Usability Study of a Robot Companion for Monitoring Industrial Processes

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***Abstract*—In this paper we present the findings of a usability study for a monitoring robotic unit tele-operated via a virtual fixtures (VF) based control framework. The study aims at investigating the impact of VF on the robot navigation as well as the impact of multimodal feedback on the user performance in a static inspection task. The findings will help in the design of the monitoring control framework to inspect a robotised welding process, as it has been researched in previous work. The study has been conducted with untrained participants, involved in four (4) different test scenarios. The experiments treated a static case in which users were asked to navigate the monitoring robot in the workspace to find a lit LED of a test-piece. The statistical analysis of the experiment metrics showed a positive impact of the VF control on the navigation of the monitoring robot even for users with no previous experience. Moreover, from the analysis of the task load index forms (TLX) it emerged that the combination of VF control and additional multimodal feedback improved the user performance without negatively impacting the effort required to accomplish the task.**

***Index Terms*—virtual fixtures, monitoring robot, user study, usability evaluation, multimodal feedback**

I. Introduction

For system integrators, optimizing complex industrial robotic applications (e.g. robotised welding) is a difficult and time-consuming task. This is usually due to discrepancies between the models and the actual behaviour of complex systems, and the system integrator needs to fine tune the final installation by trial and error to obtain the desired quality. This procedure is even more tedious when the operator cannot access the robotic system once in operation and must rely on additional sensors to acquire the necessary process information. However, it is often difficult to find a permanent placement for the sensors to be able to fully monitor the process at any given time during the trials, and this would also be a very expensive and potentially unreliable approach, if applied to all of the robot installations. While it is hard to completely remove this trial and error fashion, it is possible to provide a way to gather process information more effectively that can be used in several robotic installations. It is then proposed to provide the system integrator with a monitoring robot in addition to the robot(s) belonging to the industrial process that needs to be optimized (also referred to as *task robot(s)*). The monitoring robot can be equipped with several different sensors and can be moved into close proximity of any installed robot so that it can be used to collect information from that process during and/or after the operation without interfering. The system operator can control the monitoring robot to change its viewpoint and acquire information from various positions (e.g. inspect a workpiece from different angles). With a more effective way of gathering process data, the system integrator can perform his/her primary task (optimizing the industrial process) more efficiently. Since controlling the monitoring robot is not a primary task, the challenge is to make such interaction as flawless as possible not to overload the operator. The operator will control the monitoring robot with a camera view from its endeffector and via a joystick or similar interface.

The concept and the framework to control the monitoring robot and synchronize it with the task robot has been previously discussed in [1]. The control strategy based on virtual

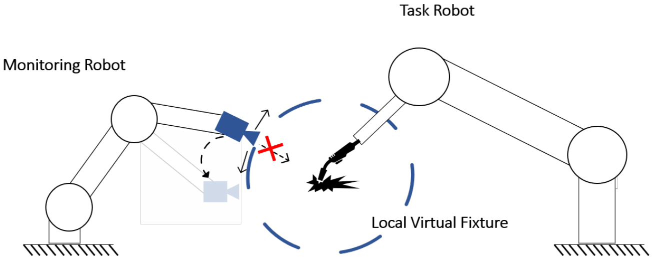

Fig. 1. Conceptual representation of a virtual fixture. The virtual fixture prevents the robot's end-effector from entering a certain forbidden region.

fixtures, its implementation and advantages in a user-centered design have been presented in more detail in the work of [2]. To the best of the authors' knowledge, there hasn't been yet in the literature a user study on the usability of such control and its effect on untrained participants when applied to a monitoring task and it will be the main contribution of this paper. Moreover, the usability study investigates on the effects on performance and cognitive load that multimodal feedback introduce and whether they are suitable for this type of applications. The experiment and its rationale is explained in section V and the data from the experiments are presented in section VI. Conclusions are drawn in section VII with some input for further discussion.

II. RELATED WORK

The idea of adopting a secondary robot with the function of a monitoring unit has been explored by an increasing number of papers in recent years, as it provides flexibility in the choice of viewpoint angle in the workspace as well as allowing any inspection to be performed remotely (so improving EHS conditions when the industrial process is carried on in a harsh environment).

Carvalho *et al.* in [3] discuss virtual reality approaches to be able to inspect an Oil offshore platform, so as to improve understanding during simulation before moving to the real industrial site.

