Cloud-Centric PaaS Framework for Robots Operation

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Abstract—**Modern trends in industrial technology include theoretical and applied research aimed at finding effective methods to control distributed dynamic systems. This research has particular importance for scientific foundations of field robotics that were greatly improved in recent years by the cyber physical ideas. In this paper we provide constructive analysis focused on possibilities of application of cyber physical approach to robots' motion planning and coordination to achieve control objectives in spatially and temporally undefined conditions. Proposed approach is based on multi-invariant actor-information representation and cooperative interaction of all components that describes a robotics system both on the physical (local or actor-based) and informational (knowledge or ontological-based) levels which are implemented using distributed resources of private cloud computing environment as IaaS and Hadoop. Actor-based representation (model) of each physical objects or artificial machine (robot) has specific attributes including name, data stack and parameters. The model describes environmental characteristics of mechanical, sensor, navigation and computer-communication components, the local interaction of which takes place onboard the robot and is needed to achieve declared control objectives. An informational model is proposed to represent common system characteristics, objective features, and robot as mobile carrier of specific operations. It is shown that system control requirements may be reduced to a "constraint satisfaction" problem. The decision of such problem is expressed by two sets of entities: a set of operations performed by robots of the group, and a set of messages that are generated by the informational model and delivered to each robots of the group using network infrastructure.**

I. INTRODUCTION. CYBER-PHYSICAL APPROACHES

In the near future new generation of artificial physical devices will be created. They will be characterized by the flexibility, elasticity and sensitivity that are common to living organisms, but will have greater strength and durability because of materials used. Such devices would be able to receive, store and transmit information about their surroundings, which will be used during their operations. Information is transmitted between physical objects and also between objects and the human operator.

Complex engineering tasks concerning control for groups of mobile robots are not yet sufficiently developed. In our work, we use cyber physical (CPh) approach, which extends the range of engineering and physical methods for a design of complex technical objects by researching the informational aspects of communication and interaction between objects and with an external environment.

It is appropriate to consider control processes with cyber physical perspective because of the necessity for spatio-temporal adaptation to changing goals and characteristics of the operational environment. Thus the priority task is to organize the reliable and high-performance system of information exchange between all entities involved in the realization of all requirements. Hereinafter, by cyber physical object we mean an open system for the information exchange processes. Data in such system is transmitted through the computer networks, and its content characterizes the target requirements achieved through execution of physical and mechanical operations, energy being supplied by the internal resources of the object (Fig. 1).

