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LABORATORY STAND FOR HUMAN ROBOT COOPERATION

Key words

Industrial Manipulators, Collaborative Robots.

Abstract

Commonly used programmable industrial robots often lack sensors allowing them to safely operate alongside human operators. Because of the required security measures, human-robot cooperation is often limited or even impossible. The presented article describes the current advancements in industrial robotics; mainly force limited robots and standard manipulators equipped with additional external sensors, which concentrate on improving human-robot cooperation. Commercially available products are described as well as completed and current research projects. In the article, we also propose a concept of a robotic system dedicated to working alongside humans, incorporating the Universal Robots UR5 manipulator.

Introduction

Despite the advancing automation and robotisation of production and research works, there are still operations that cannot be automated for the sake of their complexity or the requirement of human skills that cannot be presently performed by machines. There are some ongoing research works to find methods for the automation of these types of tasks. They are conducted in two general directions: (1) the systems using artificial intelligence (AI) for better imitation of human qualities and (2) the systems to support operators in their work and actively cooperate with them. The system presented in this paper is part of the second group of systems.

Cooperating manipulators are equipped with vision systems, specialised surroundings sensors, and software to ensure the safety of the operator and the objects in the proximity of the robot. Cooperation with human operators usually consists of precise positioning of elements or their assembly by the robotic arm as the operator hands the elements to the grip, or the cooperation is when the robot hands the elements to the operator for their ergonomics, decreased effort, more effective use of labour and a better ordered assembly path. The development of collaborating robots is one of the new directions of the development of robotics. Works in this area are performed by research laboratories and by leading producers of industrial robotic manipulators

The first programmable manipulator was developed in order to minimise the amount of waste produced during design changes. This robot, designed by George Devol, was capable of performing repeated tasks with greater precision and endurance than a typical human worker. The year 1961 marks the beginning of industrial applications for manipulators. During this year, a Unimate robot was installed for testing at a General Motors factory in Trenton [1]. Since then, subsequent technology advancements allowed industrial robots to perform more complex tasks, often requiring additional sensors, and advanced algorithms. Nevertheless, the majority of industrial manipulators could not monitor changes in their surroundings. In order to protect objects in the manipulator's workspace,

Fig. 1. Collaborative robot working alongside humans without external safety systems [2]

robots worked in environments free of dynamic changes, often performing movements only on fixed paths. Access to the workspace had to be limited only to selected, trained employees, either by using security fences or other systems that stopped robot operation in the case of intrusion.

In recent years, robotic manufacturers began introducing a new group of manipulators capable of working alongside humans without any additional safety measures [2–6] (Fig. 1). The ISO 8373:2012 norm [7] describes those machines as collaborative robots, designed for direct interaction with humans. Those machines are equipped with sensors allowing machines to detect abnormal activity in their environment. This is performed through the measurement of the force affecting each robot joint or by using other measures, such as vision monitoring. Force and power limitation allows collaborative robots to work in the direct surroundings of humans, often without the need to install additional safety systems.

1. Collaborative robots

Robots that can safely operate alongside humans can be separated into two groups, depending on implemented safety systems [8]. The first group are force-limited robots, which are designed specifically for human-machine interaction. Those manipulators have built-in force torque sensors that allow them to measure the external forces affecting the robot joints. The robot body is often designed in a way to reduce the pressure applied on the human body during contact. This is most commonly achieved by reducing the amount of sharp edges and designing the machine with mostly ovoid shapes. The second group of collaborative robots consists of traditional industrial manipulators fitted with additional external sensors and safety systems that allow for safe cooperation with humans. The robot itself cannot monitor its environment, because this role is performed by the additional equipment.

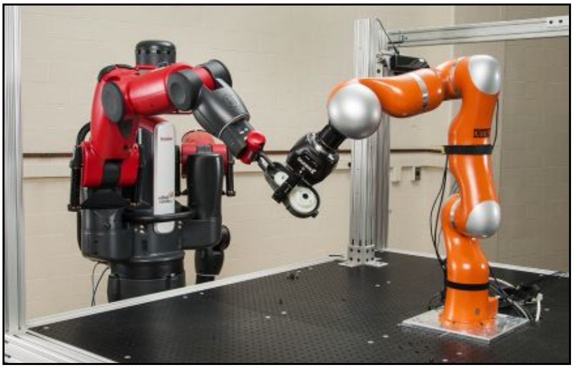

Fig. 2. Rethink Robotics Baxter (left) and Kuka IIWA (right) – examples of force limited robots [9]

