Humanoid Robot Instructors for Industrial Assembly Tasks

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ABSTRACT
We are interested in the interactive aspects of deploying humanoid robots as instructors for industrial assembly tasks. Training for industrial assembly requires workers to become familiar with all steps of the assembly process, including learning and reproducing new tasks, before they can be employed in a production line. The derived challenges in current practice are limited availability of skilled instructors, and the need for attention to specific workers' training needs. In this paper, we propose the use of humanoid robots in teaching assembly tasks to workers while also providing a quality learning experience. We offer an assembly robotic instructor prototype based on a Baxter humanoid, and the results of a study conducted with the prototype teaching the assembly of a simple gearbox.

Author Keywords
Baxter humanoid robot; Godspeed questionnaire; human computer interaction; human robot interaction; humanoid robots; industrial assembly; industry; innovation; instruction; learning; learning technology; performance; performance technology; robotic instructor prototype; robotics; teaching system; training; workplace health and safety

ACM Classification Keywords
Experimentation; Design; Human Factors; Performance; Standardization

INTRODUCTION
In industrial working environments, especially in the assembly industry, it is critical for workers to learn how to carry out a new task and reproduce it within the context of an assembly line. Before workers can be employed in a production line, they have to become familiar with all the steps of the assembly process. For example, in the case of a gearbox manufactured in a production line, workers have to train in performing the complex assembly process several times in order to ensure a flaw- and frictionless assembly.

There is a widespread need for supporting methods that help workers learn new assembly skills. Currently, "overseers" - observers or mentors - instruct, guide and supervise workers during the learning process. However, many challenges arise when relying on overseers. Drawing on our combined experience, and collaboration with the assembly industry, we present two examples of challenges we hope to address: (1) there may be difficulties in serving individual learning needs of different workers; and, (2) there are a limited number of skilled overseers qualified to teach specific components of a complex assembly processes within the relevant context of the assembly process.

Our research aims to tackle these challenges by exploring new ways to design and improve the learning process using robots. Our goal is to understand how humanoid robots can teach new assembly tasks to a worker, freeing up scarce resources of available human overseers, while providing a quality learning experience, which includes learning the tasks required and experiencing the learning process in a positive way.

Following strict research ethics and safety guidelines, we developed an assembly teaching prototype using a Rethink Robotics Baxter humanoid as an assembly task instructor. We then conducted an evaluation study of our approach to verify if it is possible to train an inexperienced worker to successfully assemble a mechanical gearbox. Our goal was to explore how humans interact in this learning situation, and to measure user experience (UX), reflecting on acceptability, intimidation, and other factors related to collocated interactions with robots [1]. The results of our study demonstrate that humanoid robots can become effective assembly line instructors, and have the potential to provide alternatives to visual-only learning systems such as print, video, or augmented reality.

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The contributions of this paper are as follows:

- A novel design and implementation of an assembly humanoid-based teaching system;
- A study providing results that explore why and how humanoid robots can be instructors for industrial assembly tasks.

The remainder of the paper starts by highlighting previous work in the area, followed by the design rationale for our prototype. We then describe the technical system components, and detail the study conducted. We conclude by presenting our results, and discussing implications for future work.

BACKGROUND

In industrial training and instruction, instructors are often drawn from the ranks of personnel who are expert in a given trade [6]. This approach can lead to shortages of available instructors capable of training large numbers of new workers, leading to a reliance on distance learning, print, and electronic resources, to extend individual instruction [16].

Robotics in Education

The use of robotics in training and education may follow patterns of adoption in other areas of work. Research on technologies that enable the integration of new forms of media interaction, such as personal computers [4], intelligent tutoring systems [5], social robots and virtual agents [11] in education and physical rehabilitation [13] are instructive.

Technology-enabled, competence-based, training has been successfully used to train doctors to perform psychomotor tasks, such as those used in laparoscopy (e.g., [9]). These initiatives were designed using a model of simulated task performance using virtual and augmented reality, and mechanical bench training activities [14]. Simulated representations of a patient, or mechanical system, were used, with students learning and performing tasks within a simplified, artificial environment.

Human-Computer Interaction

Virtual and augmented reality are employed in the training of mechanical assembly tasks (e.g., [12, 14, 22, 24]). Students demonstrate more rapid adoption of tasks when interacting with fidelity simulated control interfaces, and when manipulating tangible physical mechanical objects as part of the learning process [3].