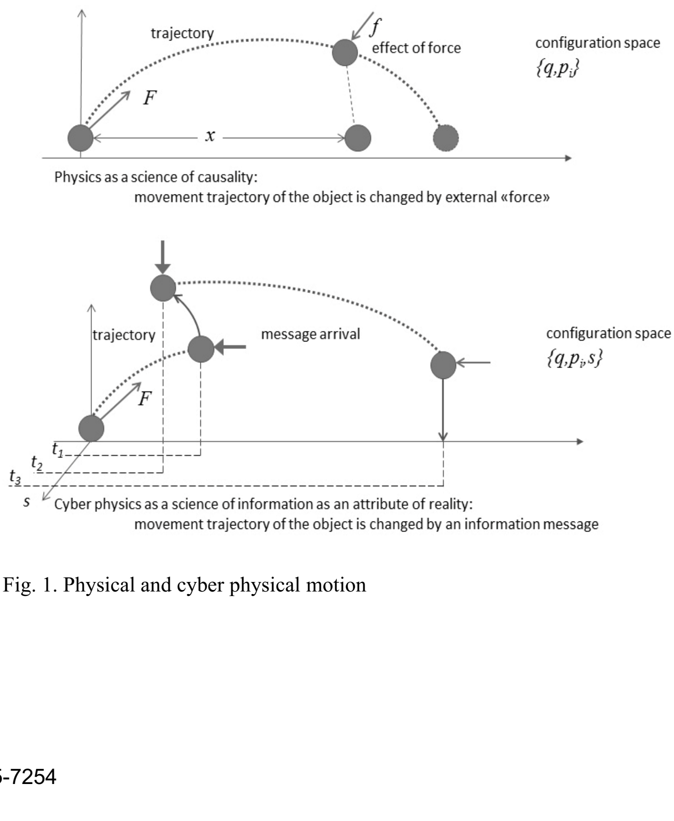

Fig. 1. Physical and cyber physical motion

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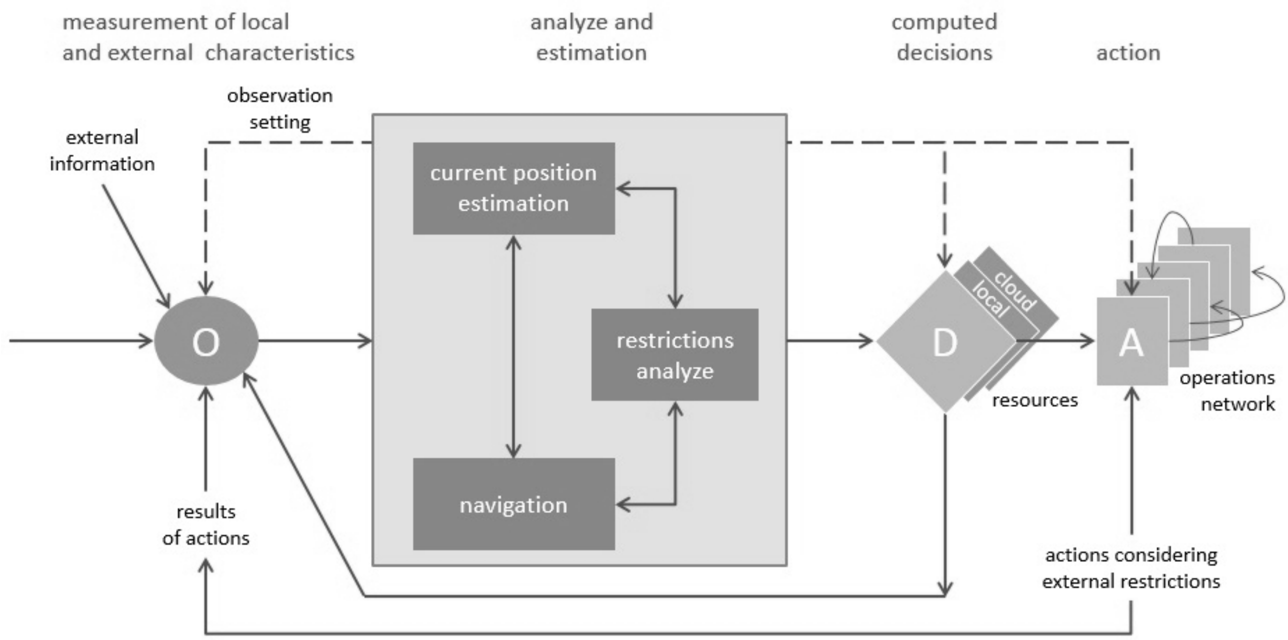

Fig. 2. Cyber physical interpretation of the John Boyd's OODA loop

An example of a cyber physical object is a mobile robot that does complex spatial movement, controlled by the content of the received information messages that have been generated by a human-operator or other robots that form a multi-purpose operation network. An ontological model of informationally open cyber physical object may be represented by different formalisms, such as a set of epistemic logic model operations parameterized by data of local measurements or messages received from other robots via computer connection.

Although there are different approaches in modern science to the application of information aspects of the physical objects, only within cybernetics such approaches have structural engineering applications. The conceptual distinction between closed and open systems in terms of information and computational aspects requires the use of new models, which take into account the characteristics of information processes that are generated during the operation of the physical objects and are available for monitoring, processing and transmission via computer network.

According to Fig. 2, cyber physical model of control system can be represented as a set of components, including following units:

- information about the characteristics of the environment (Observation),
- analysis of the parameters of the current state for the controlled object (Orientation),
- decision-making according to the formal purpose of functioning (Decision),
- implementation of the actions that are required to achieve the goal (Action).

The interaction of these blocks using information exchange channels allows us to consider this network structure as a universal platform, which allows us to use various approaches, including the use of algorithms and feedback mechanisms or reconfiguration of the object's structure for the goal's restrictions entropy reduction or the reduction of the internal processes' dissipation.

Centralized solutions allow using universal means for the organization of information exchange to integrate different technologies for both observed and observable components of the controlled system. The parameters and the structure of such control system can quickly be adjusted according to the current information about the internal state of the object and the characteristics of the environment, which are in a form of digital data.

These features open up the new prospects for the development of intelligent cyber physical systems that will become in the near future an integral part of the human environment in the information space of so-called "Internet of Things." According to the estimates [1], network-centric cyber-objects in the global information space of the Internet will fundamentally change the social and productive components of people's lives. That will accelerate the knowledge accumulation and the intellectualization of all aspects of the human activity.

