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Hands-On Learning Environment and Educational Curriculum on Collaborative Robotics

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Hands-on Learning Environment and Educational Curriculum on Collaborative Robotics

Prof. Ana Djuric P.E., Wayne State University

Dr. Ana Djuric is an Assistant Professor of Engineering Technology in the College of Engineering at Wayne State University, Detroit, Michigan. Dr. Djuric research areas are industrial robots, kinematics, dynamics, control, and advanced manufacturing systems. She supervises multiple undergraduate and graduate students in their research and is a member of Council on Undergraduate Research (CUR). Her Dipl.-Ing. degree is in the area of mechanical engineering from the University of Belgrade, Serbia, focusing in Control Systems. Her M.A.Sc. degree is in Industrial and Manufacturing Systems Engineering from University of Windsor, Canada, area of Industrial Robotics, and a Ph.D. in Mechanical Engineering from University of Windsor, Canada in the area of Reconfigurable Robotics. Prior to her arrival at WSU, Dr. Djuric worked in the industry as a machine and tool designer first and then as a Robotics software Analyst for five years. Prior to joining WSU, Dr. Djuric was an Instructor at the Mechanical, Automotive and Materials Engineering, and Industrial and Manufacturing and Systems Engineering departments at the University of Windsor.

Prof. Jeremy Lewis Rickli, Wayne State University

Dr. Jeremy L. Rickli received his B.S. and M.S. Degrees in Mechanical Engineering from Michigan Technological University in 2006 and 2008 and received his Ph.D. in Industrial and Systems Engineering from Virginia Tech prior to joining Wayne State in 2013. At Wayne State, he has created the Manufacturing and Remanufacturing Systems Laboratory (MaRSLab). MaRSLab targets fundamental and applied research in manufacturing and remanufacturing processes and systems while encouraging considerations for sustainability and life-cycle thinking in design, manufacturing, use, and recovery. Specific research thrusts include: transforming manufacturing quality monitoring and remanufacturing core condition assessment via automated laser line scanning systems; remanufacturing core management considering uncertain core quality, quantity, and timing; and integrating design for disassembly and remanufacturing into CAD/CAM tools. He has collaborated in the past with industrial partners on projects involving residual stresses in lightweight aluminum alloy side rails, manufacturing process simulation, and enhancing end-of-life truck acquisition decisions. Dr. Rickli is also actively involved in outreach activities with Athletes for Charity STEM Youth Literacy Program, which provides Detroit Public Schools with STEM educational sessions.

Dr. Vukica M. Jovanovic, Old Dominion University

Dr. Vukica Jovanovic is an Assistant Professor of Engineering Technology in Mechanical Engineering Technology Program. She holds a Ph.D. from Purdue University in Mechanical Engineering Technology, focus on Digital Manufacturing. Her research is focused on mechatronics, digital manufacturing, digital thread, cyber physical systems, broadening participation, and engineering education. She is a Co-Director of Mechatronics and Digital Manufacturing Lab at ODU and a lead of Area of Specialization Mechatronics Systems Design. She worked as a Visiting Researcher at Commonwealth Center for Advanced Manufacturing in Disputanta, VA on projects focusing on digital thread and cyber security of manufacturing systems. She has funded research in broadening participation efforts of underrepresented students in STEM funded by Office of Naval Research, focusing on mechatronic pathways. She is part of the ONR project related to the additive manufacturing training of active military. She is also part of the research team that leads the summer camp to nine graders that focus on broadening participation of underrepresented students into STEM (ODU BLAST).

Dr. Daniel Foster, Old Dominion University

Dr. Foster is an Assistant Professor at Old Dominion University in the Department of Mechanical and Aerospace Engineering. Dr. Foster earned his BS, MS and PhD in Welding Engineering at The Ohio State University's Department of Material Science and Engineering. During his time at The Ohio State,

Dr. Foster worked on numerous welding and additive manufacturing projects funded by the National Science Foundation, The Ohio State University, and Ohio Space Grant Consortium fellowships. His current research is funded by the National Shipbuilding Research Program, the National Science Foundation, and the Virginia Space Grant Consortium. In addition, Dr. Foster also has had the honor of serving as a Faculty Fellow at NASA's Glen Research Center.

