 1997):

- *Acting*: When an ant finds some food source, it starts spreading pheromones in the environment, thus creating a path that leads to food. The overall activities of the ants of the colony in spreading pheromones eventually shape a distributed field of pheromones that can be used to find food.
- *Sensing*: To find food, an ant senses existing pheromone field gradients (if any, or wanders randomly otherwise). Such field gradients, if followed uphill, eventually lead the ant to food. This makes the ant start spreading pheromones in its turn and producing further paths that increase the chances for all the ants of the colony to find food.
- *Understanding*: All that an individual ant has to do in terms of cognitive activities is computing the direction of the uphill gradient. However, the colony as a whole exhibits an incredible efficiency in finding food sources, in computing the shortest paths to food, and in adaptively reshaping the pheromone fields to account for contingencies.

In a similar way that individual ants behave as if they were a single superorganism, we envision that citizens, along with ICT agents and devices, can be engaged in large-scale coordinated activities. This would allow the city as a whole to become a sort of superorganism, via which to realize complex coordinated tasks for the good of everyone.

2.2. From individual to collective behaviors

Fig. 1 illustrates the sensing–understanding–acting feedback loop that – as in ant colonies – can contribute leveraging individual capabilities into collective ones, and eventually make collective behaviors possible. There, advanced finalized and coordinated activities are the result of the following:

- *Sensing* activities in which users, supported by ICT devices and services, get information about the current state of the environment (e.g., people location data) and can share such information (e.g., as already happens for mobile phone sport trackers) .
- *Understanding* activities in which advanced forms of contextual information are derived from the sensed data (e.g., individual citizens mobility patterns), and possibly aggregated to evaluate the global properties of a city (e.g., the global mobility rhythms).
- *Acting* activities, in the form of seemingly goal-directed global coordinated tasks, supported by the extracted information, and put in actions by groups of agents (e.g., traffic steering on the basis of the identified mobility patterns and car sharing on the basis of people mobility routines).

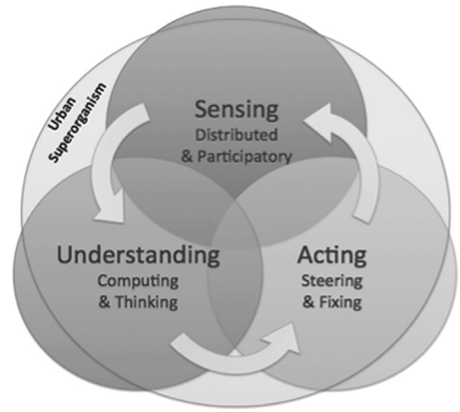

Fig. 1. Collaborative sensing, understanding and acting among humans and ICT agents can be put at work to realize advances in urban-level behaviors.

To close the feedback loop, the results of these activities clearly affect the overall state of the city and the individual state of citizens. Citizens can perceive such changes at both the individual and collective level, and can recognize the effects of their actions (Mitchell, 2005). This makes it possible to compute new actions in real time and induce a positive effect in those who recognize the effect of their actions.

2.3. The complementary role of humans and ICT agents

In this section we provide more details on the sensing, computing and actuating activities that can be put at work to enable the above described collective behavior cycle (fig. 2).

People are increasingly equipped with smart phones that are very powerful in terms of battery life, sensing, computational power and connectivity. At the same time, autonomous ICT infrastructures (sensor networks, security cameras, and robots) are likely to pervade cities in the near future. Accordingly, the future urban environment is becoming a sort of dense digital ecosystem, whose components are characterized by heterogeneous and complementary sensing, computing (i.e., understanding), and actuating capabilities.

As for sensing, capabilities in sensing from the ICT side can be provided by: (i) mobile phones equipped with GPS, accelerometers and cameras; (ii) sensors networks and smart objects that follow the Internet of Things paradigm (Fortino et al., 2012; Fortino and Trunfio, 2002); (iii) tags that exploit the near field communication technologies (NFC, RFID and Bluetooth). From the human side, the five senses of humans can, in many situations, supply and be more accurate than ICT sensors (think about the possibility of sensing opinions and “moods”, which ICT sensors can hardly provide). Also, they can be easily put at work for the community, due to the possibility of continuous accessing to online social networks, where to express and make public the sensed information (Rosi et al., 2013).

As for computing, capabilities 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. However, from the human side, one can effectively exploit the capability of recognizing complex situations and patterns (so-called human computation, Yuen et al., 2009), which machines can hardly tackle. Think, for example, at recognizing a situation in which two friends pretend to fight just for joking and are not really hurting each other.

As for actuating, the actuating capabilities from the ICT side can be provided by: (i) traffic controllers supporting control of vehicles movement (e.g., traffic lights); (ii) public displays that can be

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