However, this process requires not only innovative engineering ideas, but also the development of scientific concepts united into a universal scientific paradigm . Within this paradigm, the information should be considered a fundamental concept of objective reality, in which physical reality has “digital” basis and therefore is computable. The idea of integrating the physical concepts with the computation theory has led to the new conceptual scheme of nature descriptions, known as «it from bit». In this scheme, all physical objects, processes and phenomena of nature, which are available to be perceived and understood by a person, are inherently informational and therefore they are isomorphic to some digital computing devices. Within this paradigm information acts as an objective attribute of matter that characterizes the fundamental distinctiveness of the potential states of the real object. The distinctiveness, according to the Landauer’s principle, is an energy factor of the object’s states and that is why it gives an explanation of what are the states and how they are perceived by other objects. This distinctiveness appears while creating the systems that are capable of ensuring the autonomy of their existence during the interaction with the external environment by the self-reproduction of their characteristics. It should be noted that on the way to the widespread use of “digital reality” for the control problems there are some limitations that reflect the requirements for the existence of the special state of physical objects reflecting their changes as a result of the information exchange processes.

The selection of cyber physical systems as a special class of designed objects is due to the necessity of integrating various components responsible for computing, communications and control processes («3C» – computation, communication, control) [3]. Therefore, the description of the processes in such systems is local and the change of its state can be described by the laws of physics, which are, in its most general form, a deterministic form of the laws of conservation of, for example, energy, mass, momentum, etc. The mathematical formalization of these laws allows us to determine computationally the motion parameters of the physical systems, using position data on the initial condition, the forces in the system and the properties of the external environment. Although the classical methodology of modern physics, based on abstraction of “closed system” is significantly modified by studying the mechanisms of dissipation in the so-called “open systems”, such aspect of reality as the information is still not used to build the control models and to describe the properties of complex physical objects. In the modern world, where the influence of the Internet, supercomputers and global information systems on all aspects of the human activity becomes dominant, accounting an impact of information on physical objects cannot be ignored, for example, while realizing sustainability due to the information exchange processes. The use of cyber physical methods becomes especially important while studying the properties of systems, known as the “Internet of Things”, in which robots, network cyber-objects and people interact with each other by sharing data in the single information space for the characterization of which are used such concepts as “integrity”, “structure”, “purposeful behavior”, “feedback”, “balance”, “adaptability”, etc.

The scientific bases for the control of such systems have become called Data Science. The term “Big Data” describes the process of integration technologies for digital data processing from the external physical or virtual environment, which are used to extract useful information for control purposes. However, the realization of the Data Science potential in robotics requires the creation of new methods for use of the information in control processes based on sending data in real time at the localization points of moving objects (the concept of “Data in motion”) [2].

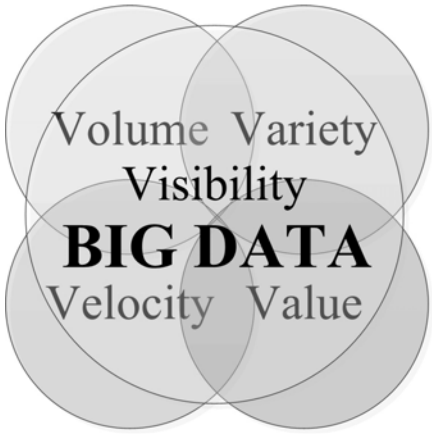

Fig. 3. Big Data structure

In general, the “Big Data” is characterized by a combination of four main components (four “V”): volume, variety, velocity and value (see Fig. 3). The general “V” is visibility of data and it is also a key defining characteristic of Big Data [4].

As a result, “Big Data” in modern science has become synonymous to the complexity of the system control tasks, combining such factors of the physical processes that characterize the volume, velocity and variety and value of data generated by them.

So cyber physical approach is now often used to describe the properties of the so-called non-Hamiltonian systems in which the processes of self-organization are described by dissipative evolution of the density states matrix. However, the cyber physical methodology may be successfully used to create complex robotic systems, the components which are capable of reconfiguration as the result of transmitting and processing digital data or metadata. The control tasks that are considered to cover the actual scope of the cyber physical approach, which is the basis of cloud computing technology and development of the methodology of cybernetics towards the metadata control.

