Principles of Building Intelligent Robotic Systems

Aliaksandr Kroshchanka
Brest State Technical University
Brest, Belarus
kroschenko@gmail.com

Mikhail Kovalev
Belarusian State University of Informatics and Radioelectronics
Minsk, Belarus
michail.kovalev7@gmail.com

***Abstract*—The paper proposes a concept for the building of collaborative robotic systems using OSTIS technology. The developed concept is based on the integration of robotic, symbolic and neural network components. The main provisions of the approach are illustrated by the project of a robotic system for sorting objects with specified characteristics. Recommendations are given on the application of the proposed concept for the construction of collaborative robotic systems in the context of the development of new generation intelligent computer systems based on the use of OSTIS technology.**

***Keywords*—OSTIS, collaborative robotics, hybrid intelligent systems, object detection, manipulators**

I. Introduction

In modern collaborative robotic systems, robots follow a set algorithm of actions, including the performance of some predefined operations (e. g., grasping and moving an object, positioning at a certain point, performing a certain operation on an object). Technically, the realization of such actions does not cause difficulties in case of an ideal workflow. However, there may be situations when there are deviations from the established algorithm of actions, for example, absence of an object in a given point by the beginning of the operation, wrong type of object or impossibility to perform the operation due to blocking of moving parts, appearance of unauthorized persons in the area of manipulator operation, etc. These problems can be solved by using machine learning methods, in particular, neural networks. For example, a detector network allows you to determine the type of object moving along the conveyor, another model calculates the position of the manipulator at the next moment of time depending on the technical operation being performed, etc. However, the use of only specialized auxiliary models, for example, a computer vision model for detecting missing objects, will not be able to help in the correct identification of the place where objects of a given type can be located and where, in case of absence of the object on the conveyor, it will be necessary to deploy the manipulator to grab the part. Information about important aspects of the manufacturing process, which is sufficiently variable, needs to be systematically stored because the alternative — the need for constant direct code editing in the context of changes occurring to the robot — is unacceptable and, moreover, can often lead to errors. In addition, the experience that such systems may acquire during their operation is also clearly important and needs to be properly represented for reuse in other contexts and processes.

Thus, the development of principles and recommendations for the construction of intelligent robotic systems is an urgent topic of research, because it allows to streamline the process of developing such systems. The use of modern tools for designing intelligent systems, which undoubtedly includes OSTIS technology, allows the representation and operation of knowledge, which is a valuable resource in robotic systems.

The subsequent sections of the paper are organized as follows: section II sets out the problem of building knowledge-based robotics systems, in the same section an overview of existing solutions is given; section III describes the proposed concept for building intelligent robotics systems; section IV describes the developed prototype of an intelligent robotics system for sorting objects of a given type; finally, section V summarizes the main conclusions of the proposed concept and describes the main conclusions of the intelligent robotics system for sorting objects of a given type.

II. Problem formulation

The idea of developing robotic systems based on the use of knowledge bases has been widely investigated in various works. For example, in [1], the authors give an overview of knowledge bases used in robotic systems to find missing tools. Emphasis is placed on finding those objects without which further workflow continuation will not be possible. However, other applications of knowledge bases are not indicated, in particular, the possibility of using them for robot self-diagnosis, which is an important function of such systems. Other studies use knowledge bases (e. g., Cyc [2] or SUMO [3]) that are not specific to robotics, which makes it difficult to use such solutions in practice. One of the most promising solutions at the moment is the KnowRob KB ([4], [5]), which is characterized by a developed ontological basis for robotics.

In the context of the above-mentioned works, we have formulated the task of developing a concept for the construction of intelligent robotic systems based on the use of knowledge, as well as outlined the basic requirements for such systems:

- support of heterogeneous components of the robot system, i. e. support of a single open interface of interaction;
- the possibility of transferring the knowledge accumulated by the system during its operation to other robotic systems with minimal changes;
- adaptive design, i. e. the ability to change the composition of the system components without having to change the interaction logic;
- support for self-modification of the system;
- the ability of the system to expand and/or improve its set of sensors and effectors;
- the ability of the system to analyze the quality of its physical and software components.

