Proceedings of the 27th IEEE International Symposium
on Robot and Human Interactive Communication,
Nanjing, China, August 27-31, 2018

Transparent Robot Behavior by Adding Intuitive Visual and Acoustic Feedback to Motion Replanning

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***Abstract*— Nowadays robots are able to work safely close to humans. They are light-weight, intrinsically safe and capable of avoiding obstacles as well as understand and predict human motions. In this collaborative scenario, the communication between humans and robots is a fundamental aspect to achieve good efficiency and ergonomics in the task execution. A lot of research has been made related to robot understanding and prediction of the human behavior, allowing the robot to replan its motion trajectories.**

This work is focused on the communication of the robot's intentions to the human to make its goals and planned trajectories easily understandable. Visual and acoustic information has been added to give the human an intuitive feedback to immediately understand the robot's plan. This allows a better interaction and makes the humans feel more comfortable, without any feeling of anxiety related to the unpredictability of the robot motion. Experiments have been conducted in a collaborative assembly scenario. The results of these tests were collected in questionnaires, in which the humans reported the differences and improvements they experienced using the feedback communication system.

I. INTRODUCTION

The Human-Robot Interaction (HRI) topic has gained a lot of research interest in the last years. Allowing a shared workspace between humans and robots, it is possible to exploit the strengths of both and minimize the effort and the time needed to finish a task. To achieve that, it is important to provide intuitive communication channels that allow to understand the motions and plans of the robots. Despite many efforts made to make robots understand and predict the human actions, there is still a lack of communication from the robot to the human worker. This can lead to a feeling of anxiety when working close to the robot for the first time, even if it is a safe robot.

The goal of this work is to improve the interaction between robot and human, giving the latter the opportunity to understand robot intentions using visual and acoustic feedback. The system developed is based on a shared workspace in which the robot can predict collision, avoid the human worker and replan its task immediately to be able to continue on different parts [1], [2], [3], [4]. The collaborative task considered in this paper is a screw assembly task. The robot has the goal to tighten the screws located on parts which are replaced by the human operator. The robot has also the capability to detect missing or defected screws. This detection demands for an additional human intervention in

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Fig. 1: Shared workspace used for evaluation

the workspace in order to check and eventually replace the defected screws.

We have added acoustic feedback that alerts the human when the robot has detected a possible collision. In this way the worker can understand when the robot is changing its planned motion and can see this change through the visual feedback on screen. Here the new goal can be visualized alongside a model of the workspace to let the human understand the new goal of the robot. Another information added is the swept volume generated by the planned robot trajectory, that could be helpful to understand the area in which the robot will be in the near future. The area of the workspace where the current robot's goal is located is also communicated through the use of synthesized speech. This allows the robot to communicate to which side of the worktable it is heading for, for example the right or left side. This information is less detailed compared to the actual goal position visualized on screen, but it could be helpful when the user cannot look away from the workpiece while he is working on it.

This system of feedback allows the user to work closely to a replan capable robot without feeling anxiety. Through this additional communication he can understand when he is in the way of the robot and make intelligent decision considering the new plan of the robot. The use of the GPU-Voxels library allows the robot to detect collisions in real time and compute the voxel swept volume representation of the planned robot trajectory.

The intuitive feedback system developed has been tested by robot experts and non-experts. The final results have been evaluated through a questionnaire in which the users could express the differences and improvements in the HRI experience with and without the acoustic and visual feedback.

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The structure of this paper is the following. In Section II, we present related work on human-robot interaction and communication. In Section III, we describe the approach to develop the intuitive feedback system. In Section IV, we focus on the evaluation method. In Section V, we present the results collected in the experiments. Finally, we provide a conclusion and perspectives in Section VI.

II. Related Work

In the last years robots have gained dynamic behaviors. This is in part because of the need to make them able to react to humans, who often can freely move. In order to handle this, the robots have developed skills to change their motion rapidly, being able to avoid obstacles by executing quickly replanned trajectories.