II. SECURE AND HIGH PERFORMANCE IAAS ENVIRONMENT IMPLEMENTING CYBER PHYSICAL PROCESSES

Cloud providers, such as Amazon, Rackspace, Heroku, and Google may provide different services based on the models of Infrastructure as a Service (IaaS), Platform as a Service (PaaS) or Software as a Service (SaaS), whose integration into a specific environment of industrial development is carried out by highly qualified engineers and IT- specialists. So far, actual challenge has been to develop cloud services for hybrid cyber physical environments where robots and humans can operate together. These services have to provide human resources as well as computing environment.

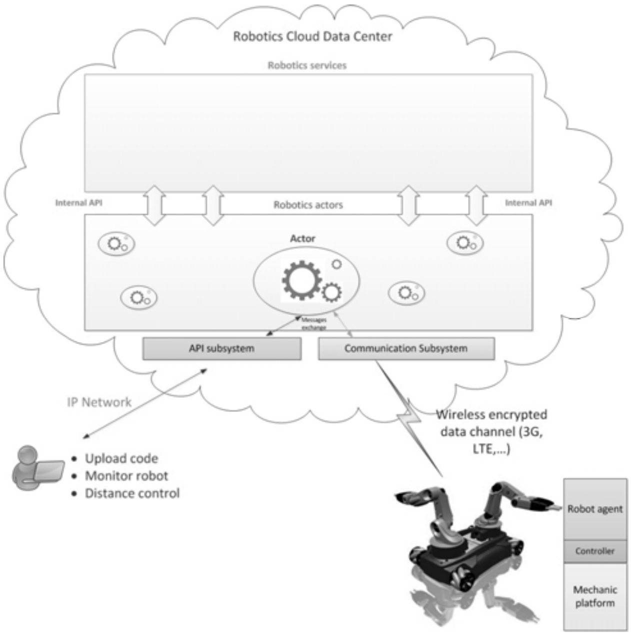

Fig. 4. Robotic cloud platform with heterogeneous computing resources

Heterogeneous cloud platform is the basis of computing infrastructure for cyber physical centers; the principal difference from the classic data centers is to provide remote access not only for computing resources or applications, but also intelligent services. Using the resources of modern cloud-based engineering centers it is possible to create equivalent social networks that bring together multiple agents, which potentially distributed over our planet or galaxy to perform coordinated actions, computation, verification of test results based on the use of different materials, virtual prototyping, and data visualization. These problems, from the point of view of the computational algorithms, can be combined into chains, which form a network of operations. Their implementation is provided within a heterogeneous cloud. The components of the platform (Fig. 4), based on the OpenStack, include: IaaS cloud class segment, computing infrastructure within the cluster, the specialized high-performance hybrid system based on reconfigurable computing nodes.

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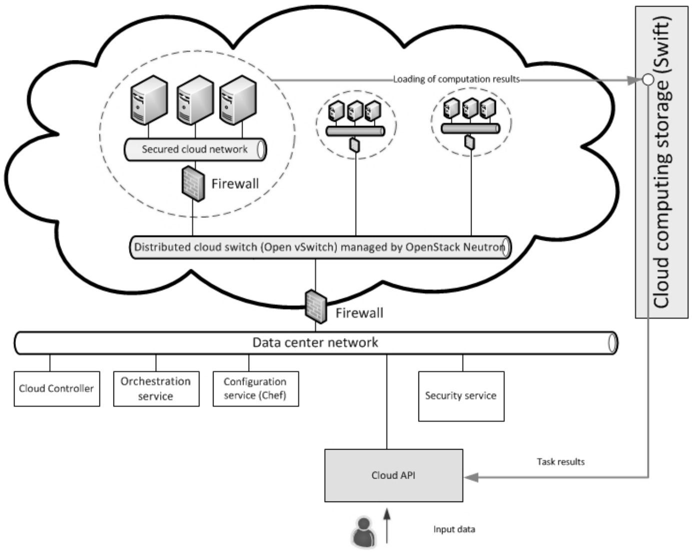

Fig. 5. Components of cloud platform and security in SDN infrastructure

In addition, computing center has access control service for the cloud services protection. Its main features are support of dynamic infrastructure, scalability, and the ability to support security policies without reference to the composition of resources. This service is built on the technology of stealth traffic filtering and software defined networks (SDN) and provides the reconfiguration of access isolation system according to the current state of the environment (the question of access control in cloud environments is discussed in detail in [5] and [6]). Static platform segments adhere to the principle of "rent" under which the filter rules of segment access are formed only by users and services running at any given time. On the platforms of this type, the situations when user needs a single virtual machine are rare. Therefore, cloud services support the dynamic creation of secure networks with a set of preconfigured virtual machines. Secured networks are connected to the firewalls which are integrated with the distributed SDN switch, Open vSwitch or OpenStack Neutron networking service (Fig. 5).

