Abstract

Background/Objectives: The objective of this study is to select the lines of research for implementing constructive and firmware solutions to create a universal robot that would perform different simple tasks. Methods: Such technical solutions will be used for further development of different types of robots of either anthropomorphic or any other random configuration designed for performing a wide spectrum of tasks in industrial, social or domestic environments. Findings: The study presents the results of the analysis of information sources and patent research studies on the areas as follows: principles of building hardware and software complexes for two-armed assistant robots that would partially replace manual labor in remote object handling operations; algorithms for controlling kinematic joints of the manipulator that implement the principles of inverse kinematics and dynamics to ensure safe working environment for man in the process of human-robot collaboration; methods of coordinated control over two manipulators. Applications/Improvements: The results of the study can be applied to constructive and firmware solutions in the process of creating a universal robot to replace manual labor in remote autonomous operations.

Keywords: Collaborative Robot, Human-Robot Collaboration, Object Operations, Robot Safety, Robot Manipulator, Two-Armed Robot

1. Introduction

Over the last several years the product lines of many industrial robot manufacturers, including such big players as ABB YuMi,1,2 Fanuc (CR-35iA),3 KUKA4 and Yaskawa Motoman (HC10),5 have been joined by small manipulators and two-armed robots called “collaborative”. These robots feature human-like sizes, kinematic principles and force capabilities similar to that of man. The application areas of these robots are represented by human-robot collaboration or by replacement of a human worker.

The existing developments in the sphere of building the control systems for manipulator robots that are designed to ensure safe working conditions in the process of human-robot collaboration aim to solve the issues associated with the control over the developed power and with the planned trajectories of movements of multilink manipulators based on repeating the movements of the operator. Thereat, such robots can only be used if their environment and working space have been predetermined and preconfigured beforehand which sets some limitations on their use in cases when the scales of the operations are changing as each robot has to be adjusted individually for the relevant modes; besides, such robots are usually static and cannot be removed. To secure the operations in the undetermined environment and in dynamically changing working situations when there are both static and movable obstacles the investigations have to be undertaken in the sphere of developing constructive, hardware and software solutions that would enable robots to copy the knowledge required for performing the operations automatically without individual programming.

The principal feature of the collaborative robots is represented by their ability to co-operate with man, their capability to interact with people in close contact without the need to fence their effective area. This possibility to
avoid any fencing leads to much more efficient use of the available space.

A collaborative robot operates either together with or instead of the human worker providing a substitute in cases where human labor is associated with intensive physical loads of danger eliminating the need to lift heavy objects or to work with toxic materials thus ensuring safer working environment and reducing the labor intensity.

Collaborative robots that feature human-like size and good leaning capabilities can easily help a man or even replace one in performing continuously repeated tasks.

Thus, the major advantages of collaborative robots are represented by the properties as follows:

1. simple introduction into the existing production environment (universality; compact dimensions; human-like sizes; adjustability);
2. safe cooperation with a man without any fencing;
3. efficient use of the available space because no fencing is needed;
4. usually light and compact and thus easily removable and occupying small areas;
5. possibility to replace a man (or provide assistance to a man) in performing the tasks associated with danger and/or intensive loads;
6. efficiency in performing continuously repeated operations and the ability to be easily reconfigured for other purposes;

Within the framework of the production process automation collaborative robots can be used for operations as follows:

1. Relocating the parts and work-pieces;
2. Assembly operations;
3. Loading conveyor belts;
4. Operating the machine tools;
5. Operations with hand tools;
6. Product classification and sorting;
7. Packing and filling.

2. Concept headings

2.1 Ensuring Safe Operations

To solve the task of ensuring safe working environment for people two ways can be pursued:

1. Computer vision techniques: circumferential video surveillance over the effective area of the manipulator measuring the parameters of the obstacles that come in the way of the manipulator, control over emergency situations such as moving or static objects, rearranging the trajectory of the movements to avoid collisions or seizing operations when the collision cannot be avoided.

2. Force control techniques: building mathematical model of the manipulator movement dynamics and control over the calculated and actually developed force in the manipulator units using torque sensors in the joints and estimating the force based on the energy consumption rate. This safety system is fundamental for such robots and it is based on the principles of force sensitive control methods.