These requirements correspond to the properties of cybernetic systems given in the OSTIS technology standard [6]. This technology is a reasonable choice for designing an intelligent robotic system, as it ensures the achievability of these properties.

In the process of building the concept of developing systems of this type, it is necessary to form a list of recommendations and general rules for designing intelligent robotic systems, and to realize an applied intelligent robotic system on the basis of the outlined theoretical provisions.

III. Proposed concept

The proposed robotic system design concept is developed using OSTIS technology.

The fundamental possibility of integrating a physical robotic system and OSTIS in the context of controlling this system is based on the developed ontology that includes a description of the basic physical components of such a system (i. e., manipulators, transporters, etc.), as well as the classes of actions that can be performed by such components.

As a formal basis for knowledge representation within the framework of OSTIS Technology, a unified semantic network with a set-theoretic interpretation is used. This representation model is called SC-code (Semantic Computer code). The elements of the semantic network are called sc-nodes and sc-connectors (sc-arc, sc-edges) [6].

Systems built on the basis of OSTIS Technology are called ostis-systems. Any ostis-system consists of a knowledge base, a problem solver and a user interface. The basis of the knowledge base is a hierarchical system of subject domains (SDs) and their corresponding ontologies. Ontologies contain descriptions of concepts necessary for formalization of knowledge within SD. Any knowledge describing some problem, its context and specification of solution methods can be represented in the form of SC-code constructs. Thus, unification of representation and consistency of different types of knowledge describing problems, their context and solution methods is ensured.

Benefits that can be achieved by using OSTIS as a design tool for intelligent robotic systems include:

- the possibility of isolating extracted knowledge, independent of the manipulator types used, and reapplying it to other robotic systems under development, eliminating the need to code single-type operations;
- convenient means of visualization, for example, with the use of SCg, which allows to determine the working conditions of the components of robotic systems;
- use of open interaction interfaces that allow adding other physical components on the fly;
- explainability of the system operation modes, which allows tracking the occurrence of emergency situations with the formation of a detailed, human-understandable report.

IV. Robotics system design

According to the proposed concept, we have carried out the design and development of a collaborative robotic intelligent system.

The main purpose of the developed system is to sort objects of a certain type while maintaining the ability to flexibly modify the filtering condition of objects. This type of robotic systems is popular and widely used in production conditions to select objects with certain properties (for example, to reject manufactured products or to organize them for subsequent packaging of only the same type of goods). Such an operation, if automated, significantly simplifies manual labor in production, reducing the amount of monotonous work performed.

The physical part of the system consists of the following components:

- manipulators (2 units);
- transporter;
- single-board computer;
- storage devices (general and for target objects);
- tube;
- camera;
- ultrasonic sensor;
- power supply;
- indicator lamp;
- auxiliary components such as conductors, relays, voltage converters, and so on.

The scheme of the main physical components of the system is shown in Fig. 1.

The main components of the software part of the proposed robotic system, as well as of any ostis-system, are **knowledge base** and **problem solvers**. The user

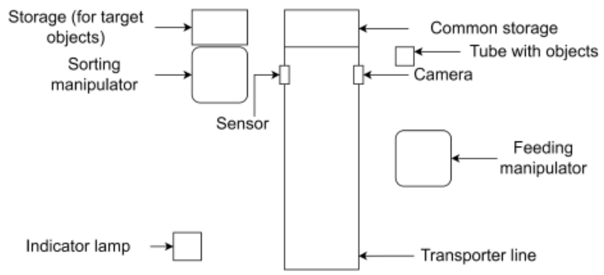

Figure 1. The scheme of the main physical components of the system

interface is the standard OSTIS technology tools for viewing and editing knowledge bases. The computer vision module, including a neural network model for object detection, is also a program component.

The functioning scenario of the developed system is reduced to the following main actions:

1) picking up the object from the tube by the feeding manipulator and moving it to the beginning of the conveyor;
2) switching on the conveyor and moving the object until the sensor is triggered;
3) disconnection of the conveyor at the moment of sensor actuation;
4) recognition of the object (type and color) by means of the installed camera;
5) moving the object from the conveyor belt to the target object storage by means of the sorting arm, if the recognized type and color match the set type and color;
6) switching on the conveyor belt and moving the object to the general storage;
7) switching off the transporter after the fulfillment of item 6.
8) switching on the green signal of the indicator when there are objects in the tube;
9) switching on the red indicator signal when there are no objects in the tube.