In particular, the work from [4] discussed a modular robot for autonomous inspection and maintenance of hazardous industrial scenarios, to be deployed in sites such the CERN laboratory where maintenance of the extensive equipment is paramount to the experiments preparation and execution. The focus in their work is mostly on how to make the navigation autonomous and enable manipulation skills in such delicate scenarios and present the information through an adaptive graphical user interface, presented in [5].

Another important work recently published is the paper from [6], where the authors propose a method to assist an operator during a teleoperation task. The approach involves an external monitoring unit that is autonomously following the manipulator robot that is controlled by the user. In order to provide the appropriate viewpoint, the monitoring system has to use motion prediction and concepts from animation and graphics in order to evaluate which pose is the best as the user control the manipulator.

It is also worth mentioning a slightly more dated, but nonetheless pertinent contribution from [7] where they also proposed to used a monitoring robot for an industrial task to be carried offshore.

Although work could be done to integrate subparts of the autonomous behaviours that have been presented in these works, this paper focuses on the challenge of having a user in charge of the *monitoring* task, and not for example of the manipulation part as in the work of [6]. The challenge introduced by a user in charge of the monitoring is in the way the system handles the navigation of the monitoring robot with respect to the task robot and the surroundings. Whenever the user stops the manual operation, the system could resume its motion according to the behaviour specified by [6].

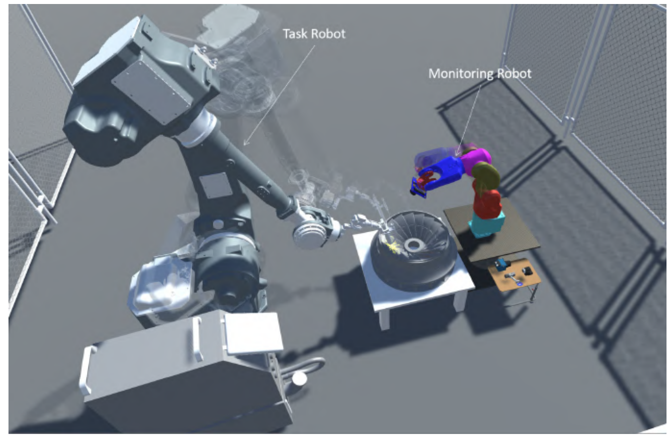

Fig. 2. Example scene in the Unity environment with a task robot (on the left) and the monitoring robot used for the experiments (on the right).

III. VIRTUAL FIXTURES

Virtual fixtures (VF) (also called active constraints) are a concept introduced by [8] as a way to anisotropically influence robot movements. Active constraints are a very important concept for many telesurgery applications, and have been thoroughly surveyed in this light by [9]. The virtual fixtures are represented by a set of preferred and non-preferred directions of motion which can be designed to be an abstract surface that the robots end-effector cannot penetrate. The fact that some directions are identified as non-preferred means that the end-effector motion will be less compliant along such directions, as if the end-effector were experiencing some resistance. We illustrate in 1 the main equation that dictates how the monitoring robot's end-effector velocity is influenced when in contact with a virtual fixture (see Figure 3 for a schematic representation):

$$\boldsymbol{v} = c([D] + c_\tau \langle D \rangle)\boldsymbol{v}_{in} \quad (1)$$

where $c_\tau \in [0,1]$ is the compliance factor for the non-preferred directions. The smaller the value of c_τ, the smaller the compliance along the non-preferred directions of motion. If c_τ is chosen equal to 0, it provides a *hard* virtual fixture, as opposed to any other value which instead would still permit motion along the non preferred directions.

The details of such control implementation and the design choices made for its adaptation for using it with a monitoring robot in tele-operation have been discussed in more depth in [2].

IV. TEST CASES AND MOTIVATION

A usability evaluation has been conducted to provide insights on the efficacy and benefits of the VF control approach and of the monitoring framework in general. It is important to evaluate in particular whether the control of the monitoring robot does not increase too much the mental and cognitive load of the operator. In fact, the goal of the operator is to inspect the workspace and the process carried out in it and not to control the monitoring robot per se.

The main questions that are being investigated in this section are the following:

- *Does the VF control framework allow the operator to control the monitoring robot without overloading him/her?* This question will be answered by comparing TLX indexes among the scenarios where VF redirection was not enabled to the ones where it was active.
- *What are the effects on performance introduced by the VF control framework?* This question will be answered by comparing the average completion time among the different experiment scenarios.
- *What are the effects of an extra feedback modality on the user TLX score and performance?* The final question will investigate if an extra feedback modality can improve performance in this particular task, and what are the effects on the users' TLX scores when this feedback is introduced, with particular focus on the users' cognitive load.