Virtual reality has been enhanced with mixed reality; simultaneous modeling of a virtual world with real-world counterparts for interaction [19]. This approach places a layer of hardware and software between the learner and the objects they interact with, because participants are required to wear specialized equipment, such as head-mounted displays.

Our research attempts to increase tangible direct manipulation while decreasing the abstraction of interface between instructor and student. Using this new approach, students will learn to assemble mechanical components *in-situ*, guided by gestural, verbal, and graphic instructions and feedback provided by a Baxter robot, with the goal of creating a fully, and correctly, assembled device.

Human-Robot Interaction

Robots have been shown to help learners overcome language barriers by combining the use of gestures with spoken commands [8,10], and can be effective as tutors providing social gestural cues to students [21]. Social gaze in robot interaction improves spatial management functions involved in mechanical assembly operations by directing attention, and movement, with nonverbal cues that supplement or augment verbal, and written, instructions [7]. In typical human-robot instruction scenarios, humans interact with robots using human movement to train trajectories and movement for the robot [2]. In this work, we explore the other side of the interaction. The robot leads the interaction, and guides the human worker's movement during the assembly process.

PROTOTYPE HUMANOID TEACHING SYSTEM

Our approach integrates a humanoid robot into a teaching system, where the robot takes on the task of overseer or instructor teaching the industrial process of mechanical assembly. We argue that while assembly tasks might be automated completely by other robots, current assembly industrial processes are still dependent on humans that cannot to substituted by robots. Therefore, we focus on addressing the current lack of skilled experts to train "novice" new workers.

The robot trains workers in the assembly process by giving instructions for each step, providing relevant information for critical complex contexts, and offering assistance for potential errors. The teaching system is not limited by time, capacity or language constraints [25] as in the human, overseer approach. In other words, the proposed system allows any person regardless of linguistic differences to be trained by Baxter, whose instructions are encoded and can be localized as needed. These efficiencies lead us to believe our approach will reduce training costs, and enable inexperienced learners, as well as those requiring additional experience, or who face language barriers, to learn and work on an industrial production line.

Early Explorations

Beginning our research, we conducted pilot sessions to study how people teach and learn technical skills, how technology can support such learning, and how the Baxter humanoid robot, can support or take on the role of instructor.

We first identified basic elements of instructions that a human uses while teaching (Figure 1). These elements include expressive gesturing, specific pointing, speaking, and demonstrating with tools such as images and video. Our exploration simplified apprenticeship-based learning demonstrated that humanoid robots have the potential to substitute many basic elements involved in teaching a new mechanical assembly task.

Figure 1. Example of one of the pilot sessions

A key design exploration during our pilot studies focused on understanding the capabilities of Baxter as a humanoid instructor. Baxter has: a rotating, face-like display, a camera, and movable arms with flexible joints (Figure 2). We explored variations of Baxter's speed of motion, range of movement, and the ability to display media. We found that Baxter is able to successfully perform complex gestural movements with its arms and grippers, but was not as fast as human motion when moving between task-specific locations. When playing multimedia, Baxter is capable of providing supplemental media (e.g., text, images and animation) that support the teaching of critical contextual aspects of assembly tasks. By implementing speech synthesis software, Baxter can also speak. This speech can operate in any language, accommodating learners not fluent in the original language of instruction.

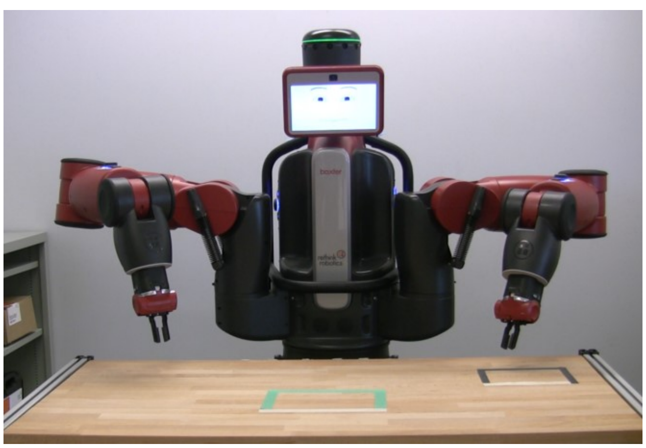

Figure 2. Baxter, our humanoid robot instructor

Another design criterion requires generic system development supporting usability with any type of (humanoid) robot. Although our work involved Baxter, the software, and methodology, can be generalized for adaptation to other robots and approaches. This transferability is achieved because of a design architecture that abstracts robot actions into simple commands (e.g., move to a specific location, show a specific rotation gesture, etc.).