Let's describe the physical components of the system in more detail.

A. Physical components

Manipulators are used for gripping and moving objects. In this project, we used manipulators with different types of grippers that are widely available on the market — mechanical (pincer) grippers (Fig. 2) and vacuum grippers (Fig. 3).

Transporter is intended for moving objects to the specified point of technological operation (Fig. 4).

Single Board Computer — a specialized computer on which the OSTIS platform is deployed and the logic for controlling the system operation is implemented. In our implementation, the SBC Raspberry PI 5 (Fig. 5) [7] was used for this purpose.

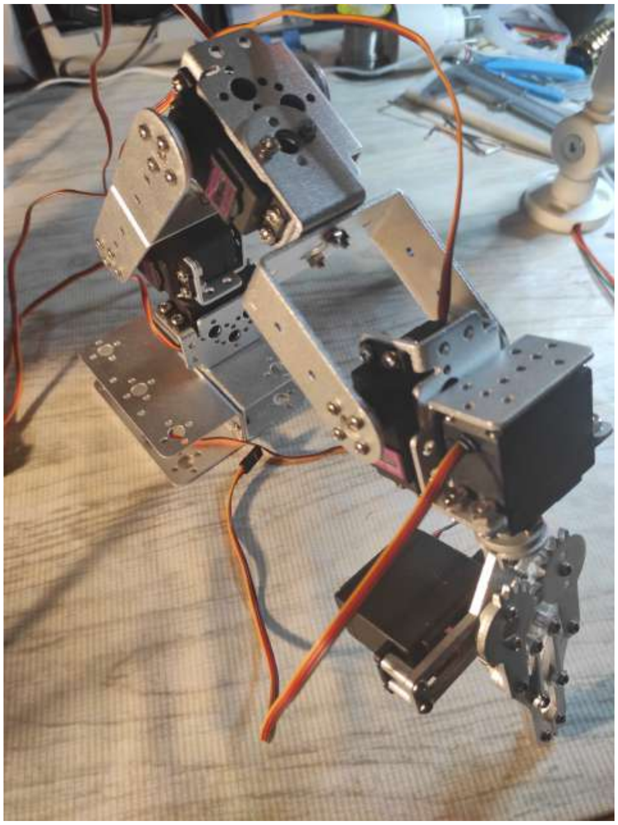

Figure 2. Manipulator with mechanical gripper

Figure 3. Manipulator with vacuum gripper

Storages — special containers used to store objects of a certain type (Fig. 6).

Tube – a container for storing objects that is shaped to be gripped by a manipulator (Fig. 7).

Camera is used to detect objects in the field of view and determine their characteristics. We used a 2 megapixel FullHD backlit camera ZONE 51 LENS.

Ultrasonic sensor is used to identify situations in which the object is in a given point of the conveyor. For

Figure 4. Transporter part

Figure 5. SBC Raspberry PI 5 with heat sink installed

our project we used the HC-SR04 sensor (Fig. 8) [8].

Power supply is required to power all physical devices in the system. We used a 360-watt, 24-volt, 15-amp power supply.

Indicator lamp is intended for light indication of the system status. In our project we used a TD-50 lamp with two color options (red and green) (Fig. 9).

B. Program components: knowledge base

The ontological approach is used for knowledge structuring, the essence of which is to represent the knowledge base as a hierarchy of subject domains and their corresponding ontologies. OSTIS technology provides a basic set of ontologies on the basis of which ontologies of applied ostis-systems are built.