V. EXPERIMENTS

The purpose of the monitoring robot is to assist the system integrator in the tuning phase of an industrial process, which is the main task for the system integrator. It is therefore important that the monitoring robot can be controlled with as little effort as possible not to increase the workload and the time needed during the optimization phase. It is known that when manual input is allowed for robotic systems, both the control scheme and the user interface greatly contribute to decrease the overall complexity for the human operator.

The modes of controlling the monitoring robot are two: *unconstrained* and *constrained*. In the first mode, the camera view (the robots end effector essentially) can be freely moved inside the workspace with a simple mapping of rotation and translation to the joysticks buttons. In the second mode, the camera view (position and orientation) is influenced by virtual surfaces defined via software.

The experiments aim at investigating whether untrained users can more efficiently accomplish the task of acquiring information from a process with the help of a virtual fixture based control. The VF based control should assist the user

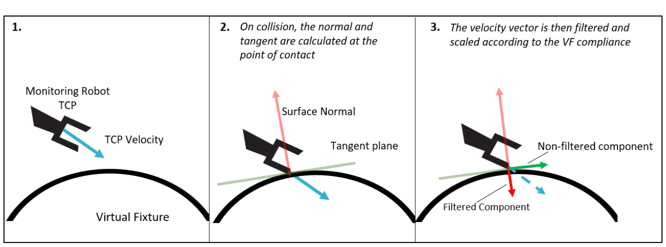

Fig. 3. Representation of the steps of the velocity filtering when colliding with a VF. The computation and control algorithm are performed in Unity.

in respecting secondary objectives such as minimum distance from specific objects or from the workpiece without requiring additional effort from the the operator. Choosing the most appropriate metrics

The metrics that are collected for both the static and dynamic scenarios are the following:

- Completion time (CT): this is the time to complete a single task, from the start event to the end event. The start of a task is identified by a LED lit and followed by a notification to the user. The task ends when the user finds and correctly classifies the lit LED's colour.
- Number of commands (NC): the number of control commands that a user inputted during a single task.
- Number of corrective actions (NCA): the number of times the system with VF actively filters a user movement that would otherwise violate a forbidden region.
- Number of pseudo-violations (NPV): the number of times that the robot collides with a VF and has to be either stopped or redirected.

The static experiment setup consists in a 6-dof manipulator equipped with a RGB camera. The experiment workpiece (see Figure 5, placed in front of the robot, is a Raspberry Pi with eight multicolour LEDs that can be lit remotely from the Unity framework.

The user's task is to identify which LED is lit at a certain time and what is its colour. To accomplish the task, the users must control the camera view via a joystick to be able to look at the correct LED and identify the LEDs colour (input mapping shwown in Figure 6).

Each user is asked to find the coloured LED 4 times in a single session. Once these four (4) attempts have been accomplished the user is asked to fill a NASA-TLX form and the experiment is then over.

Four (4) experiments have been conducted, each with fifteen (15) participants. As it is shown in table I, the number of elements that could influence the users' performance was increased from one experiment to the next. The added obstacles are invisible to the users, and have one additional property in addition to their position and shape: the compliance. As described in more detail in the work of [2], the compliance changes how "hard" an obstacle is in response to the user motion that would penetrate it. For all the experiments, spherical virtual fixtures were used. However, in some cases, overlapping so that to the user the obstacles didn't always have a spherical shape. The Unity environment is shown in Figure 7 as well as the visual feedback element used in one of the experiment scenarios.

- Scenario A - simple free motion without VF redirection, with no obstacles in the workspace. In the first experiment, the only virtual fixtures that have been used were to ensure the safety of the workspace and the robot.
- Scenario B - introduces obstacles in the workspace. The users' goal is unchanged but the robot will have constrained motion every time it will come in contact with a virtual fixture. In the second experiment, whenever the

