Cyber-Physical Control System of Hardware-Software Complex of Anthropomorphous Robot: Architecture and Models

Mikhail Stepanov, Vyacheslav Musatov, Igor Egorov, Svetlana Pchelintzeva and Andrey Stepanov

Abstract Autonomous anthropomorphous robots represent complicated hardware-software complexes designed to functioning in a changing external environment. Additional features of any particular robot are defined by its scope. Educational activity imposes tight restrictions to ensure safe work and study environment at an institution. It is required to solve many different tasks in a real-time mode. The efficiency of their solutions is defined by availability of computing resources, as well as by thorough organization of the hardware-software complex oriented toward a specialized class of the autonomous robotics tasks. With this goal in mind, we analyzed the complex of the tasks for the teaching assistant robot. Among those, one of the most important was the task of obtaining information about the environment. We analyzed the task of a trainee status examination and possible ways of its solution, and offered the architecture of a hardware-software complex of the anthropomorphous robot assistant. The set-theoretic model of a hardware-software complex was constructed. Its use would further allow defining an optimum configuration of the offered hardware-software complex architecture for anthropomorphous robots. The distributed computing system of a hardware-software complex for anthropomorphous robot assistant facilitated parallel solving of the tasks related to situation analysis, as well as planning and control of the robot operations.

Keywords Anthropomorphous robotics · Hardware-software complex · Set-theoretic model · Brain activity · Digital signals · Pedagogy · Wavelet analysis · EEG test · Neuroscience · Brain-computer interface

1 Introduction

Currently, educational robotics gains an increasing importance both at a high-school stage, and in higher education. As for secondary schools, much attention is paid to inclusive education, specifically to disabled students' adaptation to studying in

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a mainstream class. Despite some available positive experiences, there are many children with difficulties to learn in a conventional group owing to specific features of their physical health or emotional status.

Studies on the autism conducted in 2014 by the group of Christina Kostesku and Zachary Vorren, published in a Journal of Autism and Developmental Disorders, showed that children demonstrated a positive feedback to robotic systems, paid more attention to the robot rather than a person, better performed repetitive tasks with participation of the robot, while their cognitive abilities were identical no matter trained by the robot or a person.

On the basis of those results, the following requirements were imposed to teaching assistant robots:

- Small dimensions: height of the automated robotic complex (ARC) needs to be about 155 cm, which subconsciously associates ARC with a teenager;
- Compliance of behavioral modification, which represents training challenging skills (such as speech, game playing, or ability to look in the face) but can be conducted by ARC;
- Readiness for communication, creation of friendship bonds, and satisfaction of displayed curiosity;
- Psychologically appropriate design to exclude any possible harm to a child even in the case of his or her aggressive behavior;
- Ability to react to aggression and other suspicious and potentially harmful actions from the child, and to inform the operator about those.

We suggest two possible directions of using a hardware-software complex for anthropomorphous robot assistant.

- First, it is appropriate for work with disabled children. The anthropomorphous robot can be useful to disabled school students as a teaching assistant. It can be beneficial both for teaching children with mental retardation and for working with autistic students, helping to improve their social communication skills. In these situations, the methods of a biological feedback can be especially helpful. These methods include analyzing the electroencephalogram (EEG) signals, which helps specifying an emotional and psychological state of a child, concentration of the child's attention via the brain activity analysis in alpha, beta and delta ranges, and therefore, defining the strategy of operating the robot assistant.
- Another direction includes an android assistance to different age groups. The android robot can be useful at different stages of school training. For elementary school students, and for those in the 5th–6th grades, the android robot acts as an assistant (the so-called "supplementary child sitter") who would approve and adjust their behavior on the basis of a biological feedback therapy. Students of the 7th–8th grades belong to the awkward age category when similar system can be used for identification of their psychosocial and emotional problems, which can be further adjusted by using the android assistant acting in this case as a "senior companion". In high school years, especially at the specialized study schools, the connection of trainees with a robotic complex is quite possible. For example,

within the framework of their scientific activity, they can develop original control algorithms for android robots using brain-computer interface technology.