Firewalls protecting the dynamically generated cloud networks are created during computing segment initialization. An important feature of the firewall is its ability to function in the address-less mode. It allows implementing invisible protection of a cloud, and security system integration not requiring the reconfiguration of a cloud network subsystem. The firewall acts as a virtual machine. The firewall of a network segment filters network traffic according to the rules created by the access policy service. Access policy in a cloud computing environment is based on the Role Based Access Control (RBAC) model of access control. This policy can be represented as a set of following attributes:

- user IDs, that are involved in the management of virtual machines and information services;
- privileges that are described in the form of permitted information services (privileges set rules for user access to services, it is possible to change the privileges for the user in the specified virtual machine filtering rules for your firewall, which allow access to a network service);
- set of roles that can be assigned to users;
- user sessions in a computing environments based on the network connections between subjects and objects.

Access policy is translated to firewall filtering rules according to computing environment state. This state can be represented by a set of IP addresses of computing resources, with assigned user labels. Label represents a user holding the computing resource. When a state of a computing environment changes, then it is necessary to generate a new set of filtering rules and reconfigure firewalls. For this purpose, a method of the dynamic configuration rules has been developed, which consist of substitution of the network address lookup in user-owners privileges for each virtual machine. This approach formed the rules of access to the services of the computational resource and of computing resource to services of other users.

For compute tasks which require heterogeneous computing resources, it is necessary to automate creation of the protected segments. We describe heterogeneous computing system as a set of logical computing resources. Such a segment must be applied to the specified security policy to permit the possibility of access to computing resources for the owner, but forbid access to these resources to other users. When the task is complete, the results must be loaded into the data warehouse, and the computing resources are freed (Fig. 6). At the same time, it is essential to guarantee access to computing resources in simultaneous execution of multiple tasks.

We used OpenStack for creating groups of virtual machines in a cloud environment service. This service supports description of configurations in an Amazon Cloud Formation format that ensures compatibility with public services such as Amazon AWS. This service allows creating groups of virtual machines according to pattern, virtual networks, cloud-based routers and other components. The images of virtual machines contain a basic set of services. Any other application specific packages are installed using the automation services provided by Opscode Chef framework that provides automated deployment of software configurations in virtual machines and bare-metal servers. When new computation segment is being created, the security system spawns and configures virtual firewall, which is filtering the access to newly created network serving the computation. Dynamic network creation is supported by OpenStack Neutron services and by distributed virtual switch Open vSwitch. After computation is complete and the results are received, the segment is removed, the cloud resources are released, and the results are uploaded to cloud storage to become available to the other consumers of the service. Every operation is automated: there are no steps requiring human intervention.

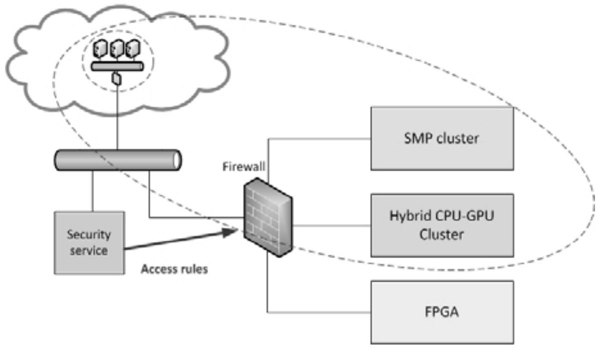

Fig. 6. Reconfiguration of hybrid supercomputer center using firewalls

Reconfigurable segments of the cloud allow solving a wide range of scientific and technical tasks, among them: tasks that operate on large data sets based on the MapReduce technology. Tasks that cannot be solved in the cloud virtual machines (for example, requiring quick access to globally addressable memory and massively-parallel or streaming computations) are transferred to dedicated hybrid clusters for high performance computing, equipped with an internal high speed communication bus, nodes-accelerators based on FPGA and GPU. Firewalls provide protection from unauthorized access to computing resources in a time of challenge and consolidation of heterogeneous segments (cloud and high-performance) computing resources into a single computation network, which components can communicate with each other, using the allowed protocols.