The key task of robotics is represented by control. Thereat, there are several distinguishable levels of control: the lowest level that includes motors, derives and different servo mechanisms; middle level that includes complexes of servo devices unified in a single functional unit; the highest level that covers the control over the behavioral model of the robot, i.e. that simultaneously controls all the systems of the robot to perform the set task. There are also many intermediate and combined levels.

In this particular project the task of control can be split in three major lines: drive and manipulator control, mobile platform control and remote control.

One of the earlier studies describes different new ideas about the effects produced by the controllable stiffness on personnel safety. Given the existing trend of using robots in industrial services and increased domestic applications, safety of man becomes an issue of major concern. Inasmuch as employing robots implies physical interactions between robots and human beings that share the working space with each other it is expected that a robot will act safely in the situations of potential collisions or contacts with people or other objects of the environment.

The great advantage here is that the elastic elements can preserve and release the energy which can be used for efficient cyclical movements or in the cases of repetitive trajectories.

Future robots are expected to perform the tasks with the same speed and dexterity as a man does. However, under the existing scenario when the range of the torque and the weight of the joints are supposed to correspond to the properties of a human being, the force of the output shaft which is characteristic for a man (as, for example,
in the shoulder joint) can hardly be used. Using elastic elements as energy storage units makes it possible to utilize the elastic strain energy once again which would improve the energy efficiency of the system considerably. Within the framework of the study the investigations have been carried out to study the processes when a robot and a man collide and the behavior of the elastic mechanisms and drives has been analyzed for these cases.

Another study describes simulations and the experiments that imitate the situations when the man gets blocked during accidents when the speed of the robot’s movements changes, or so does its inertia, the thickness of its soft covering and the stiffness of its joints. Besides, the safety of man was estimated by means of the collision detection system and the reactions of this experimental system have been analyzed. For the purposes of estimating the safety level the pain threshold of man was evaluated and then used to predetermined the threshold of the contact force. Also, in the course of the experiments the readings of the torque sensors were analyzed to identify any values that could be higher than the calculated torque. The investigation showed that the control strategies proved efficient under the conditions when the speed of movement was low, and relatively soft parts of the body such as the chest and hands were affected. However, the represented control system was not so efficient at alleviating the effects that occurred at high speed and during the collisions with the hard parts of the body. If the speed of the robot is higher than 0.5 m/s, it is very important that it should be equipped with a system of sensors for fast contact detection and for fast reaction to alleviate the consequences of the collision.

The research studies also provided the description and the experimental results of implementing the real-time trajectory planning system together with the parameters for estimating the dynamical model using robot Baxter designed by Rethink Robotics. The experimental investigations have been undertaken to test the algorithm for active evaluation of the dynamical system combined with online estimation in real-time mode (Figure 1).

In another study the authors suggest the real-time method of avoiding collisions to ensure safe robot-human collaboration. Applying sensors for determining the surrounding situations helps, to a large degree, prevent collisions in both dynamic and rigidly preset environments.

As it is, the real-time collision prevention method consists of three parts:

1. environment perception
2. collision prevention algorithm
3. robot control

Avoiding collisions is paid very much attention to in the course of studying and developing the relevant ideas. These methods assume that the trajectory should be planned and the target location should be achieved bypassing any potential obstacles. Thereat, virtual model of the environment is used (occupied space map) that include target objects, obstacles and free space.

One of the trends of the currently developed control techniques is represented by equipping robots with computer vision systems to monitor the environment and ensure safe operations, to create the map of the environment, to compare the virtual model developed by the robot with the actual obstacles in order to avoid contacts.

The comparative analysis of the sensors that can be used as computer vision system is shown in Table 1.

Such solutions as lidar or sonar will be sufficient to provide the information on the surrounding objects to the planning and control systems of the mobile platform in line with the functionality described in Table 1. However, the manipulator control and safety systems would require spatial information that can only be provided by 3D sensors (see Table 1). Thus, the specified 3D sensors represent a universal solution for multilink manipulator control and for supplying sensor information for navigation and movement control purposes.

Hence, the computer vision system as part of the developed technical solutions will possess several functional features as follows:
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2.2 Coordinated Two-Armed Operations

Synchronous assembly operations. A single process of assembling two parts which mostly implies inserting an element of one part into some special notch of the other part from the perspective of the interactions that occur between the objects can be presented as stages that follow:

1. Linking
2. Inserting/joining
3. Finishing operation.

Stage of linking is characterized by the necessity of visual control over the mutual dispositions of the parts held by the end-effectors of the manipulator. Moving the parts towards each other before linking can be effected by positioning the representations of the target locations and by orientations of the end-effectors of the manipulator pair, thereat, the position of the object in the grasp is considered known; otherwise it can be done with the assistance of visual control over the contact planes of the objects by processing the data of 3D computer vision system.