Thus, a variety of android robot applicability fields necessitates conducting in-depth studies of the tasks and architecture of anthropomorphous robot assistant hardware-software complex (ARA HSC) for a teaching professional.

2 Defining Study Task

A distinctive feature of prospective application of the robotics in educational process is the variety of tasks needed to be solved in a real-time mode.

The goal of our study includes an analysis of tasks, and determination of architecture and the methods of solving the major problems providing an efficiency of functioning in a real-time mode. We should specify that our efficiency estimates are based on conventional criteria of the real-time mode: time of a task solving and requirements to hardware resources in terms of used memory volume.

3 Tasks and Structure of ARA HSC

The ARA HSC for teaching professionals represents the cyber-physical system intended for active support of educational process on the basis of assessing an extent of mastering a training material by means of a solving the following tasks:

- Investigating brain activity patterns of a trainee on the basis of EEG examination;
- Analyzing an emotional status on the basis of recognition of a trainee face video image;
- Evaluating physical activity of a trainee (movements of a head, hands, fingers, eyelids and eyes);
- Analyzing written answers of a trainee to educational tasks;
- Assessing speech activity of a trainee (oral answers to educational tasks);
- Measuring an extent of a training material mastering by a trainee on the basis of solution results' generalization for the tasks 1–5;
- Evaluating the environment on the basis of video images of a classroom obtained by ARA video cameras;
- Choosing the standard procedure of ARA actions adequate to a current status for activating a trainee for a deeper mastering of a training material;
- Planning actions (dialog options, ARA movement) on activation of a trainee in the direction of deepening the mastering of a training material taking into account the current status;
- Planning actions (dialog options, ARA movement) on encouragement of a trainee taking into account the current status;

- Planning actions for data treatment of a trainee's current status taking into account an availability of unwanted artifacts as a part of the analyzed data set;
- Planning managing impact of the drives of a hardware component of ARA for implementation of the planned physical activity taking into account safety of interaction with subjects and objects of a surrounding situation;
- Controlling the course of implementing ARA planned physical activity and its adjustment to the status change of a surrounding situation;
- Self-diagnosing ARA subsystems for identifying a possibility of executing the objectives, or, otherwise, making a transition to a "recovery" status;
- Other tasks arising in the process of expansion of the purposes and opportunities of ARA HSC.

The provided task list conducted by ARA HSC is far from being full. It is also necessary to consider a research scope of ARA HSC under development, and, therefore, among ARA users, besides those directly participating in educational process, the following should be taken into account: a teaching professional, computing system administrator, psychologist (optionally), developers of application software, developers of the system software, investigators, and methodologists.

Considering rather limited energy resources of autonomous ARA, the tasks demanding large computing resources for their solution are subject to a transfer onto the stationary server placed in a close proximity to the classroom. Such placement would allow avoiding big tasks on the traffic. Alternatively, there are well-known problems of organizing a network interaction between the computing system of autonomous ARA and a server component of ARA HSC. Consequently, a wide variety of the problems to be solved requires the distributed organization of the computing environment in ARA HSC. At the present stage of information technology development, the so-called cloud computing approach is frequently employed in similar situations [1]. It allows using additional resources located on other servers.

Cloud computing services presume control of the cloud-computing software via conventional web browsers [1]. Cloud computing is a dynamically developing technology of information infrastructure use.

The concept of cloud computing includes a set of the following notions [1]:

- Infrastructure as a Service (IaaS) is a computer infrastructure provided, as a rule, in the form of virtualization. IaaS is the service within the concept of a cloud data treatment;
- Platform as a Service (PaaS) is an integrated platform for development, expansion, testing and support of web applications. It is presented in the service form based on the cloud computing concept;
- Software as a service (SaaS) represents a business model of software licensed presuming software development and support by the supplier. Customers are given an opportunity of its paid use, as a rule, by means of the Internet;
- Desktop as a Service (DaaS) is another business model of software licensed use, which represents slightly improved SaaS model, generally assuming simultaneous use of several services required for comprehensive work.

