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Collaborative Meat Processing in Virtual Reality

Evaluating Perceived Safety and Predictability of Robot Approach

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ABSTRACT

Efficient and safe collaboration between humans and industrial robots requires a mutual understanding that can be achieved by clearly signalling intentions and acting predictably. We present a preliminary version of a virtual reality environment, which is intended as a platform for development and evaluation of techniques that enable collaboration with industrial robots. In addition, we presents a user study for evaluating two speed profiles for having large industrial robots approach a human coworker. We compare the predictability and the perceived safety of the speed profiles, showing that test participants prefer a gradual slowdown, as the robot approaches, opposed to a faster approach where the slowdown is more abrupt.

KEYWORDS

human-robot collaboration (HRC), human-robot interaction (HRI), virtual reality (VR), musculoskeletal disorders (MSD)

1 INTRODUCTION

Technology has replaced muscle power for performing many of the most repetitive, dangerous and dirty jobs. However, across different industries, jobs still exists that are of a nature, which, so far, has meant that human hands and minds are needed. These jobs are typically found in sectors such as the construction industry and the food industry. The reason for the lack of automation comes down to machines' inability to adequately handle variation or simply cost. In some cases a viable compromise is a collaborative setup, where the human covers limitations of the robot and vice versa.

This work is part of a project with the aim to radically change the way large scale meat production is done. The goal is to develop collaborative production cells where industrial robots assist human

workers in the processing of pig meat. A cell based production paradigm differs significantly from the type of line production used in modern slaughterhouses. Although line production is very efficient in terms of throughput, it is inflexible and vulnerable to breakdowns. The high throughput is achieved by pushing employees and machines to their limits, resulting in an increased risk of breakdowns and compromises to yield and quality. Because workers are part of a high speed dis-assembly line, they are forced to repeat a limited set of motions thousands of times a day, placing them at a high risk of developing musculoskeletal disorders (MSD). According to EU regulation, employers are required to implement measures to adapt the work place to the individual, alleviate monotonous work and allow for individuals to control the work-rate [4]. Slaughterhouses employ measures such as frequent breaks and rotation among stations on the line, in an attempt to reduce the risk to the employees. But in the end, line production is by nature difficult to reconcile with a good working environment and the aforementioned directives from the EU.

Contribution

Our objective is to investigate some of the aspects of safe and efficient collaboration, specifically: Which of two robot speed profiles best convey the robot's intended stopping location and results in the highest perceived safety.

1.1 Case

Processing of pork bellies has been chosen as a case because it involves heavy and repetitive work. Currently, 6-8 butchers each man a workstation along a conveyor-belt, also called a pace-line. Each person along the pace-line has a set of specific tasks that, in general, involves manipulating the meat to a desired orientation and performing one or more cutting operations. The most physically straining tasks include collecting and delivering meat to and from storage as well as reorienting the meat between operations. By having a robot perform these tasks and the butcher perform the cutting operations, we benefit from the strength and stamina of the robot and the craftsmanship of the butcher. These changes have the potential to reduce the risk of MSD and improve yield, quality, flexibility, and clean-ability at the expense of throughput. Figure 1 illustrates the difference between processing pork bellies

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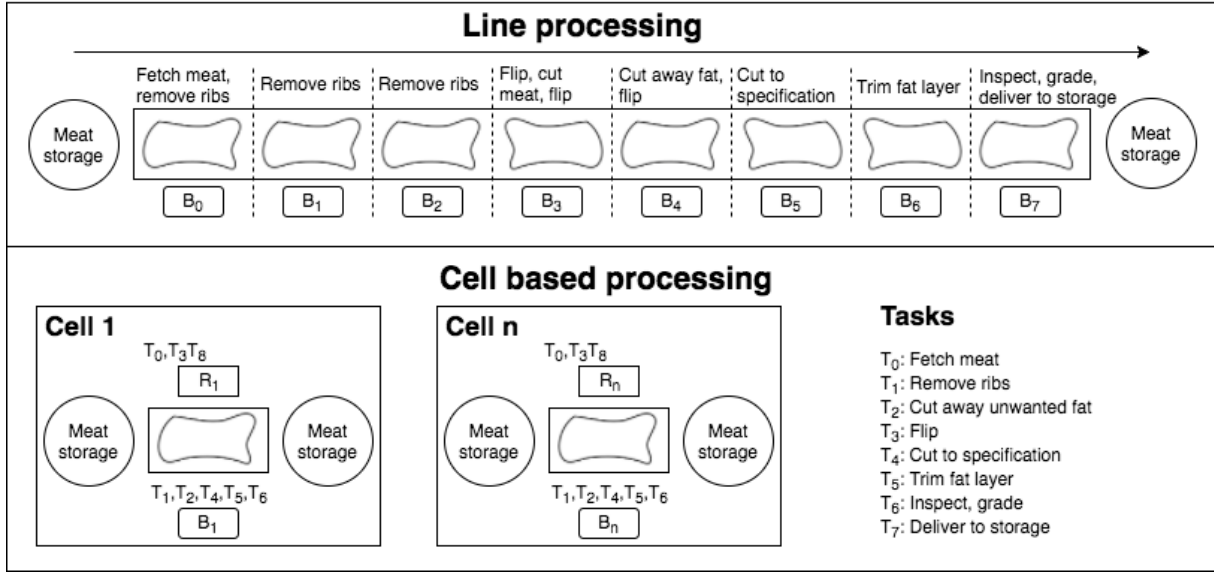