Recent approaches are using the computations of the volume that will be occupied by the robot in the near future to predict future possible collisions [5], [6]. The problem of these approaches is that they require a lot of computations in order to generate the swept volumes [7] of the robot trajectories and to check for collisions with the live environment. This is not feasible using standard CPUs [8], [9]. [1], [2], [3] describe a system that massively parallelizes these calculations using GPUs. This allows the robot to detect obstacles and replan its motion in real time. This system allows the robot to predict future collisions in the execution of a trajectory. In this way it is possible to detect and select collision free trajectories that can be executed immediately. This allows the robot to avoid idle stops, leading its motion to areas distant from obstacles.

Collaboration requires multiple entities to work together by effectively coordinating their actions to achieve a shared goal [10]. Humans are able to achieve good coordination by utilizing verbal and nonverbal cues in order to communicate their goals and intents [11]. Making robots provide this information is challenging, because this is often subtle and it is based on modalities that robots usually don't have, like gaze or facial expressions.

A lot of research has been done in the field of Human-Robot interaction. The main focus of these works is related to the better understanding of human motion and intentions to make the robot behave and react in an intelligent and efficient way [11], [5], [12], [13]. For example, [14] has conducted a study to predict human intentions based on the tracking of gaze information.

Some studies have highlighted the usefulness of revealing the intentions of the robot. [15] states that people will be more likely to see the robot as being more approachable if it shows forethoughts before performing a functional action.

[16] shows that humans are not only reacting but use prediction to plan their motion, as they try to acquire information to anticipate future motion of other objects.

Work has been done related to the information that a robot should provide to the users in assistive applications. The work made in [17] is focused on a human-robot interaction experiment to investigate what type of verbal feedback people prefer in verbal updates by a service robot.

[18] presented the results of an experiment related to the human-robot social interaction. Its purpose was to measure the impact of certain features and behaviors on people's willingness to engage in a short interaction with a robot. The behaviors tested were the ability to convey expressions with a humanoid face and the ability to indicate attention by turning towards the person that the robot is addressing.

A module that supports engagement between a human and a humanoid robot by generating appropriate directed gaze, mutual facial gaze, adjacency pair and backchannel connection events has been developed in [19]. This module implements policies for adding gaze and pointing gestures to referring phrases, performing end-of-turn gazes, responding to human-initiated events and maintaining engagement.

[20] made a study to make a mobile platform plan understandable to the humans that walk around it. A beamer was mounted on an autonomous vehicle in order to cast geometrical shapes representing the direction in which the robot will move in the near future. Different shapes to represent the vehicle's intentions were studied through the evaluation of the human's gaze during the close interaction. A similar study that highlights the importance of the communication of the robot plan is presented in [21]. A wheelchair with a laser projector is used to give path information to the passenger and to the nearby pedestrians.

Research on the nonverbal communication signals that a non-humanoid robot can utilize during human-robot collaboration was addressed in [22]. This work presented a study that explores how to use a simple multimodal light and sound signal to request help during a collaborative task. Different frequencies and intensities of the signals were studied in order to express different levels of urgencies of the help request.

There is a lack of research related to the communication that a highly replan capable robot should provide to the human. For example, considering a robotic arm in a manufacturing scenario, it would be helpful to represent the information about the space that the robot will occupy while executing a trajectory. This is as important as the understanding of the human motion, because in a collaborative task both the participants should know what the other partner is doing and wants to do.

In this work we contribute to this goal by providing the human with intuitive information relative to the robot motion. This has been done using acoustic and visual channels.

III. Approach

In order to implement and test the visual and acoustic feedback information from a robot we have decided to use a shared workspace environment monitored by 3D cameras. The point clouds related to the live environment are used to predict possible robot collisions using the GPU-Voxels library [1], [4], [23]. The use of GPU-Voxels allows the fast computation of the collisions generated by the robot swept volume related to the execution of a trajectory and the live environment. Thanks to the high parallelization of the computation through the use of the GPU, it is possible to