Techniques to Support Teaching

Many of existing learning systems use visual techniques to teach tasks. Examples include, the use of virtual, augmented, and mixed reality, and computerized simulation. While there are advantages to these approaches, such as low associated cost, portability, and ease of deployment, there are many disadvantages. Clearly, such visual-only techniques lack the physicality, spatiality, and personal aspects (e.g., facial expression and movement) a human instructor provides. These interaction cues are essential to provide effective teaching and learning. Further, occlusion of physical objects or interface elements often result when augmenting physical task components with *in-situ* visualization, thus hiding some task operations, or making them unclear, which hinder an efficient learning process.

Our Approach

We designed, developed, and evaluated, an assembly teaching system (ATS) utilizing the humanoid robot Baxter, which is capable of basic hand gestures, movement, as well as displaying media that simulates facial expression. While we acknowledge the importance of robotic gaze [7] we decided, mainly for experimental simplification, to support Baxter with basic head movements while displaying a simplified human-like face. By utilizing a humanoid robot, our proposed approach aims to provide a moderate solution between the low cost visual-only approaches, and the expensive option of making a human instructor available for all learning interactions.

The design of our prototype provides step-by-step instructions to train workers on the assembly of a simple gear box. This task includes 23 assembly steps. The humanoid robot explains each step in succession using hand gestures, visual diagrams, and speech. Our generic design, utilizing XML, supports any kind of stationary assembly process, and any kind of humanoid robot. In particular, mapping the structure of any assembly task through our XML format is achievable using the primitive learning steps we identified (e.g., robot movement, gestures, etc.). We added support to encode patterns for repeating task components, which simplifies the creation of assembly plans. Using XML for assembly tasks, our approach allows for the embedding of specialized tags to address user mistakes (e.g., branching to assist a trainee when he or she makes a mistake during the teaching process). This approach allows for future work, task flow, instructions, and potential errors that can be automatically generated by an artificial intelligence component, thereby simplifying the creation of project-specific XML content.

We conducted an evaluative study to verify whether it is possible to train an inexperienced person in a specific assembly task. In addition, we explored human interaction in the learning process with the robot. Our UX measures include reflection on acceptability, and other factors relating to interactions with robots [1].

Since our focus is on the UX, we designed our Baxter prototype to operate through a high-level Wizard-of-Oz approach [15] where, unknown to the trainee, a human operator or “Wizard” oversees the robot’s actions. This manual operation mode simulates the output of an artificial intelligence algorithm, which could be implemented in future designs. While this approach was crucial to our study, it is important to note that our Baxter prototype already includes completely functional gesture, and media modules, for step-by-step assembly instructions. The Wizard controls only the instructional flow: e.g. selecting the next step for the robot to perform, or to repeat a step.

SYSTEM DESCRIPTION

The following section describes the assembly teaching system prototype, used to evaluate whether, and how, humanoid robots can teach industrial assembly tasks.

In this work, we used Rethink Robotics’ industrial humanoid robot Baxter. Baxter is dual-armed, and 1 meter tall providing seven degrees of freedom. Pedestal mounting enables stationary usage in a single, fixed location.

Architecture

As described in the previous section, the robot should impart instructions to the user, in a human style, using arm gestures, speech, and facial expressions. Thus, our design divides the prototype system into two discrete units; the robot acting as the presentation medium, and the Assembly Teaching System as a back-end application that assumes all information processing tasks (Figure 3).

Baxter can be operated using the Robot Operating System (ROS) open-source framework [17], which allows a simple application creation using the Python API provided. The framework allows the implementation of actions such as moving each of Baxter’s joints to a specific position, controlling of grippers (hands), or setting the content to be displayed by the head (screen). These actions are published by ROS to the robot for execution.