Besides above-mentioned cloud computing notions concept, the ideas of Big Data as a Service (BDaaS) and Everything as a Service (EaaS) are rather widespread. Both notions show that, by means of a World Wide Web with cloud computing, it is possible to satisfy any needs for information processing. The latter is a primary benefit of cloud computing within the IT solutions for the business.

Taking into account our previous experiences, we selected the option of implementing GAMMA-3 system of the automated task solution with cloud computing use as a basis for developing ARA HSC [2].

The enlarged structure of ARA HSC system of the automated task solution with use of the cloud computing concept is presented in Fig. 1. In the simplified look, the offered structure consists of the interconnected system of specialized servers complemented with the server redirector (proxy server). The purpose of the server redirector is simplification of the interactions among client applications and cloud service resources. It is achieved by encapsulation, i.e. by means of concealing information from the client on the physical location of the data or the server providing required services.

For ARA HSC system, it is possible to define the following categories of the users:

- ARA per se making requests to specialized servers for data treatment, action planning, etc.;
- Teaching professionals, setting the tasks for ARA HSC at their lessons on execution and control of implementing the stages of a lesson, assessment of its results, making the amendments for the course of a lesson, etc.;
- Methodologists developing the techniques of conducting the lessons, creating standard procedures for conducting lessons, feedback procedures to possible deviations from the conventional course of the educational process, etc.;

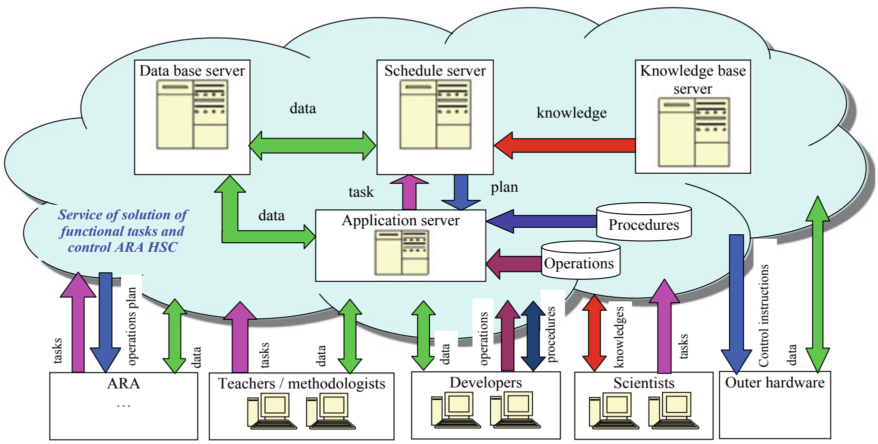

Fig. 1 The integrated skeleton diagram of the automated solution system of ARA HSC tasks with a cloud computing use

- Developers of the application software implementing computing processes on solving functional tasks;
- Developers of the system software of the bottom level providing interactions with external equipment (encephalographs, video cameras, microphones, gyroscopes, accelerometers, moment sensors, encoders, etc.);
- Investigators creating and studying the components of ARA HSC providing possibilities for solving intellectual tasks;
- Head of development exercising control of the course of executing the project;
- Accidental users (students of higher education institutions enrolled in ARA HSC project development).

For each user category, we developed customized applications giving the opportunities corresponding to the category. As the advantages in comparison with local or intranet options of implementing the automation equipment for solving design tasks, it is possible to identify:

- Lack of participation need of ultimate users in filling available local automation equipment with components implementing new methods of the management theory for solving new tasks;
- Lack of constant capacity expansion requirement of the memory devices for placement of increasing design data volumes;
- Reduction of financial expenses due to use of software product rent instead of their full-cost acquisition;
- Reduction in the total time of solving the tasks of design due to decrease in unproductive costs of designers' work hours for execution of unusual work.