Dr. Foster's research focuses on advanced materials joining and additive manufacturing, with particular expertise in in-situ process monitoring. A current research effort of his includes Improving Technical Welding Education Using Real-Time Sensory Feedback, where his lab is developing and testing the real-time feedback of manual welding to increase efficiency and cost-savings during welding training. Other topics of his is Process Monitoring of Ultrasonic Additive Manufacturing and Ultrasonic Welding. Future work includes linking in-situ data to process maps, creating a closed loop process monitoring system that can automatically adjust process parameters in real-time to ensure superior part quality.

Hands-on Learning Environment and Educational Curriculum on Collaborative Robotics

Abstract

The objective of this paper is to describe teaching modules developed at Wayne State University integrate collaborative robots into existing industrial automation curricula. This is in alignment with Oakland Community College and WSU's desire to create the first industry-relevant learning program for the use of emerging collaborative robotics technology in advanced manufacturing systems. The various learning program components will prepare a career-ready workforce, train industry professionals, and educate academicians on new technologies. Preparing future engineers to work in highly automated production, requires proper education and training in CoBot theory and applications. Engineering and Engineering Technology at Wayne State University offer different robotics and mechatronics courses, but currently there is not any course on CoBot theory and applications. To follow the industry needs, a CoBot learning environment program is developed, which involves theory and hands-on laboratory exercises in order to solve many important automaton problems. This material has been divided into 5-modules: (1) *Introduce the concepts of collaborative robotics, (2) Collaborative robot mechanisms and controls, (3) Safety considerations for collaborative robotics, (4) Collaborative robot operations and programming, (5) Collaborative robot kinematics and validation*. These modules cover fundamental knowledge of CoBots in advanced manufacturing systems technology. Module content has been developed based on input and materials provided by CoBot manufacturers. After completing all modules students must submit a comprehensive engineering report to document all requirements.

Introduction

A collaborative robot (CoBot) is a robot that can safely and effectively interact with human workers while performing simple industrial tasks. As further evidence of the importance of this growing market segment to the US economy, ABI Research recently published a new forecast putting the market for collaborative robots at over $1 billion by 2020. Peshkin and Edward (1999) were seeking a way for robots to improve ergonomics for human workers without introducing new risks from the robots themselves. What they came up with was the idea that robots and people could work in partnership, each contributing what each did best. They introduced the term collaborative robot, or CoBots, to highlight the interaction between human and machine. Their first patent on CoBots was filed in 1999 and defined CoBots as an advanced manufacturing technology capable of transforming industrial automation by functioning in the same space as humans and with human operators. CoBots work hand in hand with humans in a shared work process and support human operator. For example: a CoBot lifts and locates a workpiece while a human worker completes needed operation. The CoBot and the worker may come into direct contact with each other as a result, (Huelke M., 2013). However, there is a lack of knowledge of how best to integrate CoBots into manufacturing operations and a significant lack of methods available for small, medium, and large manufacturers to design, plan, and test CoBot work-cells.

With a predicted 150,000 CoBots to be installed worldwide in the next three years (Anandan, 2014) and a suggested net present value 25% greater than traditional robot solutions (much greater for manual solutions) (Kruger et al., 2009), it is imperative that CoBot work-cells in manufacturing be well understood and designed. The Executive Summary World Robotics (2016) predicts that double-digit growth of industrial robotics will happen between 2016 and 2019 and that linking the real-life factory with virtual reality will play an increasingly important role in global manufacturing. Within this period, Executive Summary Word Robotics also predicts that human-robot collaboration will have a breakthrough due in part because compact and easy-to-use CoBots will drive the market (Executive Summary World Robotics, 2016). With CoBots expected impact on productivity and workers' safety (Ding et al., 2013; Akella et al., 1999), it is imperative that higher education institutions incorporate this technology into learning programs for a career-ready workforce.

This paper describes an advanced, industry-driven, hands-on learning environment and educational curriculum focused on collaborative robotics and the integration of the technology into advanced manufacturing systems. A hand-on CoBot learning environment has been and is currently being created, which will be incorporated into three different courses at Wayne State University (WSU).

The CoBot learning environment has 5-modules, which cover fundamental knowledge of CoBots in advanced manufacturing systems technology. Module content has been developed based on input and materials provided by CoBot manufacturers. The CoBot learning environment targets current students, returning or lifelong students, who may already be working in industrial automation as operators, technicians, and programmers as well as WSU engineering students. Table 1 outlines the CoBot module course content and related learning outcomes. To achieve the desired learning outcomes we described below each module content.