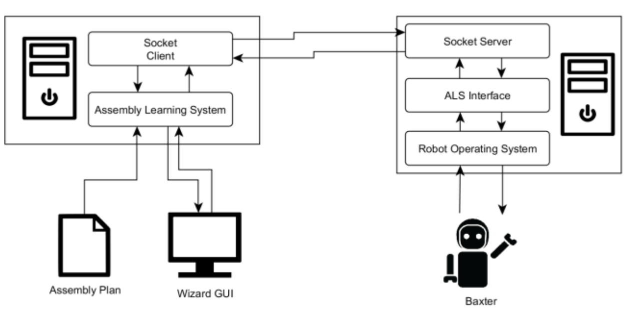

Figure 3. Structure of Assembly Teaching System Components

Using ROS we developed an application that serves as an interface for the Assembly Teaching System. By making this interface available using socket connections, the Assembly Teaching System is able to send actions in a predefined format to the interface, and thereby control the robot. This client-server architectural approach isolates the control unit of the robot from the operator application, which provides robot-instructions. This encapsulation makes the system generic, enabling it to operate with different kinds of robots without the need to revise the whole system whenever one of its components changes.

Task Representation

The Assembly Teaching System contains all information required for the assembly training. In lay terms, an assembly-training task needs to be simplified as a set of steps, which can be sent to the robot one-by-one for execution. Depending on the user’s response to a given instruction (e.g., the user correctly performed the step, or made a mistake), the software decides which subsequent step appropriate. We implemented a flowchart-utilizing state machine to represent the sequence of events for the assembly process of the gearbox object used in our prototype (Figure 4). Each state of this flowchart represents an instruction given to the user. The transition between states is determined by the outcome, or user action.

It took several iterations to identify and optimize the individual assembly steps for the gearbox object, as described in the pilot study below. Our final description involved 23 concrete assembly steps, and 22 state transitions required to represent the necessary information for successful assembly (Figure 5).

A challenge for this type of state-representation is that the generated steps only cover the ideal flow of the process, and exclude potential user mistakes. After incorporating the most common, and predictable, mistakes a user might make during the process, and then matching them with an appropriate solution, the flowchart contained more than 100 steps, and 200 different transitions, which created the need for a more precise representation.

Figure 4. Gearbox object (top) and its discrete parts (bottom)

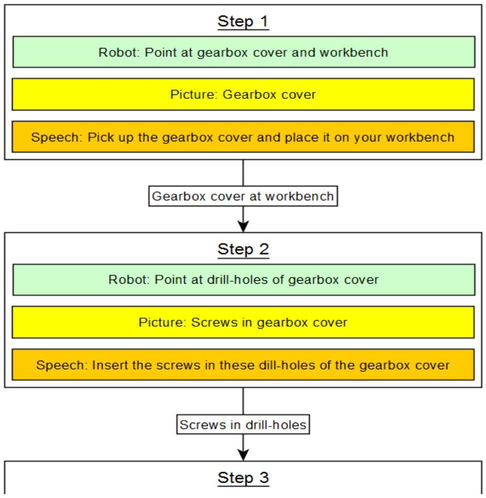

Figure 5. Example of a 3-step flow diagram without failures

Analyzing the flowchart, we isolated several repetitive instructions. Our results indicated that for these types of instructions, predicted failures, and subsequent resolution steps were always the same. One example is the instruction, "*Pick Object A and place it at Position B in Orientation C*". Predictable mistakes in this case include the user picking the wrong object, or placing it at the wrong position/orientation. These findings allowed us to introduce "patterns" to represent repeating procedures in an efficient manner. As a result, our methodology provides a significant simplification while sequencing the assembly process.

Implementation Details

We implemented a Java-based, state-machine component that maps the XML structure mentioned earlier. This method streamlines the move between the instructions' steps based on transitioning conditions. By representing steps in a data packet structure, networked communication offers an efficient means to engage the robot interface.

To provide audible information, in addition to the visual movements, we used the SemVox Ltd. ODP S3 Speech Dialogue Platform [20]. This platform enables not only speech synthesis of the information defined in the assembly instruction files, but also the ability to talk and control the system by voice input. By placing speakers and microphone near the robot, the user gets the impression that the robot is talking and understanding during the interaction.

To support evaluating the system using the "Wizard of Oz" approach, we developed a graphical user interface (GUI) that allows the experimenter to control the robot indirectly through the Assembly Teaching System. As shown in Figure 6, the GUI provides the functionality to load and navigate through an assembly plan.