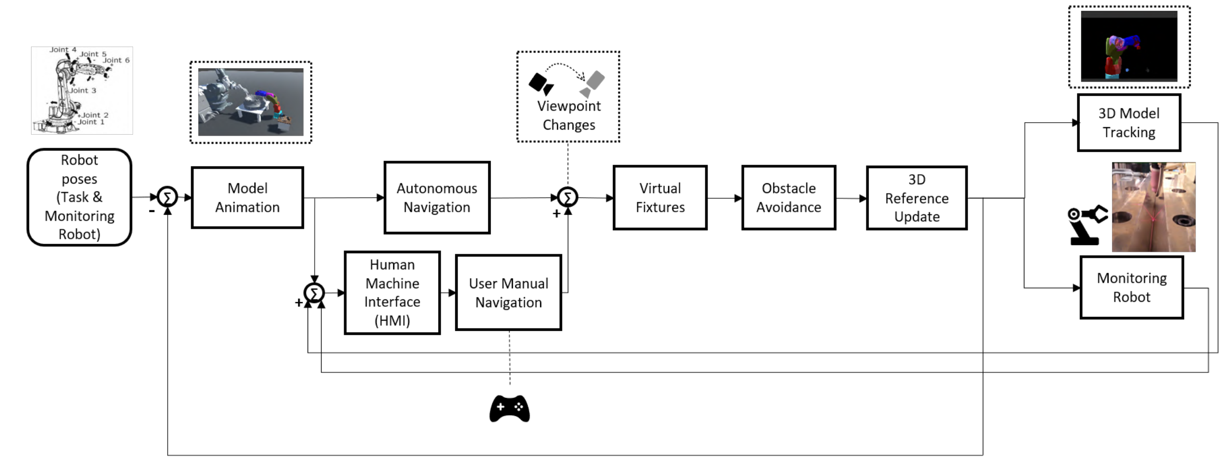

Fig. 4. The simplified control diagram of the monitoring software. Autonomous navigation (or motion) input are in parallel with the user manual navigation. The user can manually adjust the viewpoint of the monitoring robot during the operation, and the changes issued are added to the autonomous tracking motion.

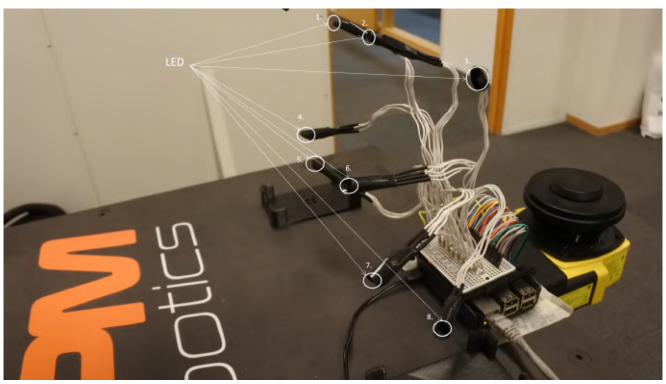

Fig. 5. Experiment piece used for the static experiment. The LEDs are triggered via a Python script on the Raspberry Pi.

robot is colliding with a virtual fixture the only motion allowed is in a direction that resolves completely the collision state, generally along the normal of the VF on the point of contact.

- Scenario C - introduces virtual fixture redirection, which facilitate the robot motion when it comes in contact with an obstacle.
- Scenario D - visual and haptic feedback component added to the experiment scenario. The feedback is provided when the user is "about to" collide with an obstacle, and

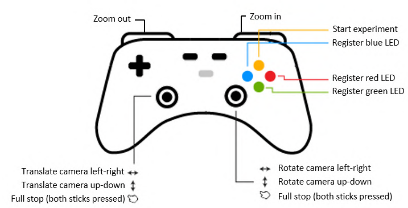

Fig. 6. Input mapping for the joystick used to control the monitoring robot. The commands are from the camera perspective, which corresponds to the robot's TCP.

also during the collision state.

TABLE I
OVERVIEW OF THE DIFFICULTY ELEMENTS IN THE EXPERIMENT SCENARIOS

	Obstacles	VF Redirection	Add. Feedback
Free Workspace	-	-	-
Obstacle Baseline	X	-	-
Obstacle Redirection	X	X	-
Obstacle Feedback	X	X	X

VI. USER TRIALS RESULTS

We describe the experiment setup, with the rationale behind (we want the monitoring robot to navigate in the work-space, and we want the user to accomplish a task that requires specific positions and orientations). Describe which different experiment have been performed (static and with obstacles) with the hypothesis behind, or at least the expected observations. Then we explain the first static experiment, with how many users and how many trials per users with what have been recorded

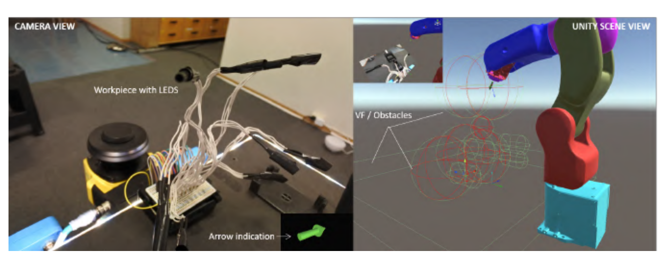

Fig. 7. The 3D arrow used for for the visual feedback in the fourth experiment scenario and the Unity scene view of the obstacles.