Table 1. CoBot learning environment modules and related learning outcomes

Modules	Contents	Learning Outcomes
Introduce the concepts of collaborative robotics	• Collaborative robotics applications case studies	an ability to select and apply the knowledge, techniques, skills, and modern tools of their disciplines to broadly-defined engineering technology activities
Collaborative robot mechanism and controls	• Collaborative robot mechanical configurations • Collaborative robot controller configurations • Tooling for collaborative robots	an ability to design systems, components, or processes for broadly-defined engineering technology problems appropriate to program educational objectives
Safety considerations for collaborative robotics	• Collaborative safety considerations • Safety devices • Risk assessment	an ability to conduct standard tests and measurements; to conduct, analyze, and interpret experiments; and to apply experimental results to improve processes
Collaborative robot operations and programming	• Operations procedures for collaborative robotics • Lead-thru programming for teaching positions • State language programming • Editing programs	an ability to conduct, analyze, and interpret experiments; and to apply experimental results to improve processes

Collaborative robot kinematics and validation	• Kinematic modeling using D-H parameters • Solving forward kinematics using homogeneous transformation matrices • Validating kinematic equations using selected points from the created trajectory	an ability to select and apply a knowledge of mathematics, science, engineering, and technology to engineering technology problems that require the application of principles and applied procedures or methodologies

All experimental activities, laboratory activities, and hands-on exercies are conducted using a Baxter CoBot.

Course Learning Objectives is:

1. Perform mathematical analysis of objects position and orientation in space using homogeneous coordinates and composite homogeneous transformation matrix.
2. Mathematical modeling of robot kinematic structure using Denavit-Hartenberg representation.
3. Solving the direct kinematic problem for multi DOF kinematic structures with different type of joints, using composite homogeneous transformation matrix.
4. Solving the inverse kinematic problem using analytical and geometric approaches applied for 2DOF, 3DOF, 4DOF, 5DOF, and 6DOF manipulators.
5. Use different methods to calculate the Jacobian, singularities, velocities and static forces for multi DOF kinematic structures.
6. Apply computer simulation and off-line programming software, such as Workspace LT, to model robots and mechanisms (rotary tables, conveyers, tools, etc.) for different applications in manufacturing systems.
7. Evaluate safety issues for robot workspace layout design (collision detection, path generation, robot Work envelope generation, etc.).
8. Communicate effectively in oral and written formats

Module 1: Introduce the concepts of collaborative robotics

This module is taught using two Baxter applications: (1) pick-and-place of selected part and (2) assembly of hose-barb fittings.
For the pick-and-place application students select several parts and create a program using both Baxter arms. This application is used to learn how to create a Baxter trajectory, use two attached grippers, synchronize motion between two arms, and select different arm configurations, see Figure 1.

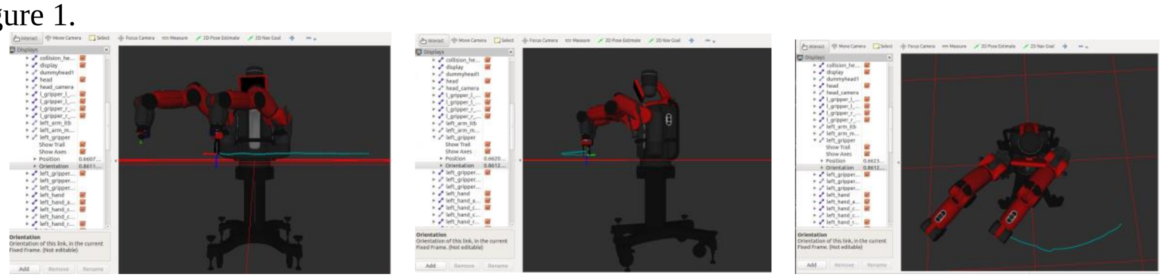

Figure 1: Baxter trajectory (front, side and top views)

For the assembly of hose-barb fittings application, students learn effects of CoBot on a generic assembly process. The exercise assembles 50 hose and barb both manually and collaboratively. Results of manual and CoBot assemblies are compared in regards to time, assembly quality, and operator feedback. A fixture to hold barb during assembly cycle was designed and 3D printed, see Figure 2.