Industrial robots belonging to the first group, i.e. those equipped with force torque sensors, and they can be considered new and innovative solutions. Two manipulators belonging to this group can be seen on Figure 2. In recent years, an increasing number of robot manufacturers have introduced collaborative robots, e.g. YuMi, a dual arm robot developed by ABB officially introduced in March 2015 at the Hannover Messe [3] or the Fanuc CR-35iA, the biggest, currently available force limited robot, also introduced in 2015 [4]. Specifications of selected force limited industrial robots are presented in Table 1. With the exception of the CR-35iA, currently available force limited robots are small industrial manipulators, with a maximum payload less than 15 kg. Most of the constructions are articulated robots, with the exception of products offered by Precise Automation, which are a Cartesian (PP100) and SCARA (PF400) manipulator.

Table 1. Specifications of selected collaborative robots [10–14]

	Weight	Range	Payload	Repeatability	Degrees of Freedom
ABB YuMi	38 kg	500 mm per arm	0.5 kg per arm	±0.02 mm	14 (7 per arm)
KUKA IIWA 7 R800	22.3 kg	800 mm	7 kg	±0.1 mm	7
KUKA IIWA 14 R820	29.5 kg	820 mm	14 kg	±0.15 mm	7
FANUC CR-35iA	990 kg	1813 mm	35 kg	±0.08 mm	6
RETHINK ROBOTICS Baxter	75 kg without pedestal	1210 mm per arm	2.2 kg per arm	Not published	7 per arm
PRECISE AUTOMATION PP100	20 kg for 635 mm travel version 32 kg for 1270 mm version	X Axis: 635 mm /1270 mm Y Axis: 300 mm Z Axis: 225 mm	3 kg without gripper	±0.1 mm	4 (Cartesian robot with rotation joint)

As stated before, the second group of collaborative robots consists of traditional robotic arms with additional external sensors and control systems, which allow them to work safely alongside human operators. A general concept of an intelligent robotic workcell, capable of monitoring its environment and manipulating randomly placed objects, can be found in [15]. Real life implementations include incorporating external vision systems that monitor the workspace of the robot to modify the trajectory of the manipulator in order to minimise the probability of human contact [16, 17]. Such systems can be expanded with elements of intelligence that allow the manipulator to foresee potential positions of workers as well as inform those workers about actions planned by the robot [18]. Both the robot path and the position of the human worker can be visualised, as seen in Figure 3 by the highlights on the floor.

Fig. 3. The Intelligent Workcell Project developed by the Robotics Institute [18]

Another example project leading to a better cooperation between humans and robots incorporates additional vision systems with stereovision sensors to improve the learning ability of industrial manipulators taught through teleoperation. As stated in [19], the goal of the IntellAct project is to address the issue of understanding and exploiting the semantics of object manipulation and reproducing human actions with machines. Task descriptions are extracted from video demonstrations showing humans performing manipulations. This data is evaluated by the control system and then performed by the machine. The ability to not only copy, but to learn, from human demonstrations, and this could significantly improve the teaching process of industrial robots and consequently simplify human-robot interactions and make them more efficient. This improvement of learning abilities of robots is achieved by combining relational reinforcement learning [20] and demonstrations. The reinforcement learning method allows machines, by trial-and-error interactions with its environment, to autonomously establish optimal behaviours. The role of the operator is to provide feedback regarding the performance of the robot. By incorporating demonstrations, it was possible to reduce the total time required to complete selected operations. Additionally, adding demonstration requests facilitates the algorithm to learn actions as soon as they are required [21].

2. Universal Robots Manipulator

The core idea behind the developed system is to allow a direct, safe cooperation between man and machine in a laboratory environment. In order to simplify and minimise the amount of additional security systems, a solution with complex safety options available out-of-the-box was implemented, i.e. a force limited robot. In the designed system, it was the Universal Robots UR5 manipulator shown on Figure UR3.