Figure 1: Transition from pace-line to collaborative robot cells.

on the current pace-line and using collaborative robot cells. The logistics of distributing operations and processing time equally across stations on the pace-line, results in the meat having to be flipped and oriented numerous times. With all of the operation gathered at the same location, these unnecessary operations can be eliminated. Figure 2 shows a selection of the operations that are performed along the pace-line.

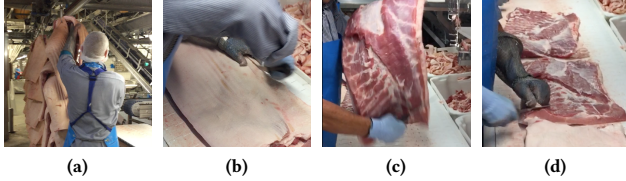


Figure 2: (a) Lifting from meat hook. (b) Cutting one side. (c) Flipping meat. (d) Cutting other side.

1.2 Human-robot collaboration

Close collaboration between autonomous, high speed and high payload robots is not currently possible. The standard for industrial robots [5] demands that the following safety requirements are taken into account when employees work in proximity of a robot.

- Safety-rated monitored stop, where the robot immediately stops operation, when a human enters the control zone.
- Hand guiding, where a worker has direct control over robot at decreased speed.
- Speed and separation monitoring, where the speed is adjusted based on the presence of the human coworker.
- Power and force limiting, where collisions are detected and the power of the robot is limited.

A lot of the considerations that must be addressed when implementing human-robot collaboration (HRC) for manufacturing is dealt with in [7], especially with regards to safety. Safety must be considered both from an equipment perspective, where a range of sensing solutions can be deployed to avoid dangerous situations, and it must be considered from a communication and mutual understanding perspective.

The aspect that is the focus here, is part of the communication aspect, specifically investigating the effect of different robot speed profiles with regards to conveying the intended destination to a human coworker. Additionally, the robot should not elicit a feeling of being unsafe, but it should give an appropriate feeling of safety in line with the actual risk to the human coworker. This is a complex subject to tackle, thus in this work we limit ourselves to simply measuring which of two speed profiles make the test participants feel the most safe.

2 RELATED WORK

Prior work has investigated speed profiles for HRC. For instance [2], which attempt to determine what robot speed would be perceived as safe. The experiments were conducted in a virtual environment where different robot sizes, types and starting speed conditions were compared. The results indicate that the perception of safe speed is significantly different depending on robot size and the initial robot speed conditions. In [10], the effect of different speed profiles on the perception of a robot's characteristics were tested. The characteristics include competence, confidence, disposition, weight and natural. It was shown that high speed led to the highest ratings across the majority of the categories, while the introduction of multiple changes in velocity or stops would negatively impact the perception of the robot. In [1] concerns are raised about the use of functional robot motions in HRC scenarios. The authors define three types of motion; functional motion where the goal is

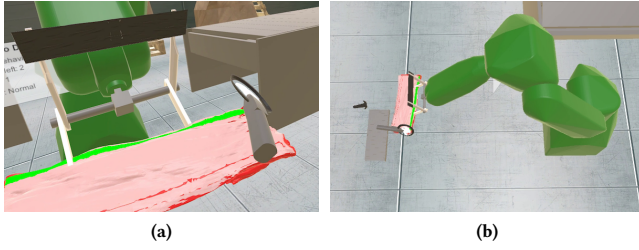


Figure 3: (a) View for human participant. (b) Overview of robot and participant working on product.