Figure 2: Experimental Setup with the 3D printed fixture

The quality of joint was measured by measuring the gap between hose and barb after assembly. The quality OK assemblies was defined as assemblies with a gap lesser than 0.03 inches. A fill gage of 0.03 inches was used to measure the gap. See Figure 3.

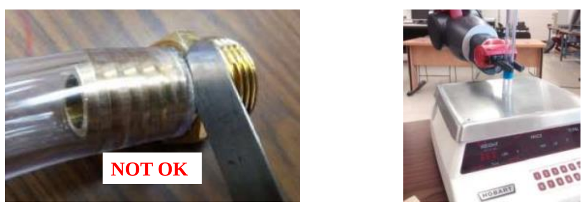

Figure 3: Measurement of quality of joint (NOT OK) and Measuring force exerted by CoBot

A weighing machine with least count of 0.01 lbs. was used to measure the force exerted by human operator in manual and collaborative operation. It was necessary to measure the force exerted by CoBot during collaborative operation. The same method was used to measure the force exerted by CoBot alone. See Figure 3. Students learn that induced fatigue is directly proportional to the force exerted by the operator. As the force increases, the induced fatigue will increase. However, the force exerted in collaborative operation is the algebraic sum of force exerted by human and force exerted by CoBot, see equation (1). From this exercise students can calculate and observe the operator (human) force needed in the collaborative operation.

$$F_{Collaborative} = F_{Human} + F_{CoBot} \tag{1}$$

Module 2: Collaborative robot mechanism and controls

Using Baxter User Guide students learn mechanical configurations, controller configurations and available tooling. In Figure 4 all Baxter parts are shown. (1) Condition ring, (2) Attention ring, (3) Display, (4) Torso, (5) Navigator (one on each forearm) (6) Lower front panel, (7) Training cuff (shown with parallel gripper), (8) Training cuff (shown with vacuum gripper, (9) Pedestal (optional) (10) Navigator (one on each side), (11) Non-active (button for future use), (12) Air filter (one on each side), (13) Power button, (14) Power and I/O panel (with DB15, USB, and Ethernet Ports), (15) Pedestal (optional), (16) Training cuff, (17) Gripper body, (18) Finger, (19) Finger position.

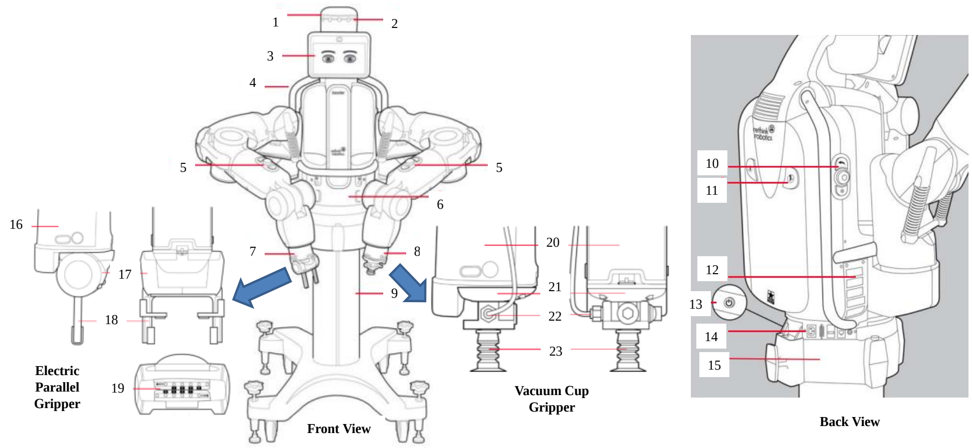

Figure 4: Hardware Overview of the Baxter Robot (Baxter User Guide)

Controlling the Baxter robot is done using a workstation operated under Linux Ubuntu. Baxter can be connected to the workstation computer using standard TCP/IP connection or a wireless connection using following steps:

Direct Connection

1. Disable Networking in Workstation computer.
2. Connect Ethernet Cable from Baxter to computer.
3. Open the Terminal using the python code:
   cdros_ws
   python pythonExamples/avahiconection.py
4. Open up a new terminal window using the python code:
   cdros_ws
   python pythonExamples/baxterinit.py
   python pythonExamples/Enable.py

Wifi Connection

Baxter can be connected to the workstation wirelessly also. For this, a standard WiFi router is necessary.