Figure 6. Storage for objects with placed objects

Figure 7. Fragment of the tube with placed objects

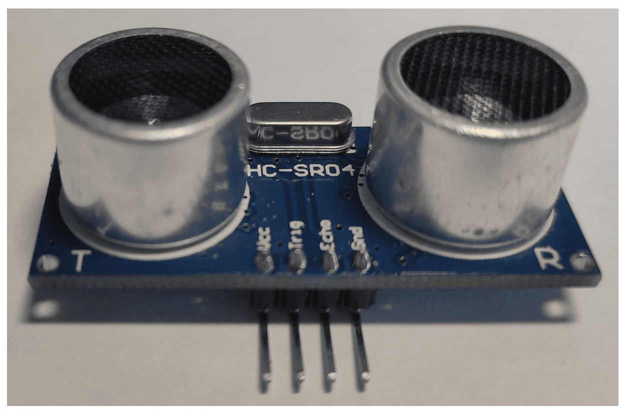

Figure 8. Ultrasonic sensor

Figure 9. TD-50 indicator lamp

The following subject domains are identified for the considered intelligent robotic system:

- Subject domain and its corresponding robotic device ontology;

- Subject domain and its corresponding ontology of physical objects — is a child of the Material Entity SD.

The robotic device SD describes the specification of the components of the physical part of the system listed above, and the specification of the actions that the system can perform with or through them.

The SD of physical objects specifies properties of the objects recognized by the system, such as color, shape, volume, weight, etc.

As the system scales up to automate more and more complex processes (line operation, shop floor operation, operation of the entire enterprise), these subject domains will be broken down into subsidiary SDs, e.g. computer vision SDs, robotic arm SDs, etc. Such development of subject domains in the field of production automation has already been done within the framework of OSTIS [9] technology.

Figure 10 shows the formalization of the system's knowledge of its own physical part in SCg-code. This formalization is necessary for the system to perform the sorting operation.

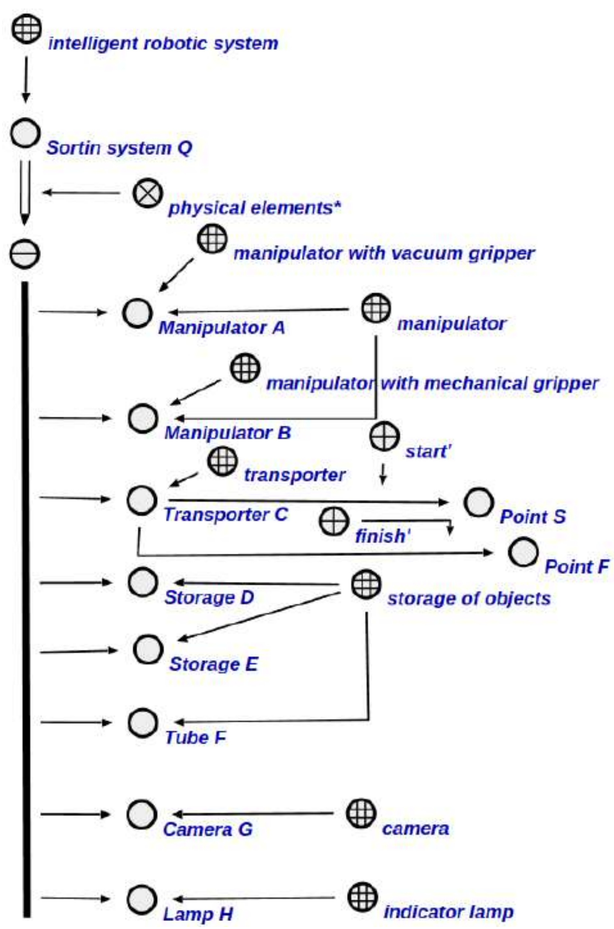

Figure 10. Formalization of the system's knowledge about its own physical part in SCg-code

According to the entity naming convention adopted in the OSTIS [6] technology standard, specific elements of the system are named with a capital letter. For convenience, each specific element is named with a letter:

1) Manipulator A is a sorting arm with vacuum gripper.
2) Manipulator B is a feeder arm with mechanical gripper.
3) Transporter C — A transporter having a starting point S as a plurality of objects placed on the transporter by the feeding arm and a point F as a plurality of objects moved by the transporter until the sensor is triggered.
4) The Storage D is a storage of target objects represented by a plurality of target objects in the storage.
5) The Storage E is a storage of objects that are not in Storage D.
6) Tuba F — an object storage represented by a set of unsorted objects.
7) and other.