The specified effect is achieved due to centralization of support and development for the automation equipment of a design task solving by the ARA HSC developer.

The proposed implementation option of ARA HSC within the framework of the cloud computing concept can be referred to the EaaS category. It is defined by the placement of all project components (data and knowledge, including programs and functions for solving conventional tasks, as well as formalized models of knowledge for solving the tasks in a non-procedural setting) in a cloud service. For the purpose of ensuring confidentiality of information for ARA HSC users, we propose applying cryptographic protection both in a network interaction and at storage of information on servers of data and knowledge.

4 Set-Theoretic Model of ARA HSC

Information technology development allows raising the system organization of information support for developing management systems to a new level. Among priority directions [3], top two places are taken by virtualization and cloud computing. The generalized ARA HSC system structure can be presented in the form:

$$S = \langle F, A, G, Rl, T, D, O\rangle, \quad (1)$$

where $F = \{f_i\}$ is a set of functional components, $A = \{a_i\}$ is a set of algorithms of component functioning $\dim(A) = n_a$; $G = \{\langle f_i, f_j, r_{ij}(f_i, f_j)\rangle | f_i \in F,\ f_j \in F, r_{ij}(f_i, f_j) = \{0|r_k\}, r_k \in Rl, n_R = \dim(Rl),\ k = \overline{1, n_R}, i = \overline{1, n_f}, j = \overline{1, n_f}\}$ is a scheme (graph) of component interrelations; $Rl = \{r_1, r_2, \ldots, r_{n_R}\}$ is a set of component interrelations for the system; $D = \{d|d = \langle p, c, m\rangle\}$, $d \cdot m \in C^{n_{m_1}} \times C^{n_{m_2}} \times C^{n_{m_3}} \times C^{n_{m_4}}$, $d \cdot c \in C^{n_{c_1}} \times C^{n_{c_2}} \times C^{n_{c_3}}$, $d \cdot p \in \{true, false\}$ is a set of types of data information structures used for solving the tasks, where C^x is a x-dimensional space of complex numbers; $P = \{p_i | p_i \in \{true, false\},\ p_i = f_{p_i}(d_x, d_y) d_x, d_y \in D\}$ is a set of the relations used in settings of the tasks being solved; $O = \{o|o = \langle o_c, o_s, o_r, o_d\rangle,\ o_s = \{d|d \in D\},\ o_r = \{d|d \in D\},\ o_c \subset \{\{\{d \cdot p\}^*\} \times Rl\}, o_d \subset Rl\}$ is a set of actions (operations) used for solving the tasks; $T = \{t|t = \langle t_S, t_R, t_D\rangle\}, t_S \subset D^*, t_R \subset D^*, t_D \subset \{\{\{d \cdot p\}^*\} \cup Rl\}, d \in D\}$ is a set of tasks, where $X^* = X^0 \cup X^1 \cup X^2 \cup \ldots \cup X^N \cup \ldots$, $X^0 = \varnothing$, $t_S = Src(t)$ are input data, $t_R = Rqr(t)$ are required results, $t_D = Dmnd(t)$ are requirements to the results of a $t \in T$ task solution.

For the purpose of optimizing the structure of considered information support service for the automated task solution, it is necessary to construct mathematical models and to conduct modeling to identify the system characteristics. It is reasonable to solve such problems using the methods of the queuing theory [4]. Its tools include analytical and simulation modelling of queuing systems and networks.