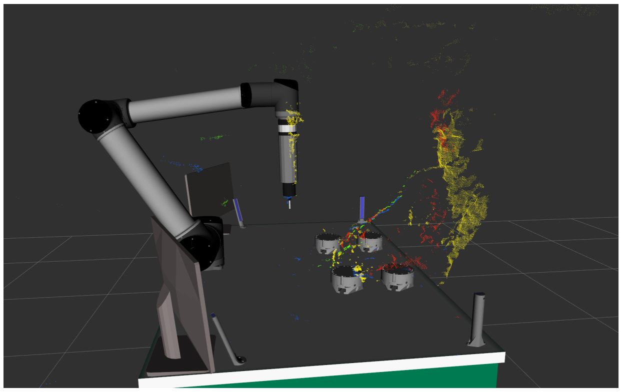

Fig. 2: Model of the shared workspace with camera point clouds

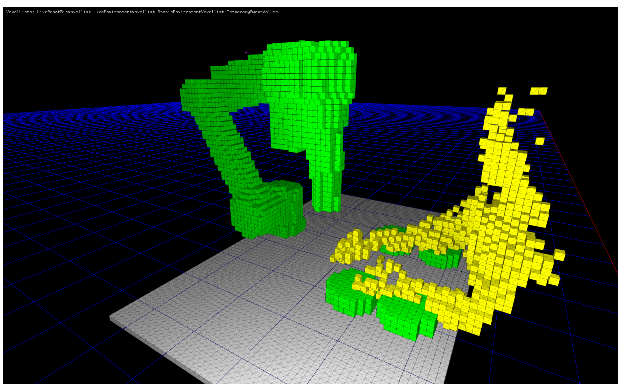

Fig. 3: GPU-Voxels representation of the shared workspace

compute the volume that the robot will occupy in the future executing a particular trajectory and check any possible collision with information related to the workspace captured by depth cameras. Fig. 2 shows the point cloud data related to the live environment within the workspace of the robot. Fig. 3 shows the representation of the workspace using the GPU-Voxels library. The yellow voxels represent the processed point cloud data related to the live environment, that are used to check possible future collisions with robot trajectories. Using this approach the robot is capable to dynamically change its motion, changing its goal when an obstacle is in the way.

Although this system allows the robot to avoid collisions, the worker can still have a feeling of anxiety when the robot is moving close to him because he has no information about the next or current planned motion of the robot. In addition, without knowledge about the robot motion, the human worker cannot plan in an efficient way on which part it is best to work without inducing the robot to continuously replan its motion. In fact, in order to work efficiently in a team, each partner should know what the other partner is doing.

The robot provides alert sounds to draw the attention of the human worker towards the robot motion to indicate that the robot has detected his presence and it will start to replan towards another goal. Another notification sound informs

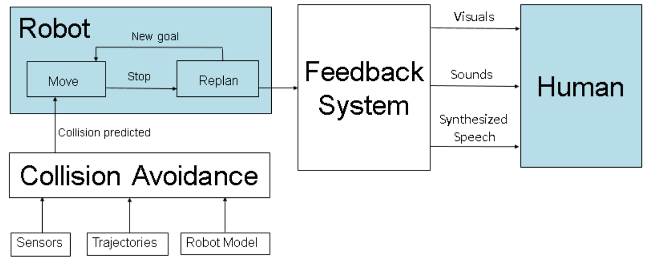

Fig. 4: Transparent robot behavior replanning communication

about the execution of a new trajectory by the robot and synthesized speech is used to inform the human where the actual goal of the robot is. In this use case with four large parts on which the robot works, the used speech phrases used were:

- *New goal: on top left part of table*
- *New goal: on top right part of table*
- *New goal: on bottom left part of table*
- *New goal: on bottom right part of table*
- *Cannot find collision free trajectories: please restore clearance*
- *Work done: waiting for new parts*

These phrases allow the human user to know that he can work without any interference in the remaining areas of the workspace. The speech is also useful to understand when the robot motion stops because of a need for a new task or because every trajectory is obstructed by the human.