Joystick Control

To interact Baxter robot students can use game controllers, or joysticks. A python utility is available for handling input devices like joysticks with common methods. The joystick controller is supported by Linux and should be compatible with the ROS joy package. The joystick controller buttons are related to the Baxter arms motion using python code. For this model we have developed a detailed lab instruction how to operate Baxter with joystick.

Keyboard control

The joint position keyboard is used for Baxter joint position control. Each key of keyboard PC is mapped to either increasing or decreasing the joint angles of a particular joint on Baxter's arms. Each arm is represented by one side of the keyboard with corresponding increase/decrease joint key couplings within the rows.

In an RSDK Shell enter the following python code:

rosrunbaxter_examples joint_position_keyboard.py

For this model we have developed a detailed lab instruction how to operate Baxter with the keyboard.

Module 3: Safety considerations for collaborative robotics

Unlike typical industrial robots that operate behind safeguarding, CoBots are designed to work effectively directly beside people in a factory setting, (Djuric A. M. et al. 2016). Students create programs with the Baxter which is designed for:

- Physical interaction between a worker and the robot.
- Avoiding accidental contact.
- Minimizing forces and slowing/stopping during human contact.

Using Baxter the Baxter ™ Safety and Compliance Overview document students (Huelke M., 2013) students learn about the Baxter’s Safety and Compliance Features are:

- *Software Control:* Baxter is designed to slow or stop upon inadvertent contact, allowing it to work collaboratively or to be co-located with an operator in close proximity.
- *Multiple Redundant Systems:* Baxter has a wide array of innovative sensors and an emergency stop function to ensure safety.
- *Lightweight, Compliant Materials:* Baxter’s arms weigh less than 20 kg, are fully covered in compliant plastic, and use protective foam at key joints.
- *Dynamic Braking:* Baxter will slowly come to rest in the event of a power loss or an E-stop.
- *Diverse Motor Enabling System:* Two separate “heartbeat” signals are maintained to keep motion enabled.
- *Human Awareness:* Baxter can recognize human proximity with its 360° sonar system, which signals its awareness of any detected nearby people.

Module 4: Collaborative robot operations and programming

Students can create different programs with the Baxter CoBot using different procedures. One procedure is described below. When the Baxter is connected to the workstation correctly the path of the robot can be recorded in the workstation using its record and playback options. It can be achieved by the following steps.

1. Open up a new RSDK Shell and enter the following python code:
   rosrunbaxter_examples joint_recorder.py -f %filename%.rec, see Figure 5.

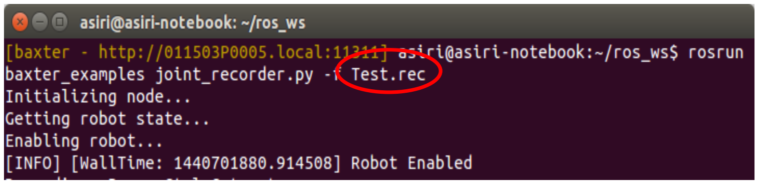

Figure 5: The terminal window appearance once the recorder command is entered

2. The Baxter Cobot recording its movementso the exact path taught to the CoBot manipulators are recorded. In this case "Test.rec" file contains all the details of the path taught.
3. Press **Ctrl+C** when done.
4. The program is saved in **Home/ros_ws** folder, see Figure 6.

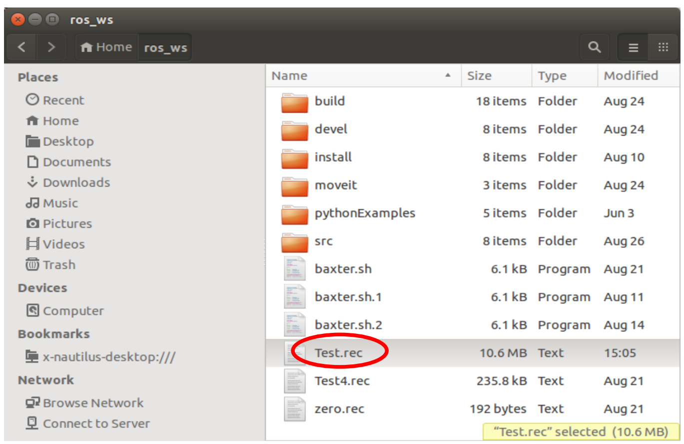

Figure 6: The destination Home/ros_ws containing the recorded file

5. In the same Terminal window enter the following python code:
   rosrunbaxter_interface joint_trajectory_action_server.py
6. Open up a new RSDK Shell without closing the previous Terminal and enter the following python code:
   rosrunbaxter_examples joint_trajectory_file_playback.py -f %filename%.rec