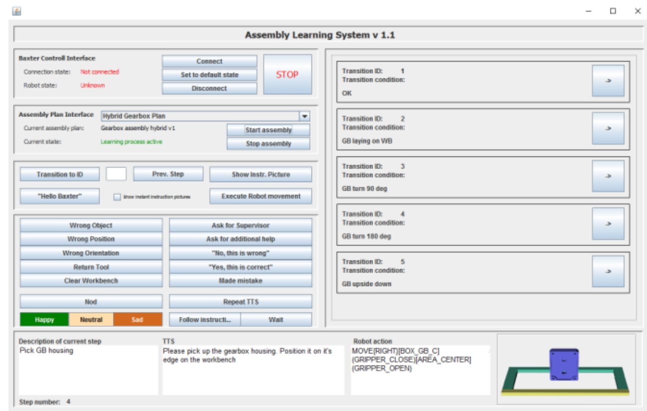

Figure 6. Main interface of the Assembly Teaching System

As soon as the experimenter starts an assembly teaching process using the Wizard GUI, the robot executes the instructions for the first step. The operator can then choose how to proceed. If the user follows the instructions given by Baxter, the operator can choose the function "OK" and the system proceeds to the next step. If the user makes a mistake, or needs guidance, the operator can choose the appropriate function from the list of mistake protocols. This action initiates a step providing a solution for the problem along with detailed, corrective information.

It is difficult to design for all user mistakes, so the Wizard GUI contains several functions to provide general help given as user feedback. The operator can choose from of a list of 12 sentences to be spoken aloud by the system. Examples of spoken feedback include "*This is the wrong position for this object*", "*Please return the tool to the toolbox*", and "*Yes, this is correct; well done*".

For complex assembly steps, or situations in which a user has difficulty following an instruction, a picture can be displayed on Baxter's screen, clarifying the instruction steps. Currently, Baxter only gestures to the correct location or indicates the action to be carried out. This behavior may be extended allowing Baxter to physically grasp or manipulate objects during the training to demonstrate complex assembly steps where the trainee has failed after multiple attempts. It is worth noting that this approach can still be limited in supporting particular assembly steps that require flexibility beyond what can be provided by a robot (e.g., complex rotation or fast interaction). Our research shows that the robot as physical entity best supports learning, and thus refrain from abstracting the learning process by merely loading images on Baxter's screen. Instead, further humanizing the robot presenting emotional, facial responses is of benefit. The robot can express mood by presenting facial expressions, which extend the anthropomorphic capabilities of the robot.

By default, Baxter's screen shows a neutral facial expression. If needed, the operator can trigger a "happy" or "sad" expression, to acknowledge that the user carried out an action correctly, or to indicate when something was unsuccessful (Figure 7).

Figure 7. Examples of Baxter's facial expressions

The Training Environment

After implementing the system, we planned the working area for the user and robot. Our aim was to create a face-to-face learning situation. The workspace was a workbench, containing separated parts of the assembly objects, a toolbox, and several process-specific areas (Figure 8).

We used a one meter high table, allowing the user to stand. The standing position is designed to make the user feel more comfortable while working with the approximately 2 meter high robot on the other side of the table. A user unfamiliar with humanoid robots might feel uncomfortable sitting at a height well below the robot. The user's position opposite Baxter, allows them to take a step back at any time taking them out of reach. This positioning, along with the table as both work space, and physical barrier, is intended to make the user feel physically safe with the robot.

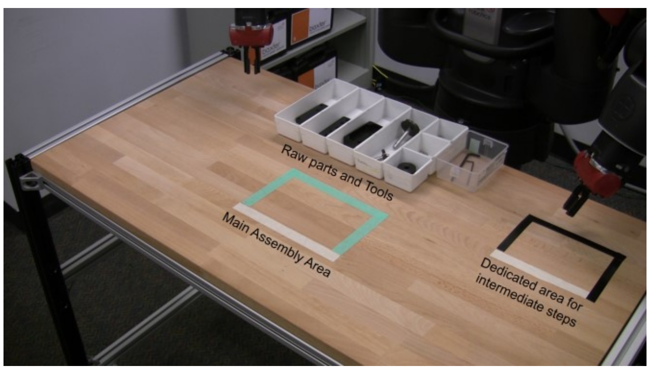

Figure 8. Spatial configuration of workbench used in our setup

On the workbench, several boxes for the raw parts and tools can be located. The workbench space is subdivided into different regions in order to prevent a collision of the robot and objects on the table, and to simplify the planning of movements. Masking tape marks specific areas on the workbench. The center marked area is intended to serve as the space where assembly is carried out. The second area can be used, to temporarily store a tool, or partially assembled object needed later.

To define the robot arm-movements for teaching each of the assembly steps on the workbench, we developed a motion-planning tool using Baxter's "Zero-G" mode. In this mode, operators manually move Baxter's limbs to specific positions capturing coordinates. The captured coordinates represent key points that can be stored in the Assembly Plan, for later use in the automatic calculation of the complete movement trajectory.

