Self-organizing Network of Autonomous Agents for Emerging IoT Applications

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***Abstract*—The paper introduces concept of networked meta-object emerging as a next generation of IoT application scope, studies its application-independent common properties and proposes, for it, a conceptual model using self-organizing multi-agent network. The paper proposes, for the networked meta-object, three layered reference architecture with the focus on reusability of software responsible for group behavior control.**

1. Introduction

Information technology (IT) landscape is currently rapidly changing: novel classes of applications and advanced intelligent technologies are being emerged in parallel affecting each other via positive feedback. Indeed, the recently introduced paradigm "Internet of Things" (IoT) proposed networked model for applications composed of physical, virtual and social objects provided with embedded computational and communication capabilities intended to solve application tasks on the massively interaction basis. This paradigm conceived initially for industry gave rise to many new methodologies, models and architectures advancing IoT to a novel intelligent IT. In its turn, attractiveness and productivity of IoT paradigm encouraged remarkable expansion of its application scope.

These mutually enabling processes caused emergence of a new class of control objects, "networked meta-objects". From the micro viewpoint, it refers to a set of intensively interacting indivisible autonomous heterogeneous objects (nodes) capable to perform various plain functionalities on request of networked meta-object's constituents and to share resources they possess. These nodes operate within some common infrastructure supporting for their communications and interactions. From the macro point of view, emergent meta-object is a single whole with dynamic connectivity of its nodes due to node mobility and node population change.

The concept of the networked meta-object emerging as the next generation of IoT is the subject of the paper study. The paper shows, by examples, that along with its "classic" applications, it is also covers many new ones those are composed of intensively interacting autonomous mobile objects. The paper justifies that multi-agent self-organizing network is the architecture paradigm that best fits the specific features of the networked meta-objects. Based on the common features of the exemplified applications mostly related to the field of group control and teamwork of autonomous objects, the paper introduces its re erence architecture emphasizing reusability issue. Finally, the paper concludes with summarizing its main contribution.

II. Application-independent Networked Meta-object Features: Modeling Issue

Fig. 1 illustrates graphically an entity called *networked meta-object*. Its components (sub-networks) may conceptually correspond to various functional components of meta-object like sensor network, sources of shared resources, cloud resources and services, distributed control objects like multi-robot system, etc. The study of some applications listed below shows that a number of common specific properties characterizes all of them, and, among them, followings are the most important:

1) Intensive interactions of its constituents operating in common communication and information spaces provided with access if necessary to cloud resources and services.
2) All shared resources and services available in the networked meta-object are of common use, i.e. there are no any holders of available resources and services.
3) Multi-task operation of networked meta-object enabling potential real-time conflicts of access to shared resources causing high importance of *real-time resources scheduling.*
4) Dynamic connectivity of the networked meta-object operating via local interactions excluding centralized control.

The first follow-up conclusion is that intensive local interactions constitute the core of the networked meta-object operation. The second is that self-organizing network of autonomous software agents situated in the shared software and communication environments is a well-suited framework for modeling of networked meta-object. Additional argument in the same favor is that, currently, there is no other technology for implementation of self-organizing network systems.

III. Examples of Applications: Autonomous Mission and Group Behavior Cases

The most popular example of IoT applications in question satisfying the features mentioned above is multi-user intelligent sensor network. In it, every sensor is capable to interact with other network sensors, perform simple local computations and supply the perceived and preliminary processed information to many consumers, on their requests. E.g., it can perceive geophysical data, weather- and/or ecology-related data. Another example is large-scale multi-purpose distributed surveillance system performing, e.g. perimeter security tasks.

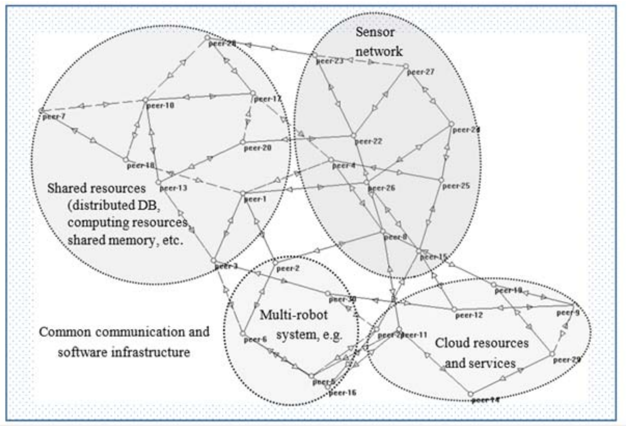

Fig. 1. Illustration of an entity called "networked meta-object" composed of a large number of interacting nodes (peers)