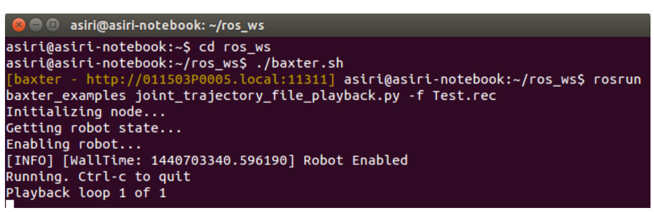

Figure 7: The view of the terminal window after playback command is entered.

Module 5: Collaborative robot kinematics and validation

Robotic kinematics is the field of study that describes the relation between frames (joints) in the kinematic chain using the homogeneous transformation matrix ${}^{i-1}A_i$ through Denavit-Hartenberg (D-H) (Denavit J. and Hartenberg R. S., 1955) parameters as showed in equation (2). ${}^{i-1}A_i$ is the link transform for the i^{th} joint; $i = 1,2,...,n$ and n is the number of links.

$$
{}^{i-1}A_i = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i \sin\theta_i & \sin\alpha_i \sin\theta_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\alpha_i \cos\theta_i & -\sin\alpha_i \cos\theta_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (22)
$$

Baxter collaborative robots have two seven Degree-of-Freedom (DOF) arms. Seven DOF arms are desirable as they provide a kinematic redundancy, greatly improving the manipulability and safety. See Figure 8.

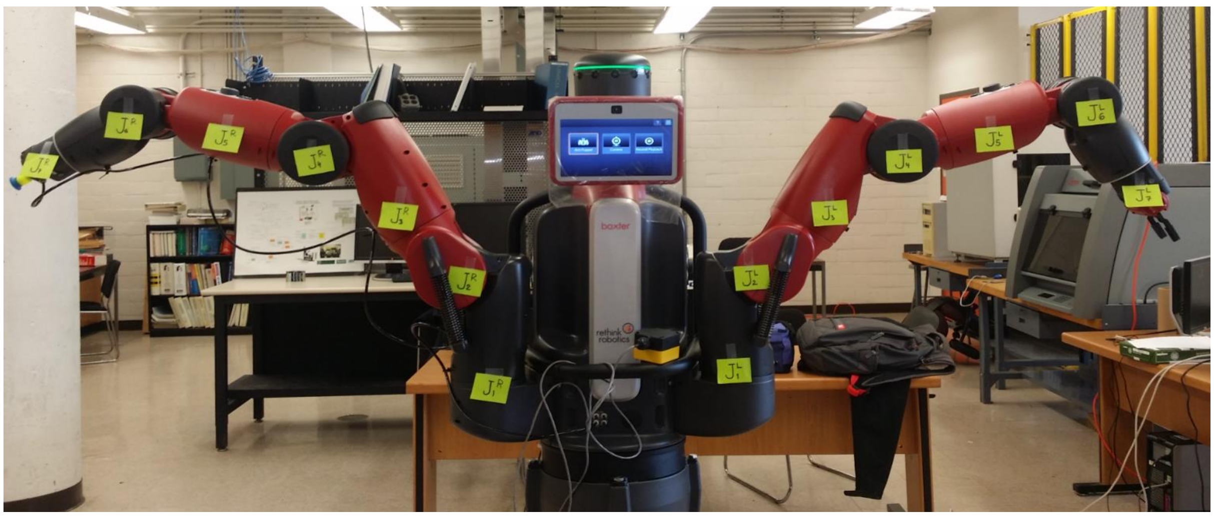

Figure 8: Baxter cobot left and right joints

The Baxter CoBot left and right arms kinematic chain has been determined by WSU researchers (e Silva et al., 2016). See Figure 9.