Acoustic feedback has additional impact if combined with visual information. To achieve that, after the robot has drawn the attention of the worker, it displays on screens the exact position of the goal that it is heading for using a model of the shared workspace. The visual feedback has been implemented through the use of RViz along with a detailed model of the workspace and the robot. In this visualization it is easy to represent the actual goal of the robot, that is updated every time after replanning towards a new, different workpiece. Fig. 5 and 6 report the representation of the workspace and the robot with the goal markers. In the figures the green marker represents the area around the current robot goal. The red arrow marker points to the exact position of the workpiece on which the robot is planning to work next.

Another way to understand next planned motions has been developed by the use of the visualization of their voxel representation, which is also used for the collision detection and replanning functions. The GPU-Voxels software computes the swept volume for each trajectory that the robot plans to execute. The visualization of this plan to the human worker is an important additional information because it allows him to have an exact spatial understanding of the volume that the robot will occupy in the execution of the next task. Using this information, he can detect the areas of the workspace in which the robot will not be working executing its current task. In fig. 7 and 8 the swept volume representation of the planned robot trajectories during execution is visualized. From the figures we can see that the robot, in the execution of the current task, will occupy only a certain area of the workspace. This allows the user to detect the areas and workpieces on which he can work without interfering with the actual robot motion.

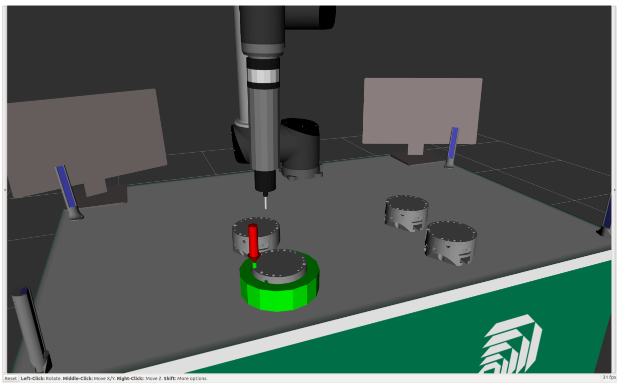

Fig. 5: Markers visualize the robot goal

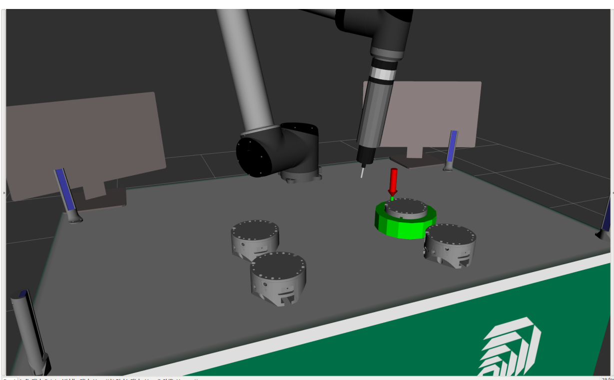

Fig. 6: Change of robot plan: goal markers updated

Every time a new trajectory is replanned, the acoustic feedback draws the attention of the human worker to check the voxel representation of the swept volume of the robot trajectory in order to make him aware of the robot plan and motion. In this way the user has a clear understanding when the robot is changing its motion and he can immediately see the details that allow him to understand the robot's intentions and planned motions, increasing the ergonomics of the teamwork. This can increase efficiency. When the human knows the robot movement and goals, he can decide in a more intelligent way on which part to work next, avoiding conflicts with the robot and minimizing replanning tasks.

Using a fast replanning system coupled with the described intuitive feedback system allows to improve the coexistence of robots and human workers in a shared workspace.

IV. Evaluation

The system developed should improve the comfort and acceptance of the human worker while working close to the