solving a task and avoiding collisions, predictable motion where the motions, in addition, are planned to match the expectations of a human collaborator, and finally legible motion, where the motions are planned to allow the human to easily and quickly infer the intention of the robot. Their results suggest that legible motion, which can be characterized as the robot exaggerating motions in order clearly convey intent, leads to the most fluent collaborations. Anthropomorphic speed profiles have been shown to be superior to constant speed with regards to prediction accuracy. In [8] this is demonstrated using the KUKA KR30 gantry robot in a virtual environment, where the participants have to predict the target position of the robot based on its movements. When using VR for conducting experiments in HRC, the perception of the virtual robot may be different from what it would have been, had the robot been real. In [6], a comparison is made between a physical and virtual robot that is otherwise similar. The comparison happens across six dimensions; Utility, Clumsiness of motion, Possibility of communication, Controllability, Vulnerability, and Objective hardness. The authors find that differences exist in some dimensions, while the difference is insignificant in other. Finally, it is concluded that VR robots can be used in place of real robots, as long as the differences are considered.

3 SETUP & EXPERIMENT

The purpose of the VR environment shown here, is to do experimentation in HRC for designing and validating a safe and efficient collaborative work cell. In this initial work, the scope is limited to evaluating the impact of two different speed profiles on human test participants when collaborating with a large industrial robot. VR has previously been used as an accessible method for conducting similar experiments [2, 8]. The VR environment for our experiment was developed using the Unity game development platform [9] and the HTC VIVE. It contains a rough model of the FANUC CR-35iA robot, conveyor belts, a cutting tool for the human participant, a 3D model of a piece of meat and a gripping and presentation tool for the robot. Two snapshots from the virtual environment are shown in Figure 3, with Figure 3a showing the view for the human participant and Figure 3b showing an overview of the robot and the human coworker's tool working on the product.

Table 1: Questions for test participants

Question	Scale(1 – 5)
How predictable was it where the robot was going to stop to present the meat?	unpredictable - predictable
How would you rate the robots movements when moving towards you?	unsafe - safe

Experiment design

The goal of the experiment is to compare two speed profiles and determine which one produces the best predictability of robot stopping point and the highest perceived safety of the collaboration. This is determined based on the responses from 15 test participants to the two questions in Table 1. The group of test subjects is 2/3 males and 1/3 females and most have no experience with VR. Each test participant was exposed to different combinations of the independent variables: speed profile and end position. The order in which the combinations were presented was mixed to obtain a uniform distribution across the test subjects.

The two speed profiles defined in Equation 1 and shown in Figure 4b were created based on findings in previous work and feed back from test subjects during initial tests. Previous work has shown that high speed, few and gradual changes in velocity is preferred [10] and that anthropomorphic speed profiles have been shown to yield the best prediction accuracy [8]. Feedback from 17 pretest participants was contradictory, as some participants complained that the robot was slow, while others complained that the robot was moving too aggressively.

$$v_1 = \begin{cases} v_0 & \text{if } d > 2 \\ 0.85v_0 & \text{if } d \leq 2 \end{cases}, \quad v_2 = \begin{cases} v_0 & \text{if } d > 2 \\ \frac{d^2}{4}v_0 & \text{if } 1 < d \leq 2 \\ 0.25v_0 & \text{if } d \leq 1 \end{cases} \quad (1)$$

Equation 1 describes the modifiers for the two speed profiles. v_0 denotes the base speed in joint space. v_1 and v_2 are modified based on the distance d between end effector and the stopping position. v_1 is characterized by the speed staying high almost all the way to the stopping position. With v_2 the speed decreases rapidly during the approach. The movement of the robot is planned through inverse kinematics using gradient descent [11], which is an iterative optimizing algorithm for minimizing the distance difference in Cartesian space. It results in higher speeds when the distance is large, typically in the beginning, and slower speeds when getting closer to the end position. The velocity of the end effector in Cartesian space is shown in Figure 4b. Since both v_1 and v_2 are modifications of the base speed v_0 , produced by the inverse kinematics, they all exhibit a gradual decrease in velocity when nearing the stopping point in front of the human coworker. The use of the modifiers defined in Equation 1 and visualized in Figure 4a result in v_1 and v_2 shown in Figure 4b.