Among the tasks to be solved, there are declarative (non-procedural) tasks, solution automation of which requires artificial intelligence methods [5]. The cloud service of the automated solution of intellectual tasks (SITaaS, or "Solving of Intellectual Tasks as a Service") has the construction tool (planning) [6] for the sequence of actions (design operations). Execution (for example, with use of the software "Instrument-3m-I" [7] as environments of actions execution for a tasks solution) of the latter would lead to obtaining required task results. Not only tasks of data processing, but also tasks of actions planning [6] included into tasks area for solving by ARA HSC. The big share of the tasks solved by PAK RAAT is related with processing and data analysis about a trainee's status. Often analysis of EEG [8–11], of physical activity data [10, 12], of video images streams for assessment of a psychophysical and emotional status of trainees carry out by artificial neural networks [13–15] as the fast means of parallel information processing. The corresponding methods are implemented as procedures and operations (modules) of different hierarchy level of ARA HSC' knowledge model. ARA HSC is using cluster of NVIDIA Jetson TX2 for big data processing. High processing rate of information by ARA HSC is the key to quickly decision making on the basis of objective data.

Set-theoretic SITaaS model is described by the expression:

$$M_{SITaaS} = \langle D, A, Rl, T, Pl, S, I_{\mathrm{P}}, I_{Pl}, I_S\rangle,$$
$$D = \{d|d = \langle p, c, m\rangle\},$$
$$d.p \in \{true, false\},$$

$$d.c \in C^{n_{c1}} \times C^{n_{c2}} \times C^{n_{c3}},$$
$$d.m \in C^{n_{m1}} \times C^{n_{m2}} \times C^{n_{m3}} \times C^{n_{m4}},$$
$$A = \{a_i | a_i = \langle \mathrm{Cnd}(a_i), \mathrm{Src}(a_i), \mathrm{Rst}(a_i), \mathrm{Dmnd}(a_i) \rangle\},$$
$$\forall a_i \in A\{(\mathrm{Cnd}(a_i) \cup \mathrm{Src}(a_i) \cup \mathrm{Rst}(a_i)) \subset D*\},$$
$$\mathrm{Cnd}(x) \in \{\{d.c\} \times \{r\}\},$$
$$\mathrm{Src}(x) \in \{\{d.c\} \times \{d.m\}\},$$
$$\mathrm{Rst}(x) \in \{\{d.p\} \times \{d.c\} \times \{d.m\} \times \{r\}\},$$
$$\mathrm{Dmnd}(x) \in Rl, d \in D, r \in R,$$
$$T = \left\{ t_i | t_i = \langle \mathrm{Src}(t_i), \mathrm{Rst}(t_i) \rangle, t_i \subseteq (\bigcup_{s_j \in S} \mathrm{tasksOf}(s_j)) \cap (\bigcup_{pl_i \in Pl} \mathrm{tasksOf}(pl_i)) \right\},$$
$$Pl = \left\{ pl_{\mathrm{i}} | pl_{\mathrm{i}}(t_{\mathrm{i}}) = \{a_j^{pl_i} | a_j^{Pl_i} \in A\}, \dim(pl_{\mathrm{i}}) \right.$$
$$\left. = n_{pl_i}, \bigcup_{a_{ij} \in pl_{\mathrm{i}}} \mathrm{Rst}(a_{ij}) \supseteq \mathrm{Rst}(t_i), \bigcup_{a_{ij} \in pl_{\mathrm{i}}} \mathrm{Src}(a_{ij}) \setminus \bigcup_{a_{ij} \in pl_{\mathrm{i}}} \mathrm{Rst}(a_{ij}) \subseteq \mathrm{Src}(t_i) \right\},$$
$$S = \left\{ s_j | \mathrm{tasksOf}(s_j) \in T \right\}, \forall pl_{\mathrm{i}} \in Pl \left(\mathrm{Src}(t_i) \xrightarrow[\mathrm{I}_{pl}(pl_i(t_i))]{} \mathrm{Rst}(t_i) \right),$$
$$\forall t_i \in \bigcup_{s_j \in S} \mathrm{tasksOf}(s_j) \left(\mathrm{Src}(t_i) \xrightarrow[\mathrm{I}_S(\mathrm{s_j})]{} \mathrm{Rst}(t_i) \right),$$
$$\forall t_i (\mathrm{Rst}(t_i) \subset \bigcup_{a_j \in A} \mathrm{Rst}(a_j), t_i \xrightarrow[\mathrm{I_{Pl}}(D, A, Rl)]{} pl_i),$$