C. Program components: problem solver

The problem solver deals with processing of knowledge base fragments, which is reduced to adding, searching, editing and deleting sc-nodes and sc-connectors of the knowledge base. At the semantic level, such operations are actions performed in the memory of the subject of the action, where, in general, the subject is the system itself, and the knowledge base is its memory.

The specification of an action in the knowledge base describes what should be done, with what, for what, by whom, etc., but the interpretation of actions according to this description is performed by agents. The problem solver of each ostis-system is based on a multi-agent system whose agents interact with each other only through a common knowledge base [10]. Each agent expects some event to occur in the knowledge base. For example, the appearance of a new specification of the action it should perform. When the event occurs, the agent performs the action and places its result in the same knowledge base.

The ostis-system problem solver has methods and tools to divide problems into subtasks and is able to explain its solutions at the level of describing the wording of subtasks and the sequence of their solution. When solving a problem, the problem solver breaks it into subtasks with an explicit description of the wording of each subtask, searches for a method of its solution and applies it.

Partitioning into subtasks begins with analyzing the goal of solving the problem set for the system. Formally, the goal of the developed system can be formulated as follows: for $\forall x$ such that $x \in$ the set of physical objects and $x \in$ the set of objects in Tube F, infer either $x \in$ the set of objects of Accumulator D and $x \in$ the set of target objects, or $x \in$ the set of objects of Accumulator

E and $x \notin$ the set of target objects. Figure 11 shows the formalization of the goal of the object sorting problem in SCg-code.

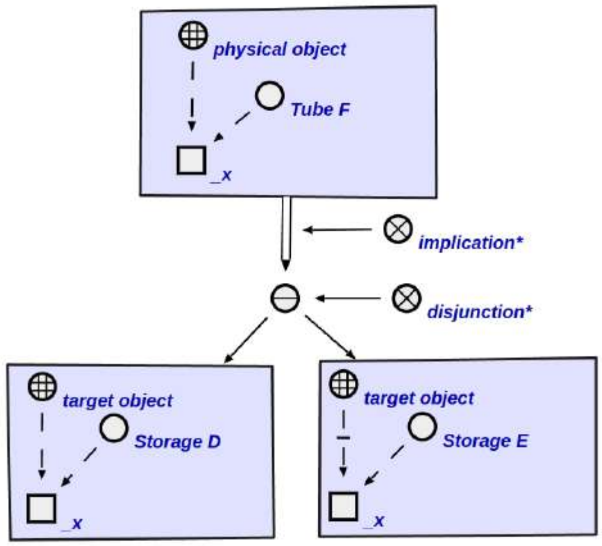

Figure 11. Formalizing the goal of solving the problem of sorting objects in SCg-code

The process of achieving the goal, depending on the system settings, can go in two directions: directly, from the initial situation, and backwards, from the target situation.

Let's consider the case of solution search from the final goal. The task solution search agent breaks the target situation into elementary sc-constructions, so-called triples and fives, and searches the system for actions or logical statements, the application of which can form the necessary part of the target situation in the knowledge base. For example, the specification of **action of moving an object to storage D** states that after its execution the object can get into storage D. However, the initial situation for applying this action is the presence of this object at the point F of the transporter and its belonging to the class of target objects. This initial situation becomes a new target of the solution search agent and the process is repeated for this target. New actions and logical statements are searched for.

Figure 12 shows the specification of the initial and final situation of the action of moving an object to storage D in SCg-code.

In the developed system, the following actions are used to solve the problem of sorting objects (given in the order in which they are found by the problem solving search agent):

1) The action of moving an object to Storage D. An object belonging to the target class and belonging to the set of objects at Point F is moved to the D storage unit. The agent interpreting this action controls Manipulator A.