The experiment begins with the robot picking up a piece of meat. It then transports the meat to either p_1 or p_2 in front of the test participant, using one of the speed profiles. The participant is then free to perform cutting operations on the virtual meat. At this point the procedure is finish and the test participant is asked to

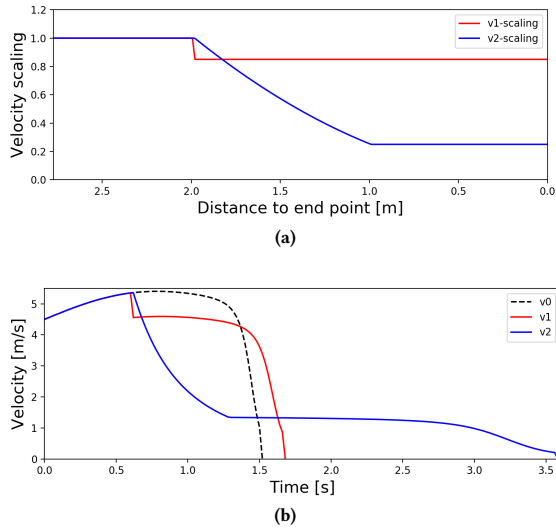


Figure 4: (a) Velocity scaling functions. (b) Speed profiles.

answer the questions in Table 1 and rate the robot's approach. The experiment repeated a total of four times for each test participant.

4 RESULTS

The experiment is evaluated by applying the Wilcoxon Signed Rank test to the responses to the questions in Table 1. With $p < 0.05$ the two null-hypotheses can be rejected:

H_{0_1} There is no difference in predictability between speed profile 1 and speed profile 2.

H_{0_2} There is no difference in perceived safety between speed profile 1 and speed profile 2.

H_{0_1} is rejected with a p-value of 0.0005 and H_{0_2} is rejected with a p-value of 0.0042. Speed profile 2 thus exhibits significantly better predictability and perceived safety compared to speed profile 1. Figure 5 shows box plots of the responses to each of the questions.

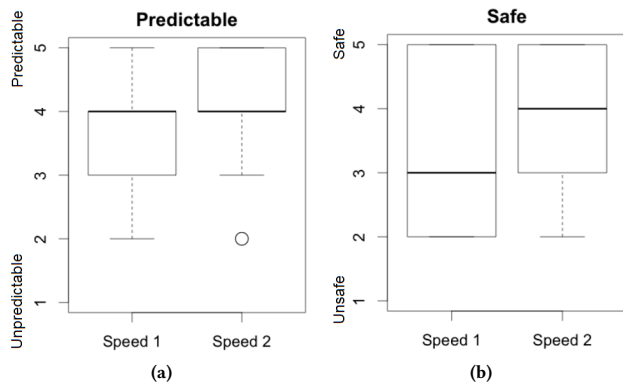


Figure 5: (a) Box plot of responses to predictability. (b) Box plot of responses to perceived safety.

The Wilcoxon Signed Rank test showed that the difference between the two speed profiles is significant, however the difference is small when looking at the distribution of responses in Figure 5. Further work is needed to determine what a good speed profile should look like. The small difference can likely be attributed to the test being conducted in a VR environment. To properly impact the test participants, they must "forget" that the robot is virtual and believe that there is a risk. It is clear from the response and for feedback during the experiments, that many test participants had trouble noticing a clear differences in the robot's movements. By letting the participants work with robot for an extended period we expect that the difference would become more pronounced, but as the participants were volunteers, the extend of the experiment was limited in order to respect their time.

5 DISCUSSION

The preferred speed profile is going to depend on the individual and is likely going to change as the human coworker gains familiarity with the robot. Our initial user studies revealed that some individuals would think that the robot is moving too slow, while others would be uncomfortable with the same speed profile. This suggest that there is a need for researching ways of adapting the robots movements to the individual. In order to substantiate the benefits of assisting human workers with robotic assistants, especially with regards to improving the work environment, we would like to measure the strain on the human worker with and without the robot assistant. Real-time measurements of this type could also allow for a proactive structuring of the work, where the nature of the work can be modified throughout the workday, based on the state of the worker. In future user studies the test participants should be allowed to get more familiar with the virtual environment and with collaborating with the robot, preferably over several hours. Introducing new technology and radically changing the way people work, is inevitably going to meet some resistance from the factory workers. Some of these concerns are probed in [3] and will also be part of our future work. Future studies will include further development and refinement of the virtual environment and the use of mixed reality techniques. This will allow us to augment the human coworker's senses with important information about the robot's intentions and data about the product.

We have presented our initial investigation into building a collaborative work cell, where the most physically straining operations involved in the processing of pork bellies will be automated, while operations that require human dexterity and craftsmanship are left to a human coworker. The investigation focused on evaluating two different speed profiles for a large industrial robot in a user study. A slower speed profile where the velocity gradually decreases is shown to exhibit significantly better predictability and perceived safety compared to a faster speed profile where the robot stops relatively suddenly when approaching the human test participants.

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