where $\mathrm{I_P}(t_i)$ is planning of the actions on a $t_i \in T$ tasks solution, for which, out of the elements of a $a_j \in A$ elementary operations set, building the procedure $pl_{\mathrm{i}}(t_{\mathrm{i}}) = \{a_{ij} | a_{ij} \in A\}$, $\dim(pl_{\mathrm{i}}) = n_i$, $j = \overline{(1, n_i)}$ is possible, such that the following conditions are satisfied: $\forall a_j \in pl_{\mathrm{i}}((\cup \mathrm{Src}(a_j) \setminus \cup \mathrm{Rst}(a_j)) \subseteq \mathrm{Src}(t_i))$, $\forall a_j \in pl_{\mathrm{i}}((\cup \mathrm{Rst}, (a_j) \supseteq \mathrm{Rst}(t_i))$; $\mathrm{I_S}(s_j)$ are the means for task solving of the software $s_j \in S$ providing required result $\mathrm{Rst}(t_i)$ on the set input data $\mathrm{Src}(t_i)$ for all tasks t_i belonging to the class of solvable tasks $t_i \in \bigcup_{pl_{\mathrm{i}} \in Pl} \mathrm{taskOf}(s_j)$ of the software $s_j \in S$; $I_{Pl}(pl_i)$ are the means for executing procedures $pl_i \in Pl$ of a task solution $t_i \in \bigcup_{pl_i \in Pl} \mathrm{tasksOf}(pl_i)$ providing required result $\mathrm{Rst}(t_i)$ on the set input data $\mathrm{Src}(t_i)$.

For implementation specified in the offered $\mathrm{I_S}(s_j)$ model of means (a cure of tasks of the $s_j \in S$ software), $\mathrm{I}_{Pl}(pl_i)$ (means of execution of $pl_i \in Pl$ procedures), $\mathrm{I_P}(t_i)$ (means of planning of actions on a $t_i \in T$ tasks solution) it is supposed to use modifications of the corresponding subsystems of the INSTRUMENT-3m-I systems [16] and the GAMMA-3 systems [17, 18]. Modification is caused by need of their placement for server components of a cloud service.

The constructed set-theoretic model will be used for carrying out researches by methods of the queuing theory for the purpose of optimization of components of system.

5 Design of a Classroom for Correctional Training

Correctional training differs in specific requirements to the conditions of conducting educational process. In this regard, the scheme of an educational group of two trainees for correctional training is offered in the Fig. 2.

In Fig. 2, the following components of a robotic system supporting the educational process of correctional training for two trainees are presented:

- *R* is a robot assistant of anthropomorphous type;
- *the classroom* (4 video cameras in the corners, 2 TV sets for reproduction of educational information, 2 workplaces for trainees, each of which includes a desk, a chair/armchair, a computer, a frontal video camera with a microphone, an audio system);
- *workplace of the teacher* (a desk, a chair/armchair, a computer, a frontal video camera with a microphone, an audio system);
- *workplace of the methodologist* (a desk, a chair/armchair, a computer, an audio system);
- *workplace of the administrator* of the information system server (a desk, a chair/armchair, a server computer).