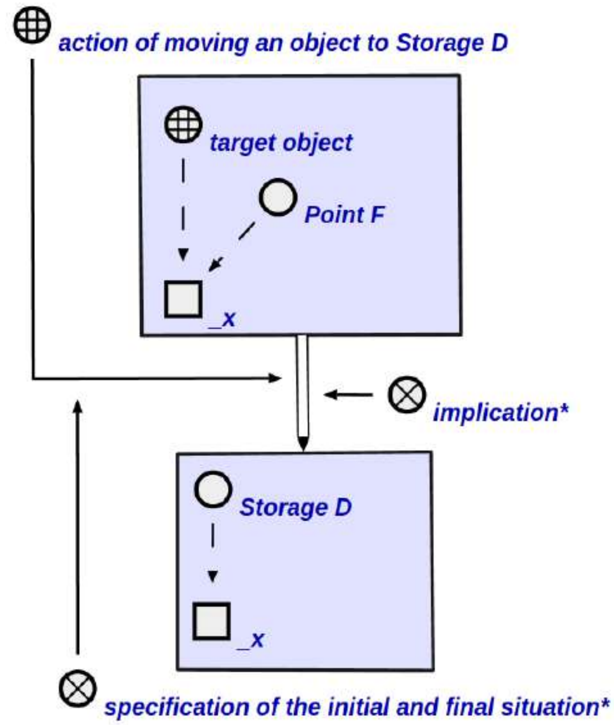

Figure 12. Specification of the start and end situation of the action of moving an object to storage D in SCg-code

2) The action of moving an object to Storage E. An object that does not belong to the target class and belongs to the set of objects at Point F is moved to Storage E. The agent interpreting this action turns on the transporter Storage E. The agent interpreting this action turns on the transporter for a predetermined amount of time.
3) The action of delivering an object from Point S to Point F. The object belonging to the set of objects at Point S ceases to belong to it and begins to belong to the set of objects at Point F. The agent interpreting this action turns on the transporter until the sensor is triggered.
4) The object classification action. The object belonging to the set of objects at Point F starts to belong or not to the set of objects of the target class. The agent interpreting this action finds a specification of the target class in the knowledge base (see figure 13) and sets this specification as the goal of a new problem solved by the agent according to the principle described above. During the search, the agent applies actions 5), 6) and 7).
5) The action of classifying an object in the image. The class of the object for which its image is specified is determined. The agent interpreting this action uses the methods described in the computer vision module to recognize the object in the image.
6) The action of determining the color of the object in

the image. The agent interpreting this action uses the methods described in the computer vision module.
7) The action of searching for objects in the image. The coordinates in the image obtained from the camera at the moment of sensor triggering are selected for the object. The agent interpreting this action uses the methods described in the computer vision module.
8) The action of moving the object onto the Point S. An object belonging to the set of objects in Tube F is moved to Point S. The agent interpreting this action controls Manipulator B.

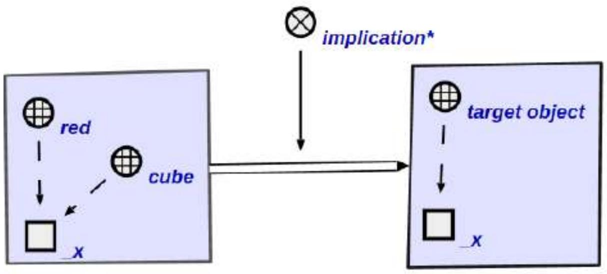

Figure 13. Specification of target class definition in SCg-code

At this point, the agents that interpret these actions use the program interfaces of the physical elements. For example, the agent for moving the object to the accumulator D implements an algorithm that uses the program interface of the manipulator A to transfer to it the rotation angles of its servos for moving the object from the conveyor to the accumulator in rigidly fixed locations. The system development plans include formalization in the knowledge base of the manipulator itself so that the rotation angles of the manipulator servo drives and the order of actions to change them are set depending on the current situation in the working area, rather than according to a predetermined algorithm.

The applied approach allows intelligent robotic systems to solve problems in a declarative way, when the order of application of methods of problem solving is formed by the system independently on the basis of the problem condition. Thus, adding new stages of object processing or methods for determining new characteristics of objects (weight, presence of certain digits, etc.) requires formalization of specifications of initial and final situations of actions and implementation of agents interpreting them, but does not require additional code for integration of these agents. Thus, the design of robotic systems is reduced to the description of the physical part and the tasks to be solved by this system without the need to program the solution of each task.