At the stage of inserting or joining the parts the thrust reaction force occur during the contact and the task of mutual positioning is thus reduced to the task of impedance control that describes the relevant interactions representing the thrust reaction as a spring and substituting the object with its weight. The direction and the values of thrust reaction forces can be registered with two-dimensional torque sensors that can be installed either on the end-effectors or in the place of junction of the end-effector connecting flanges.

The preparation stages for each of two manipulators represent the tasks of controlling single multilink manipulator (object grasp, position control, movement control, trajectory planning, solving inverse travel-time problems, impedance control).

The distinguishing features of two-armed mode operations are represented by the necessity to control the interactions at the stage of linking the objects which can be regarded as a special case of impedance control when one of the manipulators is to hold the object at the preset fixed position and to orient it while another manipulator is to adapt the position of the second object according to the law of control based on the occurring forces of contact interaction.

When equipped with two manipulators, the robot can perform operations with two big grasped objects by executing coordinated actions with both end-effectors.

### Table 1. Systems of technical vision

<table>
<thead>
<tr>
<th>No.</th>
<th>Function</th>
<th>3D sensors</th>
<th>2D sensors (lidar, sonar)</th>
<th>Video camera</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Indoor operations</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>Creating environment map</td>
<td>3D map</td>
<td>No, 2D environment maps only</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Determining geometric parameters of objects and obstacles</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>Determining coordinates of the objects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes, only for objects of known geometric shape</td>
</tr>
<tr>
<td>5</td>
<td>Recognizing the objects</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>Using for manipulator control</td>
<td>Yes</td>
<td>No, additional sensors are required</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>Using for platform navigation</td>
<td>Yes</td>
<td>No</td>
<td>Partially</td>
</tr>
<tr>
<td>8</td>
<td>Determining absolute orientation and position of the platform</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>9</td>
<td>Creating occupied space maps for planning manipulator trajectory</td>
<td>Yes</td>
<td>No, only specifying distances to the front edge of the obstacles</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Operation of several robots simultaneously</td>
<td>Sensors with active transmitter cause disturbances</td>
<td>Sensors with active transmitter cause disturbances</td>
<td>Yes</td>
</tr>
</tbody>
</table>

1. Ensuring video surveillance over the manipulator working space and obstacle detection;
2. Emergency control;
3. Determining the coordinates of the objects within the manipulator effective area;
4. Visual odometry, i.e. setting orientations for mobile robotic platform navigation and control.
Simultaneous fixation of the object position with two manipulators results in bridging of the kinematic schemes of the manipulators which leads to the decrease in the total amount of the degrees of freedom. The specific feature of this operation is represented by the necessity to preserve mutual orientation of the end-effectors of both manipulators. With this grasp pattern the object is considered rigidly fixed by both manipulators and thus no displacements of the object relative to the end-effector can occur during movements. The fixed grasp makes sure that the movements of the manipulator are fully passed onto the object; this type of grasp is especially important in cases of two-armed operations when the position of the held object must be identified unambiguously.

The task of planning coordinated movements is represented by solving inverse problems for the positions of each manipulator that form closed kinematic link with the initial data as follows:

1. Initial position and orientation of “left arm” end-effector
   \[ \{x_L, y_L, z_L, \varphi_L, \theta_L, \psi_L\} \];

2. Initial position and orientation of “right arm” end-effector
   \[ \{x_R, y_R, z_R, \varphi_R, \theta_R, \psi_R\} \];

3. Initial position and orientation of the object after accomplishing the grasp
   \[ \{x_0, y_0, z_0, \varphi_0, \theta_0, \psi_0\} \];

4. Object movement trajectory set as ensemble of points
   \[ T_0 \{x_i, y_i, z_i, \varphi_i, \theta_i, \psi_i\} \]

Where,
\( x, y, z \) – Cartesian coordinates in the system of coordinates that is linked to the robot;
\( \varphi, \theta, \psi \) – angles of rotation relative to axes OX, OY and OZ, accordingly.