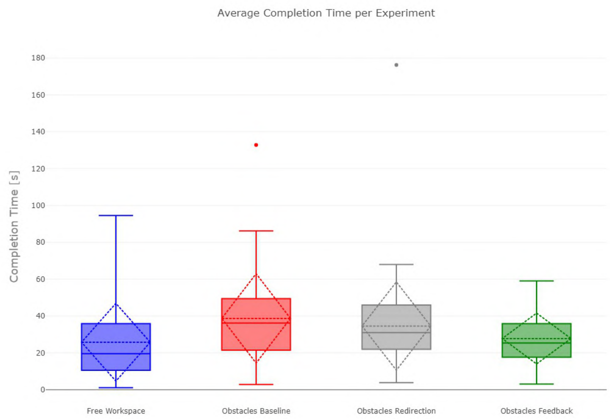

Fig. 8. Average completion times for each experiment scenario

during their trials. We discuss also the TLX questionnaire that each user had to fill after their experiment session. We show the graph of the average completion times and average actions per target.

Each participant is asked to complete a task four (4) times, consisting in locating and classifying one lit LED with the monitoring robot. For each time the metrics are collected, leading to four measurements per metric for a single user trial. Each user performs exactly one trial. We aim at avoiding a "learning trend" as much as possible since we are not interested in the decrease of completion time and the improvement of the metrics over successive trials but we are rather interested in the differences between the two group of users and their performance with the different control modes.

The participants are mostly students from the last year of BSc and first year of MSc studies (average age is 24.6 ± 1.87), with no restrictions on the type of background.

From Figure 10 it can be seen that the average effort decreases from an only obstacles scenario when redirection

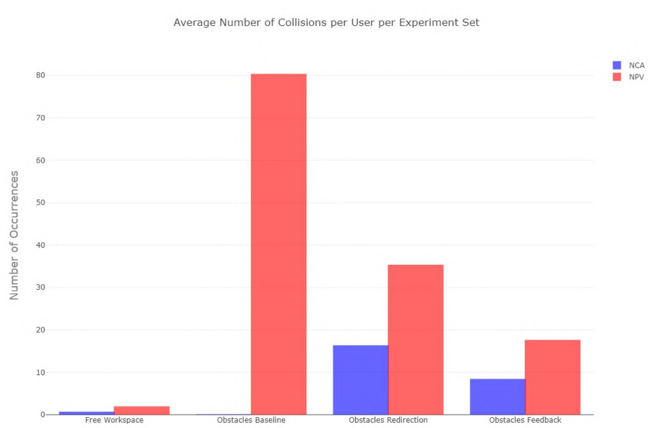

Fig. 9. Average number of NCA and NPV for each experiment set.

TABLE II

COMMON PARAMETERS USED FOR THE EXPERIMENT SCENARIOS. EACH SCENARIO HAS THE SAME MONITORING ROBOT STARTING POSITION.

Robot Starting Position (J_1,J_2...J_6)	(0.0, 90.0, 0.0, 0.0, 0.0, 0.0) [deg.]
Robot Starting Position (x,y,z)	(0.0, 0.30, 0.31) [m]
Number of LED Targets	8
Number of Trials per User	4
Robot Zooming Speed	1.0 [cm/s]
Robot Movement Speed	1.0 [cm/s]
Number of Obstacles in the Space	10

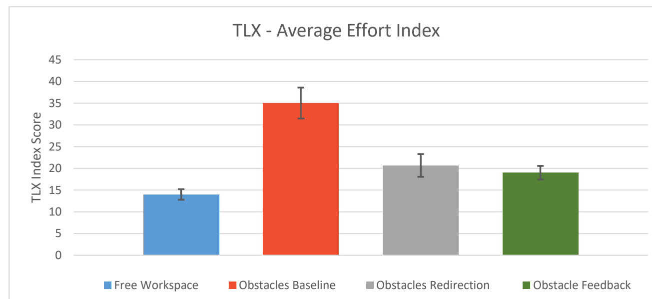

Fig. 10. Average effort index from the TLX forms.

and additional feedback are introduced, remaining however still greater than the first scenario of the free workspace. This pattern has also characterized the CT analysis, and still positively hinting that although obstacles are increasing the difficulty of the task, redirection and additional feedback contribute in making the task easier for the user.