D. Program components: computer vision module

To solve the subproblem of detection of the given objects, the authors have formed a dataset of images of geometric bodies obtained by 3D printing. This sample includes photographs of three geometric bodies (cube, cylinder, cone) taken from different angles and with different camera angles. The total dataset size was 200 images, which were manually labeled. Examples of photos from the dataset, as well as photos from different angles of the same body, are shown in Figures 14 and 15.

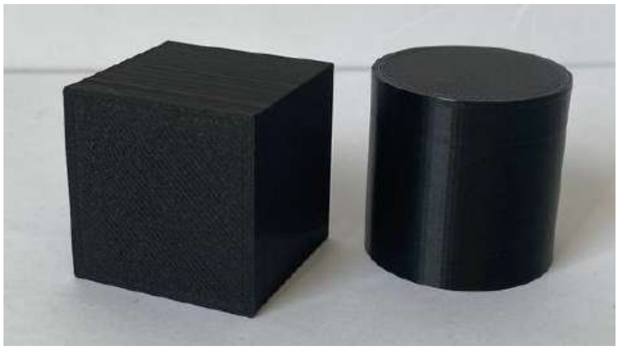

Figure 14. Objects from a dataset of figure images

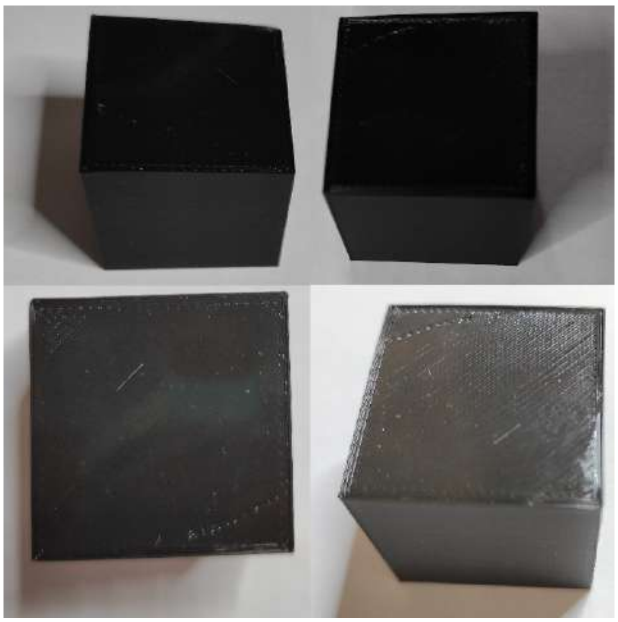

Figure 15. Images of one body taken from different angles

We used a pre-trained YOLO version 7 [11] as a neural network-detector to solve the subproblem of detecting objects of a given type. The whole dataset was split into training and test subdatasets in the ratio of 4:1. After 100 epochs of model training we got $mAP = \mathbf{97.4}\%$.

After training, the model acquired a good level of object recognition, and in some cases was even able to detect objects that were different in color from those in the training dataset (Fig. 16).

Due to the invariance of the model to the color of objects, a simple comparison using the Euclidean metric with a given reference color value was used to determine it.

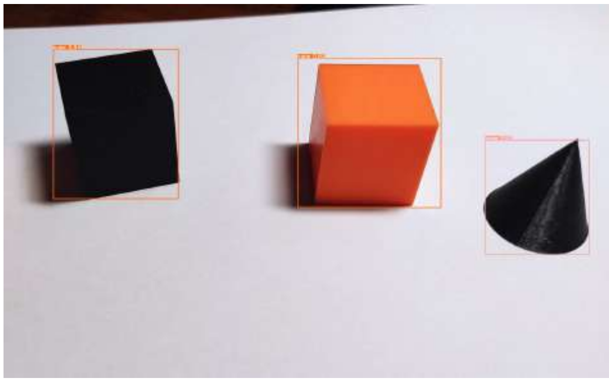

Figure 16. Objects detected after model training

V. Conclusion

This paper proposes a concept for the development of robotic ostis-systems. The proposed approach is based on the integration of robotic, symbolic and neural network components in a single system. The application of OSTIS technology for building intelligent robotic systems is substantiated, and the formalization of this subject domain is performed. Practical advice on the development of robotic ostis-systems is given.