Formation of the intermediate movement trajectories of the end-effectors \( T_L \) and \( T_R \) is done by solving reverse kinematic problem. To synchronize the movements in one the manipulators (slave) it is possible to use the combined impedance-based control system.

### 3. Method

#### 3.1 Manipulator

To ensure personnel safety and also for the purposes of protecting the units of the manipulator from the external shock loads the structures of the drives of the manipulator rotation links that make a part of the developed assistant robot can use special designs of the servo drives in which the output shaft is driven by two electric motors that rotate in different directions; between the output shafts of the gearboxes of such motors and the output shaft of the drive elastic elements are installed (springs, elastomers, etc). Counter-rotations of the drives ensure the forced contractions of the springs that result in higher stiffness of the output shaft. Synchronous positioning control over the pair of the motors within the controllable stiffness drive makes it possible to regulate stiffness depending on the required operation mode.

One of the types of the controllable stiffness drives is represented by the so-called consecutive elastic actuators that are, in fact, a half of the controllable stiffness servo drive. Here one electric motor is used in which the elastic element is installed between the output shafts. Such drives do not make it possible to change the stiffness of the output shaft; however, such structures can absorb the shock loads ensuring protection from the external effects.

Using such types of drives has a number of advantages as compared to the conventional drives that feature stiff connections as far as they make it possible to determine indirectly the externally applied force without using any special sensors.

Thus, the servo drives with controllable stiffness of the output shaft can be used for construction and integration solutions in developing the manipulators of the collaborative robots.

#### 3.2 Control System and Human-Robot Collaboration

In the course of the analysis of the information sources a great number of studies have been found to investigate the manipulator control systems based on controllable stiffness drives in terms of ensuring personnel safety. Besides, applying elastic elements as the accumulators of energy makes it possible to use the elastic strain once again that improves the energy efficiency of the system considerably.
It has been demonstrated that to ensure safe working conditions in the course of developing the manipulator positioning system the following functional features have to be implemented:

1. environment perception;
2. algorithm for avoiding collisions;
3. calculating trajectories and robot position control.

Much attention is paid to preventing collisions in the course of studying and developing the relevant ideas. These methods imply that the trajectory should be preplanned and the target locations should be achieved by bypassing the obstacles. For this purpose the virtual model of the surrounding objects is used (occupied space map) that include targets, obstacles and free space. The methods of planning the manipulator trajectory are founded on solving the reverse kinematic problem and are assisted by additional simulations of the virtual models of the manipulator and the obstacles in the course of their potential collisions.

It is suggested that in order to control robots in the unknown dynamic environment the trajectories of their movements should be planned in the process of their movements directly. One of the approaches implies that a set of virtual spheres should be used to represent a robot and a man in the course of the interactive studies of the potential movements of the manipulator end-effectors that would thus create the trajectory that prevents the possibility of collision. Recently, visual sensing has become the best choice for integrating the collision avoidance method founded on applying the depth sensors.

Within the framework of human-robot collaboration successful cooperation can be achieved by pursuing two different ways that go in parallel. In case of physical interaction the robot can predict and respond to the moving intentions of man by measuring and estimating the forces that occur directly in the process of contact interactions. In case of contactless interactions the coordination of the actions can be ensured by the information exchange through direct communication (gestures and/or voice commands) or through indirect communications by identifying the intentions (for example, by predicting the movements of the operator).

In order to identify the emergency situations under real-time conditions it is suggested that the sensors of the environment should be used (sensors, 3D models of the surrounding objects and of the working area) whose data upon processing can be used for the purposes as follows:

1. for remote real-time monitoring of robot-assisted assembly operations;
2. for proactive prevention of collisions to ensure personnel safety.

The forced limitations of the manipulator speed modes within different preset effective areas make it possible to practice direct human-robot collaboration with the predetermined safety parameters.

The servo loops are usually used for the purposes of controlling the drives of the manipulator rotation joints. There are either position-based or force-based closed loop control systems. The force-based systems control the load on the rotation joint of the manipulator which can be detected either by torque sensors or analytically by applying the current state of the dynamic model of the manipulator. The position-based control systems ensure tracing the preset angular position of the joint. The combination of these two types of systems is also possible. The control system architecture can be represented by predictive regulators, adaptive regulators that apply neural network emulator of the controlled object, PID controllers.