EVALUATION

We conducted an exploratory study to answer the question of whether and how a robot can take on the tasks of an overseer when teaching industrial assembly tasks. As part of this work, we analyzed how efficiently a robot can impart knowledge when operating an instructor. As mentioned above, our study went through, and was approved by, a rigorous ethics process at the host university[1]. In addition to the required elements, security measures were added when the robot physically led participants including, (1) active observation by the researcher throughout the process allowing intervention as needed; and, (2) a fail-stop button positioned at the side of the participant allowing him or her to immediately shut down the robot. As part of the research ethics committee's process, a protocol for introducing, and reviewing these procedures, and safety measures, was presented in detail with each participant. One of the areas of interest for our team was the level of comfort experience by human operators interacting with the Robot instructor. As such, we watched closely for moments of even the slightest discomfort to maintain the integrity of our work, and to refine our process for broad-based adoption. Participants in the study were interested in the work because of the human robot interaction, but we encouraged an awareness of discomfort to explore any potential challenges for future implementations of the approach. This focused, and labor-intensive approach to research is one of the key reasons that our test group was kept to 15 participants. At the same time, the intense focus of this approach is one that provides clear outcomes for the research team to analyze, synthesize, and further test.

Participants

We recruited 15 participants (10 M / 5 F, mean age 27 years) from a local university for our study. In the recruitment process, we considered participants of varying age and gender and did not require prior knowledge of industrial assembly tasks. All participants who volunteered were included in the study, and the demographic composition of participants was a direct result of this open recruitment process. Out of the 15 participants, two were familiar with complex assembly tasks, though not with the gearbox object used in this study.

Task & Context

For this study, we used a small gearbox as the assembly object (Figure 4). The gearbox contains 16 parts that have to be put together in specific position and order. We identified the steps needed for the assembly and specified an order in which the steps must be performed. Our approach, requiring a strict order of actions, simulated a realistic scenario in which workers must strictly follow a

[1] Study Id: REB16-0943

specified method of assembly with no room for improvised action, or trial-and-error approaches.

The gearbox used for our study is simple. An experienced worker should be able to assemble it in less than 5 minutes. While simple, the model provides a valid assembly task, and includes the opportunity to make several assembly mistakes during the process.

The experimenter controlled the assembly teaching system through two computers while sitting three meters away from the workbench and table. Since the experimenter assumed the role of the “Wizard” of the system, he or she had to be aware of what participants were doing at all times. To simplify the Wizard task, we streamed live video of the workbench to the second computer used by the experimenter using Baxter’s head-monitor camera.

Structure

Each session lasted around 45 minutes, starting by welcoming the participants and giving them an overview of the project, and the robot. Participants were first trained (multiple times) in the assembly with the robot as the instructor. Afterwards, they were asked to carry out the assembly process on their own to assess the success of the training. The self-assembly was the last practical part of each session. Participants were asked to carry out the assembly on their own without help. In addition, they were specifically told that self-exploration of the task was prohibited, and that they must carry out the steps in the order Baxter instructed.

We implemented post-session questionnaires to obtain insight into the personal experience of participants. We used the “Godspeed” Questionnaire [1], which is an established model for rating human experience with robots. 23 of the 24 questions from the full Godspeed questionnaire were used, with question 9 “Artificial” removed because it was confusing to participants (based on our pilot sessions). We then asked participants to complete a questionnaire we designed to rate specific parameters of the robot in the study. We included questions asking if they liked Baxter and our system, if they would rather train with a human, if Baxter’s movements were helpful for understanding the task, and if they wanted to talk to Baxter.

Study Description

We conducted a pilot prior to our evaluation to refine our study protocol, and assess whether the system, and study design would fulfil the stated purpose of the study.

Pilot Explorations

During the pilot study, we experimented with two different assembly plans. The first one was a highly detailed assembly plan, dividing the assembly instruction into 24 discrete steps (without error handling). Each instruction from the robot included great detail. We also used pictures to clarify complex instruction steps, displaying them on Baxter’s screen, providing hints to the user. The second assembly plan simplified the first, combining each group of logically associated steps into a single step. This streamlined plan required only 12 steps, enabling faster assembly, if, and when, the user performed the steps without errors.