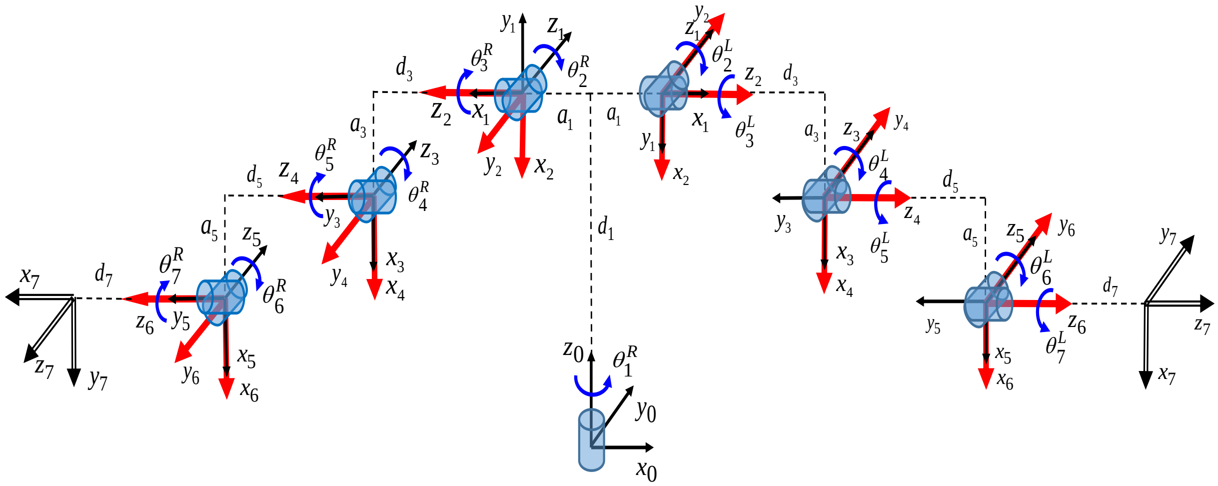

Figure 9: Baxter cobot left and right arm kinematic chain (e Silva et al., 2016)

The Baxter D-H parameters have been generated, see Table 2. For each joint the D-H parameters are: twist angle of the Left/Right Arm (α_i^L, α_i^R), linear displacement in z-axis, d_i, linear displacement in x-axis, a_i, and joint angle of the Left/Right Arm (θ_i^L, θ_i^R).

Table 2: D-H parameters for the Baxter cobot left and right arm (e Silva et al., 2016)

i	d_i	θ_i	a_i	α_i^L	α_i^R
1	d_1	$\theta_1^L = 0^\circ, \theta_1^R = 180^\circ$	a_1	-90°	90°
2	0	$\theta_2^L = 90^\circ, \theta_2^R = -90^\circ$	0	90°	-90°
3	d_3	$\theta_3^L = 0^\circ, \theta_3^R = 0^\circ$	a_3	-90°	90°
4	0	$\theta_4^L = 0^\circ,\ \theta_4^R = 0^\circ$	0	90°	-90°
5	d_5	$\theta_5^L = 0^\circ, \theta_5^L = 0^\circ$	a_5	-90°	90°
6	0	$\theta_6^L = 0^\circ,\ \theta_6^R = 0^\circ$	0	90°	-90°
7	d_7	$\theta_7^L = 0^\circ,\ \theta_7^R = 0^\circ$	0	0°	0°

Students use the Baxter forward kinematics (Eq. 3) model to learn robot kinematics and validate the equations by testing selected points from the trajectory.

$$ {}^{0}A_7^{LR} = {}^{0}A_1^{LR}\ {}^{1}A_2^{LR}\ {}^{2}A_3^{LR}\ {}^{3}A_4^{LR}\ {}^{4}A_5^{LR}\ {}^{5}A_6^{LR}\ {}^{6}A_7^{R} \quad (3)$$

Several points from the Baxter trajectory has been selected to demonstrate the procedure of forward kinematic calculation and validation, see Appendix A.

Conclusion

In this paper we introduce the first industry-relevant learning program for the use of emerging collaborative robotics (CoBots) technology in advanced manufacturing systems. Through this program we are preparing future engineers to work in highly automated production and use advance manufacturing tools. Wayne State University offers different robotics and mechatronics courses, but currently there is no course on CoBot theory and applications. To follow the industry needs, we developed CoBot learning environment program, which involve theory and hands-on laboratory exercises in order to solve critical CoBot automaton challenges. This material has been divided into 5-modules: (1) *Introduce the concepts of collaborative robotics, (2) Collaborative robot mechanism and controls, (3) Safety considerations for collaborative robotics, (4) Collaborative robot operations and programming, (5) Collaborative robot kinematics and validation*. These modules cover fundamental knowledge of CoBots in advanced manufacturing systems technology. Modules material has been developed based on CoBots manufacturers information, industrial need and theoretical requirements in engineering program.