To solve the problem of ensuring safe working conditions for the surrounding people two ways can be pursued:

1. Computer vision techniques: circumferential video surveillance over the effective area of the manipulator estimating the parameters of emerging obstacles that come in the way of the manipulator, control over such incidents as moving or static objects, rearranging the movement trajectory to prevent the collision or stalling completely when the collision cannot be avoided;
2. Developed force control techniques: building the mathematical model of the manipulator dynamics and controlling the calculated and actually developed force in the manipulator units using the data obtained by the torque sensors in the joints and estimating the force based on the energy consumption rate. This safety system is fundamental for such robots and it is based on the force sensitive control methods.

A currently important problem for preplanning the movements is to form a curved trajectory; thereat, analytical and numerical methods are applied to calculating the optimal path of the end-effectors. Analytical methods are based on solving the reverse kinematic problem which is extremely difficult for the manipulators that possess a
large number of the degrees of freedom (more than 4). This project suggests that the manipulators should possess no less than 6 degrees of freedom thus ensuring the possibility to perform grasping operations within the wide range of positions.

For the purposes of modeling the robot control systems, for simulating the control algorithms and for imitating the interactions with the dynamically changing environment the robot operation system (ROS) is widely applied. ROS represents a set of services that ensure functional features as follows:

1. HAL – hardware abstraction layer;
2. Transportation of messages between the processes;
3. Low level units control;
4. Supporting and performing a large number of functions;
5. Process graph representation;
6. Graphic module set;
7. MATLAB support;
8. Multisite operations

The robot control and simulation system developed based on ROS can be easily integrated as plug-in software for controlling the units of the robot.

Operation system of the robot also includes a powerful tool for physical simulation together with the tools for adjusting the parameters of the manipulator virtual model, for calculating trajectory and for control operations.

3.3 Control System for Coordinated Operations of Two Manipulators

The principal distinguishing feature of two-armed robots is represented by their ability to perform assembly operations. Two arms make it possible to control the movements and to link the parts in the process of assembly. As compared to the conventional single manipulators, the two-armed ones can be of multitask nature, i.e. they can perform several functions simultaneously or perform complex operations in coordinated manner (for example, linking the parts in the process of assembly); they are also economically efficient due to their ability to replace two conventional manipulators; thereat, they can be equipped with simpler end-effectors and thus the sophisticated special end-effectors can be replaced due to the availability of such feature as dual manipulator grasp pattern.

Performance of the coordinated operations assisted by two arms can be subdivided into the simplest operations that generally can be symmetrical, asymmetrical, congruent and non-congruent. The reason for such simplification of movements and for such subdivision into the simplest components is that in this case it would be easier to solve the problems of real-time trajectory planning for both manipulators.

The coordinated movements of two manipulators that are performed as a combination of the preset activities on the objects and that are executed in single and in two-armed modes make it possible to formulate the task for performing complex manipulations with parts and work-pieces, including sophisticated assembly operations. Assembly operation is understood as an activity that involves two objects or parts and implies performing one action or a combination of actions as follows:

1. Placing the parts with the preset orientation including mutual alignment along generatrices;
2. Linking the corresponding parts and elements at specified orientations;
3. Performing certain activities on one object while the second one remains static (screwing/unscrewing, joining/disjoining, displacement or gliding along generatrices);
4. Synchronous rotation of the parts with two manipulators along the preset axis;
5. Synchronous relocation of the part with two manipulators into the specified destination point in the effective area.

Inasmuch as the velocities of the manipulators are rather slow in case of performing coordinated movements when the object is simultaneously grasped and moved, the forces caused by the dynamics of the manipulator can be neglected. The control system should automatically maintain the preset pressing force (in terms of its power and direction) in the course of relocating the object. As far as the velocities of the manipulators are quite slow, the forces generated by the dynamics of the manipulator can be omitted. The solution to the problem is thus reduced to controlling the forces measured by the torque sensors and to adjusting the velocity of the output joint of one of the manipulators.

For the purposes of controlling the coordinated movements of two manipulators the hybrid position-force systems and the impedance control systems are widely applied. The position-force control system represents subdivision into the movement components and the
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Indian Journal of Science and Technology

Vol 9 (42) | November 2016 | www.indjst.org

force-based control loop, while the impedance control system simultaneously controls movements in all directions to achieve the desired interactions between the manipulator and the environment.