In the pilot study, three participants were allowed to train in the gearbox assembly process up to three times with Baxter’s help before being asked to assemble the object without assistance. At the beginning, the detailed plan was followed by a short questionnaire asking if further training was needed, and if the comprehensive (detailed) plan should be used. Depending on the answers, the participant would train for a second, or even a third time, or he or she would be directed to self-assemble the gearbox object.

Final Study Design

Following our pilot explorations, we conducted our study with the 15 participants we recruited. Our final study design utilized what we learned from the pilot sessions. In this section, we provide a detailed description of how we conducted the formal study.

Our pilot created disparities between participants who selected different levels of exposure to Baxter’s training by allowing them to decide to opt out of the second or third training run. To achieve greater consistency, we decided not to vary the procedure between participants. All participants were asked to perform the assembly three times with the robot. This modified structure was used when conducting the full study.

The feedback from the pilot indicated that the steps of the first assembly plan were too detailed, and consequently too time-consuming. Using this feedback for the full study, Baxter offered the simplified assembly plan as a default, only reverting to the detailed plan if needed. This procedure provided adaptive capacity in the training process to address the learning speeds of individual participants.

Initially, we noticed that some participants focused on pictures that accompany the assembly instructions, and did not pay enough attention to Baxter's movement and speech. Consequently, they made several mistakes since they were missing relevant information, which could not be derived from the pictures. Therefore, we decided to limit the use of pictures during the training, and only provide them as needed. If the user got stuck on a particular step, the experimenter could manually trigger the GUI to display a picture to help the participant complete the step.

We wanted to ensure participants waited until the robot finished the explanation of a step, before they attempted to carry it out on their own. This approach supports a more complete learning experience; and connects to previous studies [18,23] that explored how light can be an effective indicator for turn taking. We implemented a feature for Baxter that turned signal lights on while something was being explained. When the light turned off, the user would understand the robot has finished the instruction, and the user should now carry out the step.

RESULTS AND DISCUSSION

The goal of our study is to assess the practicality of Baxter, as a humanoid robot, in teaching technical assembly skills. As mentioned earlier, our study involved participants who have trained with the robot using three training sessions.

The results revealed interesting insights into the effectiveness of our approach to supporting the learning of assembly tasks without a human overseer. Tellingly, every participant was able to learn the assembly task from the robot, and then self-assemble the gearbox object in a timely manner.

Baxter Training Results

Participants trained with Baxter for three sessions prior to conducting the self-assembly. As expected, our results show that participants' learning improved after each training session. As detailed in Figure 9, after each subsequent session, participants needed fewer steps to complete the assembly, made fewer mistakes, and required less help from the robot. We argue that it is the presence of the robot, and not the repetition of the task, that provides the most effective and efficient learning experience. This outcome arises from our process, which asks participants to refrain from self-training or step memorization, in order to focus on robot-provided instructions.

The combined training and assembly time of each participant, is a major factor of user performance. As shown in Figure 10, almost all participants required less time for each subsequent session with Baxter. This efficiency also extended to the self-assembly of the gearbox object.

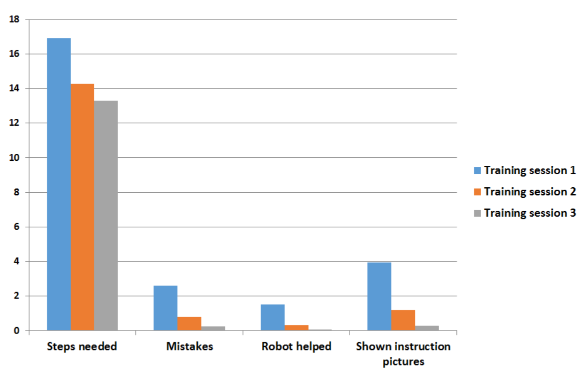

Figure 9. Average participants' performance with Baxter

During self-assembly, all participants managed to complete the task without mistakes, and in a reasonable time (average = 4 minutes). All participants except two followed the training steps taught by Baxter, indicating that Baxter was effective in teaching participants the assembly tasks.

Questionnaire Results

The questionnaire responses also support our claim that Baxter is an effective and efficient instructor of the assembly tasks. All but two participants also stated they liked Baxter, and the teaching system. 11 of the participants said they liked Baxter's feedback such as moving arms to guide them. As one expressed, "*I think I could remember how to position the objects thanks to Baxter's arm movements*". Interestingly, those who said they liked the robot suggested Baxter would be helpful training people with disabilities, or those who lack language skills required to work in industry.