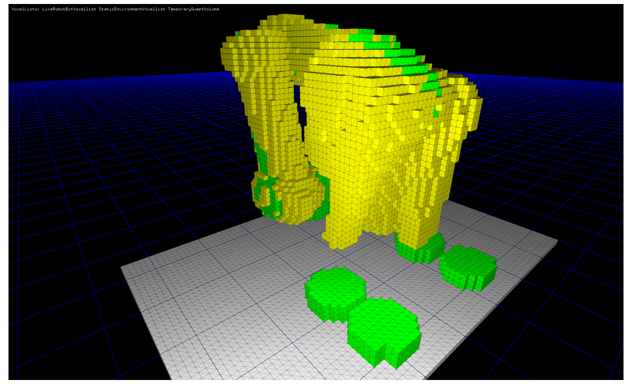

Fig. 7: Swept volume of the planned robot trajectory

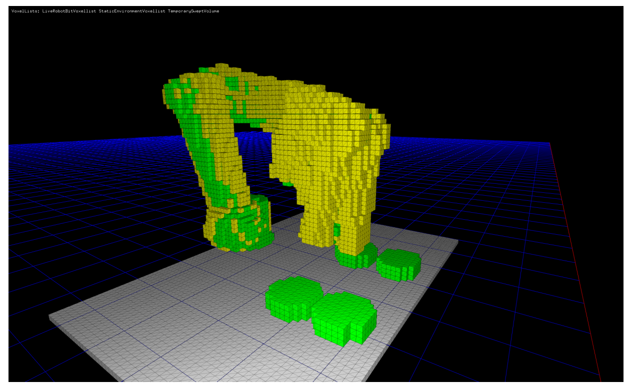

Fig. 8: Swept volume of the remaining planned robot trajectory

robot. In this way he can work without worrying about the robot until he receives information of its new goal. After that he will acquire the knowledge of the new plan of the robot, without worrying about unpredictable motions. The transparent robot behavior should also lead to an increase of the efficiency in the completion of the task. The human, having information about the motion of the robot, can select in a more intelligent way the parts on which he wants to work next. This allows the robot to avoid the continuous replanning of its motion without reaching any goals.

To evaluate the developed feedback system, a collaborative screw assembly task was developed. The robot task consists in tightening the screws positioned on four parts placed on the worktable and detecting missing and defected ones. The workspace is shared with the human worker, that in the meantime has to replace the worked parts with new ones and check the defected screws detected by the robot. The robot is obviously capable of avoiding collisions and replanning its motion in order to not interfere with any detected obstacles in the workspace.

To evaluate the system, we set up a user study with 5 robot experts and non-experts. They had to perform some screws placement and inspection tasks in the shared workspace. Each person had to perform the task first without the acoustic and visual feedback and then with the developed communication system. At the end of each experiment a questionnaire related to the experience of the interaction with the robot has been filled. The main points of interest focused on the feeling when closely working with the robot, the understanding of the robot's goals and motions, the understanding of the volume that the robot will occupy and the evaluation of the effectiveness of the visual and audio feedback.

V. Results

In this section we present the results of the interaction experiments with the robot and the users.

The following two charts in fig. 9 and 10 are scaled from ”Strongly Disagree” to ”Strongly Agree”. The following statement were analyzed:

(A) I was worried that the robot moved towards me
(B) I had a feeling of anxiety working close to the robot
(C) I foresaw the robot's goals
(D) I perceived when the robot had to replan to avoid collision
(E) I felt the need of more information related to the robot motion

The first chart in fig. 9 reports the result related to the human-robot interaction without the use of acoustic and visual feedback. From the chart we can see that some users had a feeling of anxiety working close to the robot and they were worried that the robot moved towards them. Many of them had also the problem of not understanding the robot's goals and motion replanning. Most of them felt a need for more information related to the robot motion.

The chart in fig. 10 reports the answers to the same statements but related to the human-robot interaction with the use of the acoustic and visual feedback. This chart shows that using the transparent robot behavior, all the users had no feeling of anxiety and they were not worried about the robot motion. All of them have also understood clearly when the robot had to replan and its goals.

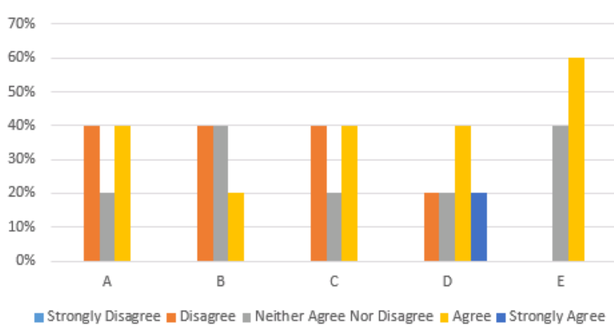

Fig. 9: Results without the use of visual and acoustic feedback

Comparing the two charts in fig. 9 and 10 we can notice that the acoustic and visual feedback helped the users to understand when the robot replanned to avoid a collision and changed its goal. We can also notice that the users have experienced a better feeling of comfort in the close interaction with the robot.