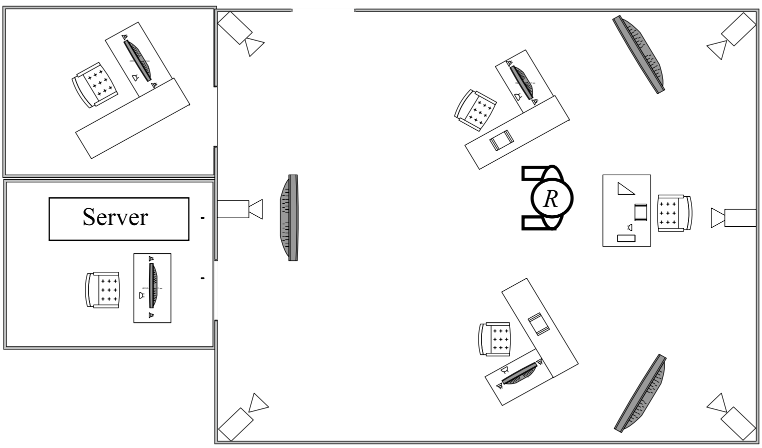

Fig. 2 The scheme of a classroom for two trainees for correctional training

6 Scheme of Component Interactions for Robotic System Supporting the Correctional Training Educational Process

The scheme of component interactions for the robotic system supporting the educational process of correctional training for two trainees is presented in Fig. 3.

Some of the depicted in Fig. 3 includes the following:

- *subjects of educational process* (teaching professional, methodologist, administrator, instructor);
- *active equipment* of a classroom: means of receiving and displaying information (the encephalograph, the microphone, the video camera, the TV set);
- *robot assistant* components, managing which is among the functions of the control system (head, motors of manipulator, pedipulator, range finder, video controller, gripper).

The control of classroom equipment and robot components, depending on the current situation, is carried out:

- according to conventional scenarios;
- according to the program (action plan) constructed by the planning server subsystem of ARA HSC (Fig. 1).

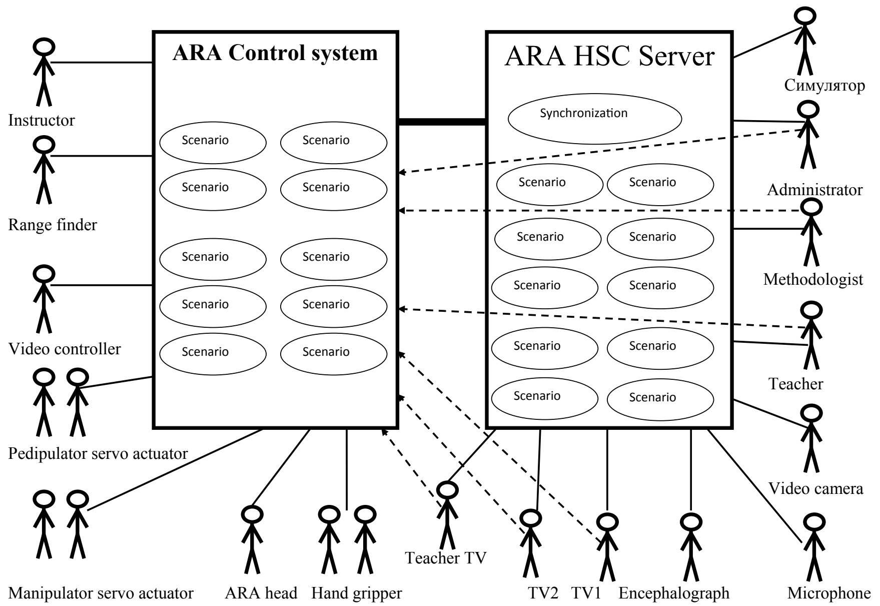

Fig. 3 Scheme of component interactions for robotic system supporting the correctional training educational process for two trainees

7 Conclusion

The study is devoted to the issue of using anthropomorphous robots in education. The distinctive feature of this field of robotics use is a necessity of a large number of solutions for computationally difficult tasks in a real-time mode. The hardware-software complex of anthropomorphous robot assistant (ARA HSC) for a teaching professional is proposed. The architecture is developed and the set-theoretic model of ARA HSC is constructed. The scheme of components' interaction for ARA HSC is provided.

The developed set-theoretic model ARA HSC will be further used for conducting the studies using the queuing theory methods for optimizing the architecture and structure of ARA HSC components.

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