Future Work

The CoBot learning environment modules will be used for development of a new undergraduate course: Introduction to Collaborative Robotics and Applications.

Acknowledgments

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Appendix A

Trajectory points	**Joint values (radians)**	**End-effector values (mm)**

1	theta1_Pendent = 0;
	theta2_Pendent = 0;
	theta3_Pendent = 0;
	theta4_Pendent = 0;
	theta5_Pendent = 0;
	theta6_Pendent = 0;
	theta7_Pendent = 0;
		0.0000 -0.0000 0.0010 1.0880
		0.0000 0.0010 0.0000 0.0000
		-0.0010 0.0000 0.0000 0.1910
		0 0 0 0.0010

2	theta1_Pendent = -0.86401468;
	theta2_Pendent = -0.54609716;
	theta3_Pendent = 0.003067962;
	theta4_Pendent = 0.738228254;
	theta5_Pendent = -0.05637379;
	theta6_Pendent = 1.361791444;
	theta7_Pendent = -2.01488376;
		-0.3952 -0.9182 -0.0287 500.1831
		-0.9170 0.3961 -0.0472 -607.6696
		0.0547 0.0077 -0.9985 39.1013
		0 0 0 1.0000

3	theta1_Pendent = -0.86401468;
	theta2_Pendent = -0.54609716;
	theta3_Pendent = 0.003067962;
	theta4_Pendent = 0.738228254;
	theta5_Pendent = -0.05637379;
	theta6_Pendent = 1.361791444;
	theta7_Pendent = -2.01488376;
		-0.3952 -0.9182 -0.0287 500.1831
		-0.9170 0.3961 -0.0472 -607.6696
		0.0547 0.0077 -0.9985 39.1013
		0 0 0 1.0000

Appendix B

Assignment Example # 1 - Collaborative Applications of Industrial Robots and Cobots Applications

Scope:

The objective of the first assignment is to familiarize students with different type of Collaborative robots and their applications.

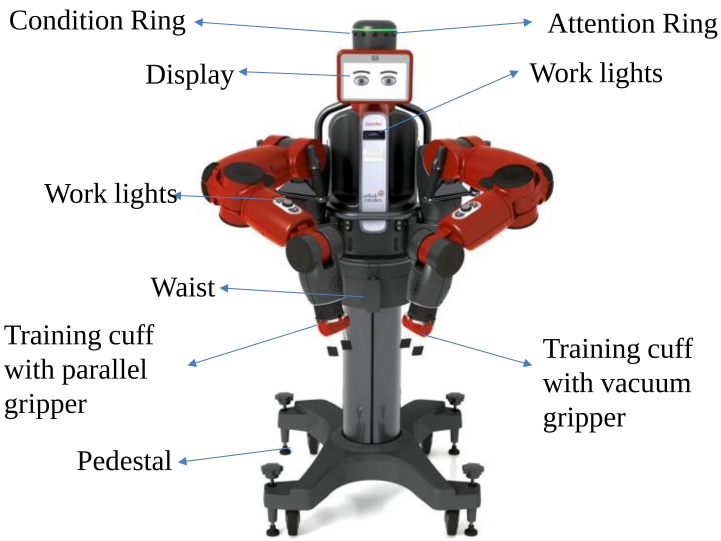
Requirements:

- ✓ Search for different 10 Cobots and find 5 applications. Present your results in a table.

	Applications / Cobots	Pick and place	Medical	…..	…..	…..
1	Baxter	√				
2	UR			√		
3	….		√			
4						
5						
6						
7						
8						
9						
10						

- ✓ Do a literature survey in the same area and make a brief summery.
- ✓ Undergraduate students: 5-7 papers.
- ✓ Graduate students: 10-12 paper.
- ✓ Go to the CIM lab and create a simple program with Baxter robot. Record a video and e-mail the instructor (Ana Djuric).

Baxter Collaborative Robot



Rules:

- ✓ This is an individual assignment.
- ✓ It is worth 10% of the course final grade.
- ✓ More details on the assignment will be discussed in class.
- ✓ Submit a comprehensive engineering report to document the above requirements.