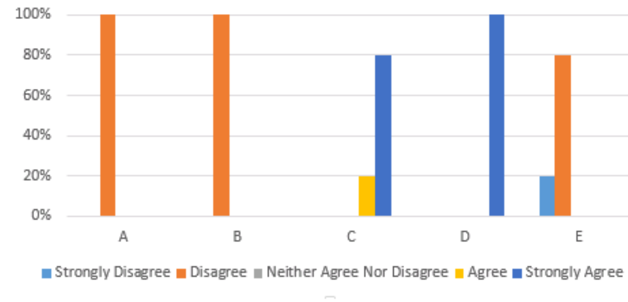

Fig. 10: Results with the use of the visual and acoustic feedback

The chart in fig. 11 reports the answers of the users regarding the following statements to understand their impressions related to the addition of the acoustic and visual feedback from the robot:

(A) The visual information about the robot's intentions was helpful
(B) The acoustic feedback helped to understand when the robot was replanning
(C) I had the feeling that more robot feedback (for example augmented reality) would help
(D) I have clearly understood the robot's goals
(E) The visual and acoustic feedback helped me to feel more comfortable in the interaction with the robot

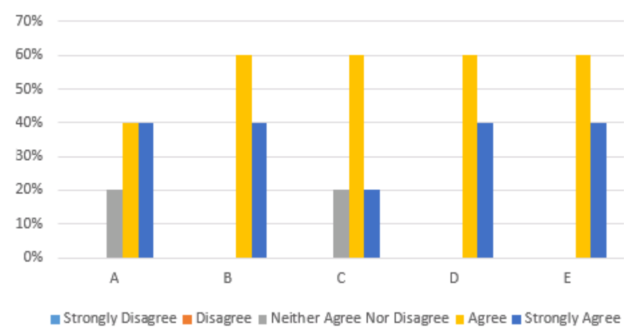

Fig. 11: Results of the questions related to the transparent behavior system

This last chart shows that the users have found that the combined use of the acoustic and visual feedbacks was helpful and useful in order to understand the robot's motions and goals. All of them have also agreed that the addition of this information helped to achieve a better feeling of comfort in the human-robot interaction. Many have also agreed that adding more feedback channels, like for example using augmented reality, could improve the interaction even more. During the experiments we found that the experience background of the users didn't influence the interaction much. As expected, the people with less robotics experience were more worried about the robot motion in the experiment without any feedback system.

Analyzing the results of the experiments we can say that the users felt the lack of information related to the robot motion that has motivated this work. Our transparent robot behavior system based on visual and acoustic feedback helped them to understand the robot motions, making them feel more comfortable in the interaction.

VI. Conclusions

The work of this paper showed that the use of visual and acoustic feedback to give information related to the robot execution plan helped the human users while working close to robot. The use of the system developed showed that the users had a better understanding of the robot motion. Furthermore they were able to understand when the robot had to replan its motion in order to avoid them. This helped to avoid the discomfort caused by not understanding the intentions of the robot, even if programmed with intelligent behaviors and collision avoidance features.

Using this system the human workers feel more comfortable and have a better understanding of the robot motion and goals. This allows the users to make better decisions in order to accomplish better team work with robots in a shared workspace.

Future work will focus on further improvements in the robot-human communication using for example augmented and virtual reality. In this way the user has the possibility to directly see the visual information on the work-table. This allows also to represent the robot's swept volumes in a more intuitive and understandable way. Further work will focus also on the possibility to make the human acknowledge the new plan of the robot. For example, using speech or gestures he can agree on the robot's new plan or force it to other goals.

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