4. Result

Based on the results of the analysis of the technical level of the research studies in the sphere of the multilink manipulator control, methods for ensuring safe working environment for human workers the conclusion can be made that the optimal solutions for implementing the methods of coordinated control over “two-armed robots” can be summarized as follows:

1. Using the principles of virtual simulation of the movements of neighboring manipulators based on the calibrating data that have been obtained from them.24
2. Applying the approach that suggests mutual calibration of two manipulators by means of using special benchmark elements that are held simultaneously by the end-effectors of both manipulators and the method of automated calibration that renders any additional measurements unnecessary as described in USA patent applications.25
3. In the process of performing assembly operations under two-armed operation mode it may be necessary to adapt the movements on site based on the undetermined processes that occur in the course of the direct contact between two parts; for this purpose the two-armed robot control system can be equipped with the control loop that is founded on the single manipulator adaptation method.30
4. The safety system of the manipulator control can employ the principles of delimitating the effective area according to the patent31 that describes the delimitation principles of the areas intended for human-robot cooperative operations under limited velocity modes.
5. To switch the modes of the collaborative robot operations the principles of the safety dispatching control system32 can be applied.
6. The manipulator control safety system can be equipped with the control loop that would regulate the velocity of the manipulator end-effectors taking into account the degree of danger associated with this type of obstacles which could be represented by different parts of human body; thereat, the method of movement segmentation33 can be used.

Based on the undertaken analysis of the patent and license situation the modern trends of developing multilink manipulators and mobile chassis can be summarized as follows:

1. using mobile platforms for manipulator installations;
2. using multilink manipulators;
3. protecting the units of robots from external impacts and backlash compensation;
4. employing computer vision systems for controlling the effective area of the manipulator;
5. measuring developed forces.

As a result of the patent search the following modern trends of developing the methods of multilink manipulator control to ensure safety in human-robot collaborative operations have been identified:

1. planning trajectory of multilink manipulators;
2. ensuring safe operations by means of implementing special structural solutions;
3. ensuring safe operations by means of applying computer vision systems;
4. ensuring safe operations by using different modes of manipulator control;
5. copying robot knowledge.

Based on the undertaken analysis it becomes possible to predict the image of the future assistant robot. The construction will be represented by no less than two multilink manipulators installed on the mobile chassis. Improved operational safety in the course of human-robot collaboration will be ensured due to the active and passive control included in this system. The active system will consist of the robot sensor system that would measure the developed torque and the externally applied forces. The passive system will include the computer vision system together with 3D environment reconstruction system: 3D vision surveillance camera (stereoscopic system or depth sensor) for detecting obstacles and people, for identifying the objects, for ensuring safe operations in the changing environment of the manipulator effective area. Joint application of both active and passive systems will be mutually reinforcing and thus reducing the possibility of any emergencies, especially in case of a short-term blockade of the computer vision system that may be caused by the blind areas formed in the process of the manipulator activities or caused by the obstacles. The collaborative robot will use the mobile movable platform. To protect the units of the manipulator from any shock loads, to compensate
backlash and to detect outer disturbances a pair of servo drives with controllable stiffness and with antagonistic scheme of transmission to the rotational units will be used as the rotation drives.

The method of controlling the kinematic links of the two-armed multipurpose robot to ensure safety in the course of human-robot collaborative operations will include the combined processing of the data obtained from the computer vision system and from the feedback sensors. The images including 3D images obtained by the computer vision system will be used for creating 3D map of environment in the working space of the effective area of the manipulator and also for creating the occupied space map specifying free areas and detecting the obstacles. Processing the data of the computer vision system will make it possible to determine geometric parameters of the obstacles in the effective area of the manipulator providing the information to the trajectory planning unit for recalculating the current trajectory in order to avoid any undesirable contacts with the specified obstacle. These systems of the feedback sensors are used for determining the developed forces and for controlling the values that exceed the calculated limits, thus ensuring the identification of any emergency situations. The control system will operate in two modes: safety mode and programming (learning) mode. In programming mode the contact impacts on the units of the manipulator will cause movements in the direction toward the applied force, and in the safety operation mode they will stall the manipulator. In safety mode the impacts on the units of the manipulator will stop the robot.

5. Discussion

Notwithstanding the fact that the impedance control features less precise positioning of the joints as compared to the position-force based methods, this control method enables adaptation to the external forces. Thus, when the manipulator is controlled in the mode of kinesthetic learning (mode of compliance), the impedance control system can be used. At the next stage of the study the opportunities for applying the coordinated control methods will be investigated with two manipulators in the mode of kinesthetic (compliant) learning.