Built this way, the infrastructure allows to dynamically create secure computing segments and thus provides an opportunity to organize a simultaneous execution of various tasks on a single set of hardware resources Fig. 6). This solution implements reconfigurable federated cloud with one interface and multiple computation segments. A similar approach was used for organizing a mobile cloud for intelligent transport systems [7].

The proposed approach of organizing cyber physical data center which is based on cloud services enables ability to reconfigure computing resources for different computation tasks. Integrated security services allow sharing computing resources between different users and clients. Reconfiguration of computing resources by using cloud firewalls is not a standard approach. It requires additional resources and makes platform more complex. From other side, it provides opportunity of reconfiguration of resources on network level. Stealth technology allows leaving applied software without modification. Dynamic computation segments creation service allows to effectively use the IaaS resources on demand.

The proposed infrastructure as a service cloud platform, named Pilgrim, serves hybrid computing resources in datacenter of St. Petersburg Polytechnic University.

III. PAAS ENVIRONMENT FOR ROBOTS

It is necessary to extend infrastructure as a service computing environment to organize the operations of cyber physical systems. It is impossible to create a scalable software environment just by using virtual machines and virtual networks. To organize the cyber physical operations the following formalism had been proposed:

CPO = <Avatar, Agent, Platform>,

where Cyber Physical Object (CPO) is decomposed into three instances:

- Avatar is the brain of an object. It is represented by a set of processes inside high performance computing environment.
- Agent is client software that runs on a robot itself. It can be placed on a controller or a small computer. It doesn't perform complex computation operations. Agent collects data from robot's sensors and sends control signals to a platform. All data is sent to Avatar and Avatar sends control messages. However, some agents might have autopilot functions engaged when connectivity with Avatar is temporarily lost.
- Platform is a physical representation of a CPO. It could be vehicle, manipulator, UAV, etc. Platform is managed by Agent's controller.

Let's describe the tasks to be performed by an Avatar of CPO:

- Avatar decides which operation has to be performed by its Agent and Platform.
- Avatar converses with another Avatars using internal cloud communication bus.
- Avatar converses with available services: databases, storage services, Internet services (it can even use Wikipedia to get required information).
- Avatar launches computation and data management processes inside a cloud. It could by, for example, big data tasks driven by Apache Hadoop, high performance computing tasks, etc.

According to the above, an actor based architecture was proposed. Actor primitive as a computing unit was proposed in a model developed in 1972 [8]. In this case Avatar is presented as a set of actors:

Avatar={actor1,actor2,..actorN}.

Each Avatar's actor has its own program code, which is presented in high-level language. In our Platform implementation, Scala and Akka platform were used, but, in general, that can be done in any language that supports the

Actor model: Java or Erlang, for instance. Actor models allow to scale out the cloud environment and organize effective communication between Avatars and other services. Message-centric architecture allows for transferring internal messages from avatars to their agents using access gateways.

Avatars in a cloud have ability to subscribe to custom events generated by other actors. For instance, one CPO collects images from its camera. Avatar of such CPO performs image analysis and if the results are of some interest to the system, sends an event to a hub, and all avatars interested in this topic extract required data from message and generate control data for their agents.

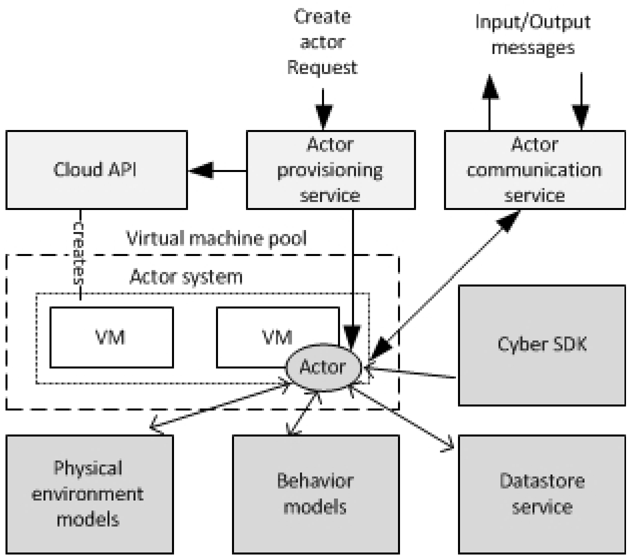

Fig. 7. Cloud-centric software architecture

Cloud-centric software architecture is presented on Fig. 7. Actor provisioning service handles requests from users or agents. Based on request data it allocates a new actor in actor system, which is deployed on multiple virtual machines. If all virtual machines are fulfilled by another actors it invokes cloud API and creates new virtual machine for an actor system. Actor can communicate with an agent by sending and receiving messages through Actor communication service. It translates actor's messages to ProtoBuf data and sends it over network. Cyber SDK is a library, which consists of generic robot algorithms, utility methods, etc. Behavior models is a storage of serialized data, which represents robot's behavior. It could be neural networks [9], input data for algorithms and other parameters. Physical environment models service provides descriptions of physical environments such as maps, routes, etc. Actor could communicate with these services by using theirs API based on message driven architecture.