Areas for future work include:

- increasing the versatility of the proposed concept by expanding the range of described types of robots and other auxiliary devices;
- finalization of the existing prototype system for implementation in production processes;
- implementation of diagnostic agents for the system components;
- finalization of the agents for calculation of the manipulator trajectory for arbitrary object position.

References

[1] M. Thosar, S. Zug, A. M. Skaria, and A. Jain, "A review of knowledge bases for service robots in household environments," in *International Workshop on Artificial Intelligence and Cognition*, 2018. [Online]. Available: https://api.semanticscholar.org/CorpusID:198963468

[2] D. B. Lenat, "Cyc: A large-scale investment in knowledge infrastructure," *Communications of the ACM*, vol. 38, no. 11, pp. 33–38, 1995.

[3] I. Niles and A. Pease, "Towards a standard upper ontology," in *Proceedings of the International Conference on Formal Ontology in Information Systems - Volume 2001*, ser. FOIS '01. New York, NY, USA: Association for Computing Machinery, 2001, p. 2–9. [Online]. Available: https://doi.org/10.1145/505168.505170

[4] M. Tenorth, D. Jain, and M. Beetz, "Knowledge processing for cognitive robots," *KI*, vol. 24, pp. 233–240, 09 2010.

[5] M. Tenorth and M. Beetz, "Representations for robot knowledge in the knowrob framework," *Artificial Intelligence*, vol. 247, no. C, pp. 151–169, 2017.

[6] V. Golenkov, N. Guliakina, and D. Shunkevich, *Otkrytaja tehnologija ontologicheskogo proektirovanija, proizvodstva i jekspluatacii semanticheski sovmestimyh gibridnyh intellektual'nyh komp'juternyh sistem [Open technology of ontological design, production and operation of semantically compatible hybrid intelligent computer systems]*, V. Golenkov, Ed. Minsk: Bestprint [Bestprint], 2021, in Russ.

[7] "Raspberry Pi Datasheets," mode of access : https://datasheets.raspberrypi.com. – Date of access : 01.04.2024.

[8] "HC-SR04-Ultrasonic.pdf," mode of access : https://www.handsontec.com/dataspecs/HC-SR04-Ultrasonic.pdf. – Date of access : 01.04.2024.

[9] V. Golenkov, Ed., *Tehnologija kompleksnoj podderzhki zhiznennogo cikla semanticheski sovmestimyh intellektual'nyh komp'juternyh sistem novogo pokolenija [Technology of complex life cycle support of semantically compatible intelligent computer systems of new generation]*. Bestprint, 2023, in Russ.

[10] D. Shunkevich, "Agent-oriented models, method and tools of compatible problem solvers development for intelligent systems," *Otkrytye semanticheskie tehnologii proektirovanija intellektual'nyh sistem [Open semantic technologies for intelligent systems]*, pp. 119–132, 2018.

[11] C.-Y. Wang, A. Bochkovskiy, and H.-Y. M. Liao, "Yolov7: Trainable bag-of-freebies sets new state-of-the-art for real-time object detectors," 2022.

ПРИНЦИПЫ ПОСТРОЕНИЯ ИНТЕЛЛЕКТУАЛЬНЫХ РОБОТОТЕХНИЧЕСКИХ СИСТЕМ

Крощенко А. А., Ковалёв М. В.

В статье предлагается концепция к построению робототехнических систем коллаборативного типа с использованием технологии OSTIS. Разработанная концепция базируется на интеграции робототехнического, символического и нейросетевого компонентов. Основные положения подхода проиллюстрированы проектом робототехнической системы для сортировки предметов с заданными характеристиками. Даются рекомендации о применении предлагаемой концепции для построения робототехнических систем коллаборативного типа в контексте разработки интеллектуальных компьютерных систем нового поколения, основывающихся на использовании технологии OSTIS.

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