In the process of performing assembly operations there may emerge a necessity to move on site because of the undetermined processes that occur in the course of the direct contact of two work-pieces. In this case in the process of linking two parts in order to clarify mutual orientation of the contact areas of the objects the cooperative processing of the data from the torque sensors of the end-effectors and the data obtained from 3D computer vision system can be performed in combination with the impedance control system. This method also solves the problem of the undetermined position of the object in the end-effector of the manipulator. Another method of determination is represented by video control over the grasped object that is aimed at identifying its orientation and location in space to build the updated mathematical model of multilink manipulator kinematics taking into account the object that is held. The reference points/areas can be represented directly by the elements of the parts which interaction (linking, screwing/unscrewing, etc.) will occur during this operation. Investigating the methods of determining mutual orientation and positions of such areas relative to the manipulator end-effector which holds the object should become one of the subjects of the investigations during the further stages. Solving the problem of determining orientation and location of the object in the end-effector, or in other words, specifying the kinematic model of the movements of the working surfaces of the manipulated object is an important task for performing coordinated operations with two manipulators. Geometrically, the task of performing assembly operations is reduced to linking two contact surfaces of two objects in space.

The novelty of developing the control system for coordinated operations with two manipulators is represented by the synthesis of the well-proven methods of solving the problems and of empiric verification of operability of the combined control system that integrates the methods of impedance control and position-force control with the spatial information on the manipulated object which is obtained in the course of processing the data from the computer vision system. In order to use the advantages of each method efficiently they should be reduced to one and the same time basis by means of the experimental investigations of the software implementation of the mathematical model that describes the interaction between the manipulator and the objects.

6. Conclusion

Based on the undertaken analysis of the information sources and given the identified level of the technology and the current trends, the following lines of research have been selected for each object of the next stages of the investigations:
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1. Principles of building hardware and software system of the two-armed robot assistant which could partially replace manual labor in remote manipulations with objects:
   a) Using robot design with two manipulators of no less than 5 degrees of freedom each;
   b) Applying instruments for measuring the developed torque in the joints of robot;
   c) Protecting joints of the manipulators by using servo motors with controllable stiffness of the output valve;
   d) Installing manipulators on the mobile movable platform;
   e) Using mobile four-wheeled chassis as mobile platform;
   f) Using video camera, microphone and loudspeaker the operator-side and the robot-side to equip the telepresence system with all required technical tools.

2. The algorithms for controlling the kinematic links of the manipulator founded on the principles of inverse kinematics and dynamics to ensure safe operations in the course of human-robot collaboration:
   a) Calculating orientation and location of the manipulator applying inverse kinematics and using generalized Jacobi matrices;
   b) Applying the mathematical model of the manipulator dynamics for controlling the developed forces;
   c) Using computer vision tools to determine free zones in the effective area of the manipulator;
   d) Planning trajectories of the manipulator movements to prevent contacts with obstacles;
   e) Manipulator servo motor velocity control in different zones of the working area;
   f) Processing the data obtained from the feedback sensor system to control emergencies;
   g) Force-based manipulator joint control system with torque sensors;
   h) Using the tools of robot operation system (ROS) for implementing the methods of manipulator control.

3. Methods of coordinated control over two manipulators:
   a) Implementing the combined system of position-force and impedance control that should be applied at different stages of the interaction;
   b) Using the tools for identifying reference points/areas which interaction (linking, screwing/unscrewing, etc.) is envisaged for this operation;
   c) Determining orientation and location in space of the held object.
   d) Using virtual model of the second manipulator as an obstacle (occupied space) for solving the reverse problem of position and for planning the trajectory of the first manipulator.

7. Acknowledgements

This research study was financially supported by the Ministry of Education and Science of the Russian Federation under Grant agreement No.14.577.21.0191 dd. October, 27, 2015 (Unique identifier of the agreement: RFMEFI57715X0191); the grant is provided to perform the applied research studies on the subject: “Investigating scientific and technical solutions and developing an experimental prototype of a multi-purpose two-armed robot assistant on a mobile platform that can replace human workers in various remotely performed tasks”. The work on the project is carried out at the Moscow State University of Mechanical Engineering (MAMI).

8. References

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