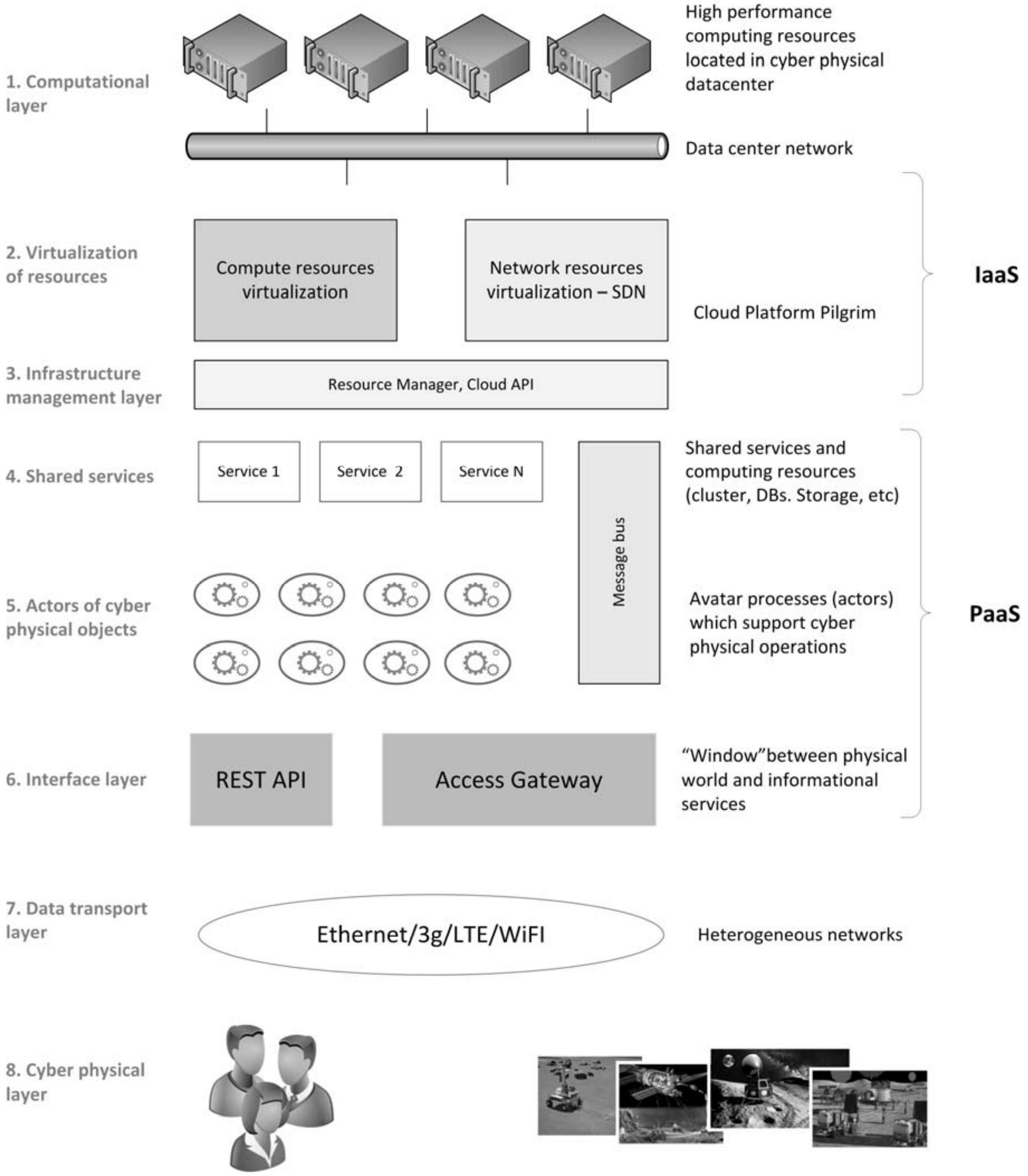

Fig. 8. Architecture diagram of cloud platform for cyber physical operations

Platforms of such avatars can be distributed all over the world: in this case, all communication is performed inside a datacenter without sensible delays. Fig. 8 presents architecture diagram of a PaaS platform.