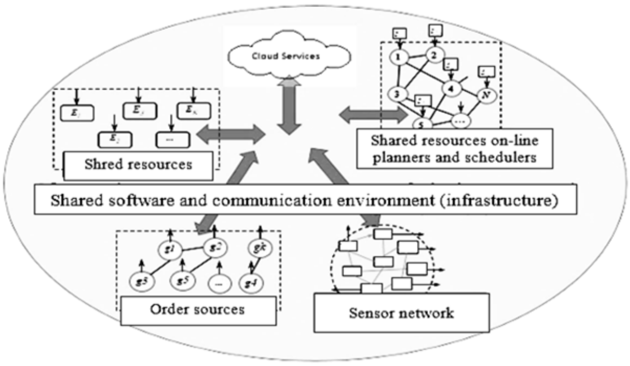

Fig. 2. Generic components of a networked object put into shared communication and software infrastructure

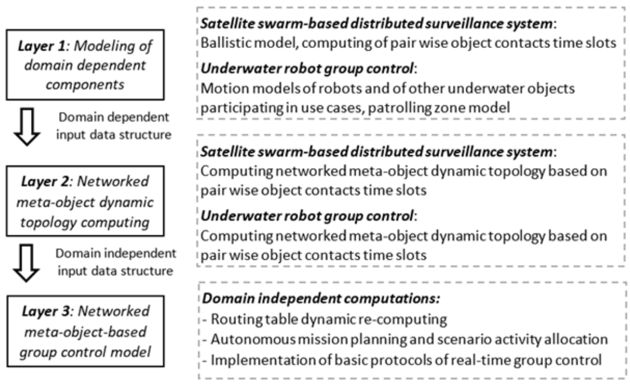

Fig. 3. Layered reference architecture of networked meta-object

Several new IoT applications were studied. Among them,

- Space-based distributed surveillance system composed of a large number of small satellites.
- Group of autonomous underwater robots performing autonomous patrolling inside underwater space of a seaport.
- B2B-production network composed of distributed companies interested to cooperate due to their complementary capabilities, and some others.

These applications are representatives of what is called *group control*, or autonomous *teamwork* problem that is being the subject of great concerns and intensive researches since the middle of 1980th and until the present days. For this problem, the strict logic-based theoretical foundation, agent-based architectures, basic protocols, as well as a number of supporting software tools were developed, to the end of 1990th. However, classic logic-base BDI-models of multi-agent systems and developed technologies and software tools found out too inefficient and are now out of practical use.

In contrast, the practical experience proved that the proposed networked meta-object model relying on massively interacting self-organizing agents of simple functionalities found out much better from both implementation technology and target product efficiency viewpoints. Its generic character, reference architecture for target application modeling and reusability are discussed below.

IV. Reference Architecture and Reusability Issues

Analysis of the application-specific networked meta-objects mentioned in the previous section proved that all of them are composed of the semantically same components (Fig. 1, 2):

- The *tasks (orders)* incoming from external world or originated from internal nodes those meta-object has *to perform*;
- *Shared resources* the nodes of the meta-object possess that are necessary to fulfil incoming flow of tasks (orders);
- *Information sources* like sensors or cloud storages providing of information about context of order execution, etc.
- *Cloud services* and *resources* available from the Web providing the meta-object with additional functional capabilities, resources and information.
- *Software* supporting for *real-time planning* and coordinated *scheduling* of shared resources.
- *Shared software and communication infrastructure* transforming the set of autonomous entities into a networked meta-object operating as a single whole.

These semantically common components of the networked meta-objects representing various application domains make possible to use of practically same reference architecture that, in its turn, permits to elicit reusable (application-independent) components at software implementation level. The proposed reference architecture is depicted, in practically self-explaining form, in Fig. 3. In it,

Layer 1 performs *domain-dependent* computations, e.g., satellite motion-based pair wise visibility relations between nodes (satellites, ground control points, ground objects to observe) thus determining meta-object connectivity intervals.

Layer 2 transforms domain-dependent information (e.g., visibility relations) to domain independent network graph.

Layer 3 performs domain-independent (reusable) software implementing use cases of the infrastructure where the meta-object nodes "live" and interaction protocols of group control.

V. Conclusion

The paper justifies an expressive and efficient networked meta-object model for emergent intelligent IoT applications represented in terms of self-organizing multi-agent ad-hoc network operating based on local interactions. It is exemplified by several applications from the distributed group control field implemented as software prototypes. The paper contribution is also the reference architecture of meta-object implementation which important advantage is reusability issue.

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