Performing the one-way analysis of variance (ANOVA) on the users effort scores, it can be stated that there is statistically significant difference between the groups ($F(3,56) = 13.89$, $p = 6.98 \cdot 10^{-6}$). Furthermore, the post hoc tests showed that there is a statistically significant difference between the *Obstalce Baseline* scenario and *Obstacle Redirection* ($P = 0.003$), but not significant enough between *Obstacle Redirection* and *Obstacle Feedback* ($P = 0.59$). This latest result is likely to indicate that the VF redirection plays the bigger role in decreasing the perceived effort to accomplish the task. It is a positive finding in that the most difficult part of the task consisted in avoiding the invisible obstacles, rather than just controlling the monitoring robot to reach a different point of view. The additional feedback did not seem to increase the overall mental load according to the results of the TLX: the mental, physical and temporal scores remained fairly consistent across the different experiment, suggesting that the task was not "rushed", was not demanding in terms of physical abilities, nor was requiring high problem solving capabilities which is still consistent with the intention of the experiment scenarios. However, the additional visual and haptic feedback did have an effect on the performance score. In

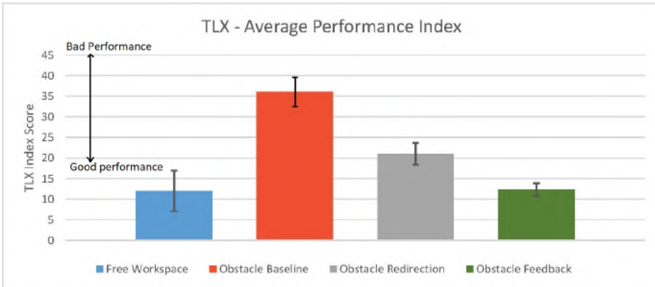

Fig. 11. Average performance index from the TLX forms.

TABLE III
STATISTICALLY MEANINGFUL DIFFERENCE FROM THE ANALYSIS OF VARIANCE (ANOVA)

	Statistical Difference		
Scenarios	CT	Effort	Performance
Obstacle Baseline *vs.* *Obstacle Redirection*	X	X	-
Obstacle Redirection *vs.* *Obstacle Feedback*	-	-	X

particular, there is statistically significant difference between the different experiment performance scores ($F(3,56) = 10.89$, $p = 9.75 \cdot 10^{-6}$), with the graph comparison shown in Figure 11.

The most interesting detail is that in this case, scenario C (*Obstacle Redirection*) and scenario D (*Obstacle Feedback*) present a statistically significant difference ($P = 0.035$), and at the same time the performance reported in the scenario D, where the additional feedback was provided, is very close to the average performance reported in the free workspace of scenario A. Combined with the previous finding, this analysis suggests that the monitoring robot navigation is actually improved by the VF redirection, and the additional feedback has the effect of making the users feel more efficient at accomplishing the task: if this effect cannot be concluded by looking at the completion times alone, it resonates in the decrease of NCA and NPV thanks to the presence of the additional visual clue and haptic feedback of the duration of the collision with an obstacle.

VII. CONCLUSIONS & FUTURE WORK

This paper examined the effects of different elements in the monitoring framework on users' performance and the relationships with their task evaluation. Four different experiments were carried out, each experiment with 15 users that were instructed to navigate the monitoring robot to find an LED target multiple times. Each scenario introduced an additional element in the system that affected the navigation, either negatively (like the invisible obstacles) or positively (like VF redirection and additional visual and haptic feedback). Following the experiments with a statistical analysis of the user responses and metrics, it was observed that the VF redirection affects positively the navigation of the monitoring robot. The average CT showed a meaningful decrease from the scenario with obstacles only to the scenarios where obstacles were present but redirection was enabled (see also Table III for the ANOVA summary).

Moreover, the extra feedback modality affected the performance score from the TLX form, with the most statistically significant difference. The results indicate that the additional visual feedback, together with haptic information about the duration of the collision with an obstacle, positively affects the user's performance, and in the presented form are suitable candidates for the type of navigation task that the monitoring robot is expected to carry out in an actual industrial setup.

It is important to mention that the development of the monitoring robot and the VF redirection control finally aims at addressing challenges that are faced in the welding industry during robotized welding. The usability evaluation has a key role in understanding what were the effects of the proposed control framework and monitoring solution in a laboratory setup that replicates part of the difficulties encountered during and actual industrial case.

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