Platform is split into eight levels. Levels 1-3 represent an infrastructure layer and are provided by the Pilgrim IaaS platform. In general and with some restrictions first three levels might be implemented in another IaaS cloud, for example, in Amazon VPC cloud. Levels 4-6 are the heart of PaaS platform. It is Avatar's actors placed into their containers and service's actors which provide interface to computing and information services. Level 7 is a data transmission layer. Each Agent has its own interface for connecting with data center. It could be GSM or WiFi connection, or a radio channel. The last, eighths level is an Agent world. All robots, operators and other cyber physical objects are represented by this level.

Such architecture and CPO decomposition have following advantages:

- PaaS paradigm helps platform users to write code on high level language (Scala, Java) and simply load it into computing environment.
- Avatar as a brain of a CPO can be easily replaced during runtime. One robot can play a lot of different roles: everything depends on the Avatar.
- There are no cognitive functions inside Agent. So, complex logic cannot be reverse engineered: Agent is useless without its brain.
- High performance computing environment allows to perform operations which are impossible to implement on relatively low-power mobile hardware.
- Platform allows to perform fast communications between CPOs distributed over long distances.
- Also, such architecture allows to organize network-centric systems with shared knowledge base and information actualization in real time.

IV. Conclusion

The proposed approach to the cyber physics as a new interdisciplinary science focuses on the organization of the engineering infrastructure and software architecture, that providing an opportunity for communication between physical, mechanical and information-computing processes arising during network-centric interaction of intelligent robots and their virtual "avatars". Using the metaphor of "information ashes" allows us to emphasize the importance of presenting physical connections as one of the forms of information relations underlining the idea that "everything is from bit". Operating space for virtual image of physical objects can be formed by specific cloud-centric infrastructure based on robust communication channels, Big Data repository. The designed software architecture of cloud computing infrastructure is the reliable carrier of the control algorithms that form robotic operation network as the constructive model for interactions of cyber physical objects.

References

[1] V. Zaborovsky, M. Guk, V. Muliukha, and A. Ilyashenko, "Cyber-physical approach to the network-centric robot control problems", *The 14th International Conference on Next Generation Wired/Wireless Advanced Networks and Systems NEW2AN/ruSMART 2014*, LNCS 8638, pp. 619-629.

[2] A. Lukashin, L. Laboshin, V. Zaborovsky, and V. Mulukha, "Distributed packet trace processing method for information security analysis", *The 14th International Conference on Next Generation Wired/Wireless Advanced Networks and Systems NEW2AN/ruSMART 2014*, LNCS 8638, pp.535-543.

[3] L. Zhang, Y. Fallah, J. Rezgui. "Cyber-Physical Systems: Computation, Communication, and Control". *IJDSN*. 2013.

[4] Infographic: The Four V's of Big Data, Web: http://www.ibmbigdatahub.com/infographic/four-vs-big-data.

[5] A. Lukashin, V. Zaborovsky, and S. Kupreenko. "Access Isolation Mechanism Based On Virtual Connection Management In Cloud Systems", *13th International Conference on Enterprise Information Systems (ICEIS 2011)*, pp. 371 – 375.

[6] V. Zaborovsky, A. Lukashin, S. Kupreenko, and V. Mulukha. "Dynamic Access Control in Cloud Services", *The 2011 IEEE International Conference on Systems, Man, and Cybernetics (IEEE SMC 2011)*, Anchorage, Alaska, USA, October 9-12, 2011 – pp. 1400-1404

[7] V. Zaborovskiy, A. Lukashin, S. Popov, and A. Vostrov "Adage mobile services for ITS infrastructure", *Proceedings of the 13th International Conference on ITS Telecommunications (ITST)*, 5-7 Nov. 2013, pp. 127-132.

[8] C. Hewitt, P. Bishop, and R. Steiger "A Universal Modular Actor Formalism for Artificial Intelligence", *IJCAI*, 1973.

[9] Alexey Lukashin and Anton Lukashin. "Resource scheduler based on multi-agent model and intelligent control system for OpenStack", *The 14th International Conference on Next Generation Wired/Wireless Advanced Networks and Systems NEW2AN 2014,* LNCS 8638, St. Petersburg, Russia.