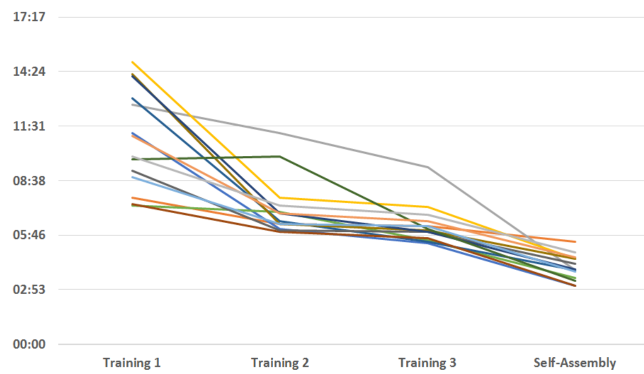

Figure 10. Participants' task completion time

Godspeed Results

The results of the Godspeed Questionnaire]1] revealed that most participants viewed Baxter as having human-like aspects, and thought that Baxter was conscious of their presence. This finding is also supported by our questionnaire responses highlighting that 12 participants were comfortable with the robot and Baxter's movement, with three participants claiming to be less comfortable, but only at the beginning of the interaction. As one participant expressed, "*When my arm hits the robot's arm, I was at first a little bit scared. But then I realized that nothing can happen to me and I started feeling comfortable*".[2] Supporting the anthropomorphic power of Baxter is the uniform declaration of a desire to speak with the robot. One participant made this clear by stating, "*As I got stuck at a step, I wanted to ask the robot what to do. It would be nice if I could talk with him [or her]*".

A well-trained, knowledgeable, and empathic human instructor can adapt to learners' abilities, and understand and respond to social cues as part of an optimal learning experience. A humanoid robot also offers learner adaptation, can engage in some social cues, but provides elements not available in human instructors. Consider the need for instructors to train immigrant workers who speak different languages. A humanoid robot can easily operate as

[2] As discussed in Evaluation, our study followed a strict safety protocol, adding additional measures beyond those required by the host university's research ethics committee. An observation such as this might give us pause, but it was just this type of observation we encouraged our participants to share. Safety is of utmost concern, but so to is the perception of safety. Beyond the ethical approach our team is committed to following, we are also aware that learning cannot occur if the subject does not feel safe in their work environment.

a multilingual instructor by offering translated versions of instruction materials. This option is particularly promising for teaching discrete procedures and tasks. Additionally, when working in such a multilingual, multicultural teaching environment, the disparity in social cues between the different learners, reduces the need for social cue expertise carried by the ideal human instructor described. Some participants expressed feedback supporting these assertions saying, *"[I think that] using, a robot for simple assembly tasks is more efficient than a human teacher*", and "*I guess a human could detect any mistakes better than a robot. But involving a robot as overseer has many other advantages*".

Implications for Design

Here, we present the main insights gained from our study to support inform the important considerations for designing future humanoid-based teaching systems. First, it is important to optimize the design of arm movements so movement is parallels the speed of humans. Some participants complained that Baxter's movement was slower than expected. Second, integrating machine-learning techniques into the design of future humanoids might improve the learning experience. This dynamic capacity would allow the robot instructor to respond to some of our participants' expectation that Baxter be able to adapt to their skill level. To address this desire and realize learning and outcome efficiencies, the system implementation should include smart decisions, and adjust the level of instruction relative to each learner. Third, it may be useful to use mixed reality in conjunction with humanoid robots to create a richer learning experience when demonstrating challenging instructions, rather than using robot face screens to display simple images.

CONCLUSIONS AND FUTURE WORK

We presented a novel approach for teaching technical assembly tasks utilizing a humanoid robot as instructor. We implemented an assembly-teaching prototype utilizing the humanoid robot Baxter with a flexible approach to teaching assembly tasks. We also conducted a study assessing the effectiveness of our approach, which provided feedback supporting our claim that humanoid robots are effective and engaging instructors of technical assembly tasks.

We envision various directions for extending our work. An experiment integrating our approach into an actual industrial setting would provide valuable data. A comparative study of our humanoid-based teaching system, and assembly learning systems based on visual-only techniques such as augmented reality would support the refinement of interaction, and identify contextual appropriateness for the use our approach. Within our current model, the use of the "Wizard of Oz" component assumed some of the higher level technical responsibility. Future development could take on more of the process, requiring less supervision at each step, eventually replacing the wizard, rendering our system fully autonomous.

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