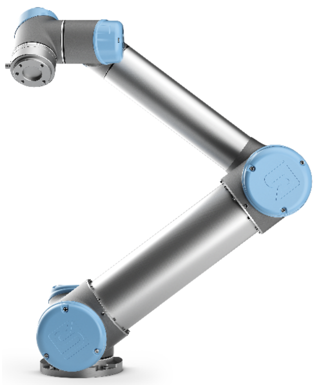

Fig. 4. Universal Robots UR5 manipulator [2]

The UR5 manipulator has built-in safety systems that allow it to work alongside humans without additional equipment such as light curtains or physical barriers. The integrated safety systems include, among others, the detection of external forces affecting each robot joint. This is performed by measuring the electric current in each robot drive, which increases if external force is used to hinder robot movement. The gathered data is then used to stop robot operation if the measured force exceeds the specified peak value. Additionally, the operator can determine safety planes inside the robot's workspace, which limit the total area of operations for the robot arm. Other functions include limiting the maximum momentum and applied power of the robot arm, the maximum joint speed, and the angular position of each joint [22]. Lastly, it is possible to move the robot arm by hand, both in order to program the manipulator and to use it as an assistant in transporting objects. The basic parameters of the industrial robot are presented in Table 2.

Communication between the robot and the control unit can be performed either with the I/O ports or with one of the communication protocols using the Ethernet port. When using the TCP/IP protocol, the manipulator can act as both a server and a client. In the first instance, the robot control box is capable

Table 2. Parameters of the Universal Robots UR5 manipulator [23]

Weight:	18.4 kg
Payload:	5 kg
Reach:	850 mm
Speed:	All joints: 180°/s Tool: Typical 1m/s
Repeatability:	±0.1 mm
Degrees of freedom:	6 rotating joints
I/O ports:	Control box / Tool conn. Digital In. 16 / 2 Digital Out. 16 / 2 Analog In. 2 / 2 Analog Out. 2 / -
I/O power supply:	24V 2A in control box, 12V/24V 600 mA in tool
Communication:	TCP/IP 100 Mbit, 100BASE-TX Ethernet socket & Modbus TCP
Collaboration operation:	15 Advanced Safety Functions Tested in accordance with: EN ISO 13849:2008 PL d, EN ISO 10218-1:2011, Clause 5.4.3
Power supply:	100-240 VAC, 50-60 Hz

of receiving and performing instructions without the need to write programs on the robot controller. The downside of this method is the lack of ability to send return data through the socket back to the client. However, this is possible when the robot is working as a client. In order to incorporate this method, it is necessary to develop a program tasked with communicating with the server using the dedicated Universal Robots script language. Robot communication can also be achieved with the Modbus TCP protocol. The UR5 manipulator is capable of working as a Modbus client (master). There are four signals available for communication: digital inputs, digital outputs, and input or output registers [21].

3. System concept

The idea behind the project is to develop a demonstration system that will actively work with the operator. The basic element of the stand is the robot fixed to the table and opposite the operator (Fig. 5.). The stand will be equipped with a vision system consisting of two or three cameras to identify the manipulated elements. All elements of the system will be connected to and controlled by a computer with specialised software. Additionally, in the field of view of the human operator, there is a display to show the operation instructions and system parameters depending on the performed task. The wrist of the robot will be equipped with a special tactile sensor to allow the human to operate the robotic arm.

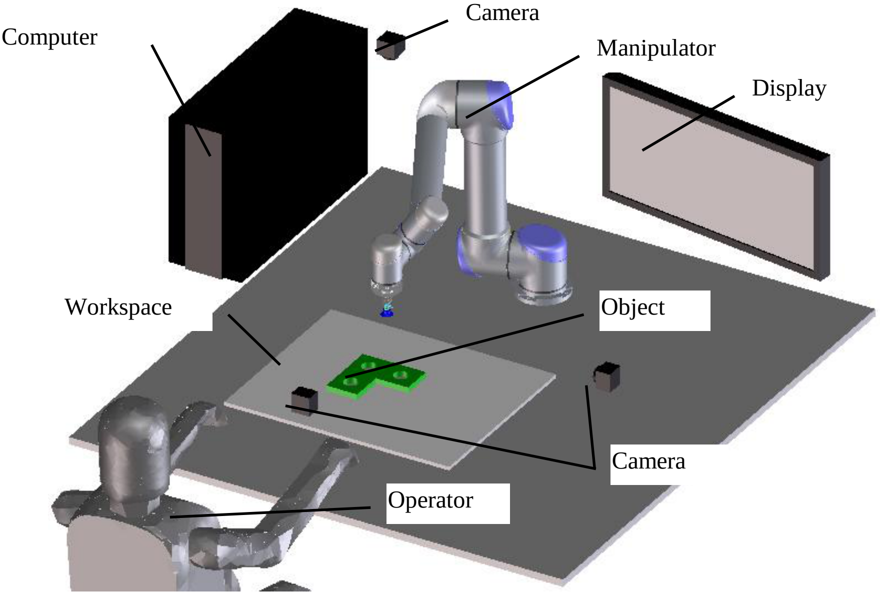

Fig. 5. The concept of a stand for cooperation of robot and human

The task performed by the stand is a sample assembly task, where the proper order of assembly and installation positions are important as well as proper handling of delicate and complex objects. The task of the robot is to handle the element precisely and firmly, and the task of the human operator is to position the object properly. If the object is complex or has features that are difficult to recognise by machine vision systems, it is required that the human operator recognises the proper position of the objects and hands the object to the gripper. If the object is held firmly by the gripper, there is no risk of the manipulator dropping the object or of hitting an obstacle.

Part of the system is the cooperative software, which is installed on an external machine and coordinates all elements of the system. The core of that software is a database with instructions on handling the selected elements, which determines the order of the assembly by instructing the operator via a display. The software acquires data both from the vision sensors and from the control grip, and it controls the movements of the robot.

The algorithm for cooperation is fairly straightforward and resembles a typical assembly algorithm except for the fact that, during the operation, the leading role is being continuously taken over by one of the actors, i.e. either the robot or the operator, depending on what skills are required in the given step of the operation. This is similar to a board game where the two players take their turns to make their move.

In the presented sample task of the assembly of complex and delicate parts, the sample algorithm may look like the one presented in Figure 6. The part is selected accordingly to the instructions stored in the database. The selection is made by the movement of the robot to one of the parts located in the workspace and displaying the proper message on the display. The complexity of the part requires the human operator to put the part into the gripper of the robot, so picking the part is actually done by the operator. Then the robot moves the part near the assembly slot as stated in the database and sets the limits to the allowed position of the grip by allowing, for example, only angular movement along the main axis of the assembled element. Then the operator sets the proper angle of assembly and allows the robot to move the part into its final position. Lastly, the next part for assembly is selected.

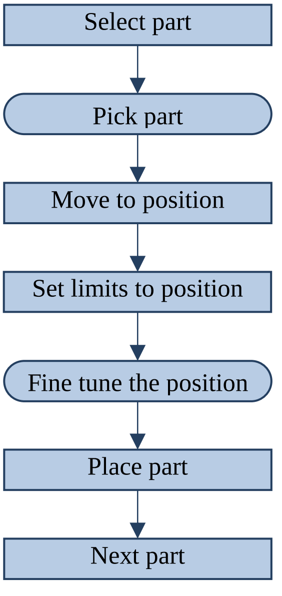

Fig. 6. Sample cooperation algorithm. Rectangular elements denote the operations directed by robot, rounded elements denote operations directed by human. See the text for explanation

Summary

The paper presents the concept of a laboratory stand intended to develop the complete system of a cooperative robot. The stand is based on commercially available industrial manipulator design to allow human-robot cooperation and equipped with additional sensors and specialised software.

The concept of the system assumes automatic recognition of handled elements with use of vision sensors and the use of specialised software and databases to make decisions about the order of operations. Since the operator is instructed by the system on the processing of objects and elements, the system allows fast and safe assembly of products as well as fast and easy switching of the assortment produced.

The presented concept fits well into the modern trends of the development of production systems. The cooperation of humans and robots offers the best features of the two: the precision and safety of handling elements by robots and the cognitive and manipulation skills of human. The concept is a result of previous works performed at the Institute for Sustainable Technologies – National Research Institute in Radom and will be further developed into a fully functional physical stand and will find its application at the Laboratory of Mechatronics of the Institute.

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Stanowisko laboratoryjne z robotem współpracującym z człowiekiem

Słowa kluczowe

Manipulatory przemysłowe, roboty współpracujące.

Streszczenie

Powszechnie wykorzystywane roboty przemysłowe pozbawione są czujników i systemów pozwalających na bezpieczną pracę wspólnie z operatorami. Ze względu na wymagane środki bezpieczeństwa i higieny pracy współpraca człowieka z robotem jest ograniczona lub całkowicie niemożliwa. Prezentowany artykuł przedstawia obecny stan techniki w zakresie współpracujących robotów przemysłowych, głównie robotów o ograniczonej sile ramienia oraz standardowych robotów przemysłowych doposażonych w układy sensoryczne pozwalające na współpracę człowiek-robot. Przedstawiono wybrane produkty dostępne komercyjnie oraz wybrane, zakończone jak i trwające projekty badawcze. W artykule przedstawiono koncepcję systemu robota przeznaczonego do współpracy z człowiekiem z wykorzystaniem robota UR5 firmy Universal Robots.