Reach Out and Help: Assisted Remote Collaboration through a Handheld Robot

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Abstract—We explore a remote collaboration setup, which involves three parties: a local worker, a remote helper and a handheld robot carried by the local worker. We propose a system that allows a remote user to assist the local user through diagnosis, guidance and physical interaction as a novel aspect with the handheld robot providing task knowledge and enhanced motion and accuracy capabilities. Through experimental studies, we assess the proposed system in two different configurations: with and without the robot's assistance in terms of object interactions and task knowledge. We show that the handheld robot can mediate the helper's instructions and remote object interactions while the robot's semi-autonomous features improve task performance by 24%, reduce the workload for the remote user and decrease required communication bandwidth between both users. This study is a first attempt to evaluate how this new type of collaborative robot works in a remote assistance scenario, a setup that we believe is important to leverage current robot constraints and existing communication technologies.

I. INTRODUCTION

Collaborative remote assistance tasks usually involve a less experienced person (local worker) who has to manipulate a set of physical objects with the help of a remotely situated expert. Examples for such tasks are maintenance [1] and inspection [2] of remotely located systems and expert-guided surgery to train remote novice surgeons [3], [4]. Within such setups, the issue is the effective communication of actionable instructions from the expert to the worker. The expert's perception of the workspace is limited by the competences of the local worker and the capabilities of the communication interface.

Remote maintenance is of particular interest for industrial applications [5]. Modern products and plants are characterised by increasing complexity which requires high expertise to diagnose and solve problems. However, it might be expensive to get an expert on site and guidance through a conventional audio-visual medium is too inefficient. Some solutions have considered remote guidance through augmented reality (AR) [5], [6] and semi-autonomous telemanipulation systems [7]. Crucially, what is missing is a remote assistance setup that combines the advantages of physical access through telemanipulation with the ones of cooperative guidance and task solving.

Handheld robots [8]–[12] are intelligent tools that process task knowledge and environment information, which allows for semi-autonomous assistance in collaborative task solving, and combine these with the natural competences of human users for negotiating obstacles and resolving complex motion planning tasks effortlessly. We argue, that such a system could bridge the aforementioned gap between remote guidance and telemanipulation, with the handheld robot helping both the effective communication between the workers and task outcomes. We thus explore this setup guided by the following research question:

Q How does the handheld robot's autonomy and task knowledge affect performance and communication in a remote assistance setup?

Our main contribution is the introduction and evaluation of a new paradigm for remote assistance through handheld robot collaboration. The system is assessed through user studies within a partially simulated pipe system maintenance task.

II. RELATED WORK

In this section, we review the latest work on handheld robots, as well as the state of the art of remote guidance and telemanipulation systems.

A. Handheld Robots

The concept of a general-purpose handheld robot was first introduced in [8], which describes an intelligent tool that can perceive the environment, has task knowledge and is able to act through an actuated tooltip with 4 DoF. These features contribute to a decreased workers’ task load. Further work has introduced a 6-DoF kinematics design [9] and extensive research investigated robot-human communication for user guidance [10] and the perception of users’ attention and
intention for improved cooperation [11], [12]. These works were motivated by the question how handheld robots and humans benefit from each others’ strengths within a single-user collaborative setup. A principle underpinned by Moravec’s paradox [13], but turned into a collaborative benefit: Users carry out the broader tactical motion with their intuitive navigation and obstacle avoidance skills and benefit from the robot’s speed, accuracy and from the robot’s task knowledge. The result helps to reduce the time of task execution and the number of errors and particularly help users of handheld robots to carry out tasks for which they have limited expertise.

While the introduction of the robot’s task knowledge brings advantages, a crucial aspect remains open, that is where this knowledge might come from e.g. whether it could be learned or derived from a remote expert and mediated through the robot. In this work, we start with exploring to what extent a handheld robot is suitable for a remote assistance human-robot-human setup and whether the benefits of the robot’s partial autonomy can be observed analogous to aforementioned work.

B. Remote Guidance

Remote guidance systems allow a remotely located person to assist a local person through instructions and directions. Research in this field aims to overcome the limitations of traditional consulting methods such as audio or video calls. Current solutions require a camera at the worker’s site which is either stationary [2], [4], [6], [14], [15], portable (e.g. smartphone or tablet) [1], [5], [16]–[18], worn by the local user [6], [19], [20] or operated by the helper [21]–[24].

These solutions have in common that the video feed of the local workspace is displayed to the remote helper either on a desktop screen, tablet or smartphone alongside audio communication. However, the methods are distinct in their respective communication features for the helper’s instructions to the local user. While early work introduced video markups, such as drawings and predefined shapes [4], [15] or their projection in the workspace [21], a new trend goes towards exploiting the benefits of AR technologies. These works focus on the communication of the expert’s instructions through world-stabilised annotations for maintenance purposes [1], [5], [16], [17] and remote guidance through hand gestures [6], [18], [19] or captured full-body motion [25]. By comparison, only little effort was spent on the exploration through embodied guidance i.e. mediated through a robot. An example is GestureMan [22], [23], which is a mobile robot equipped with an actuated camera and pointing stick. However, the pointing mechanism is limited by a few DoF and thus infeasible for manipulation.

We note that while the above-mentioned works offer efficient solutions for the communication of instructions, they do not allow any direct physical interaction within the collaborative setup. This leaves local workers in charge of carrying out any manipulative actions by themselves.

C. Telemanipulation

In contrast to remote guidance systems, telemanipulation allows a remote operator to execute physical operations i.e. through a remote-controlled robot rather than instructing another person. Application examples exist in the form of sedentary robots for the remote maintenance and inspection of machinery [26], [27] or hazardous environments e.g. nuclear [7], [28] or fusion [29] power plants. Notably, [7] demonstrates how the automation of manipulation subtasks can facilitate the task for an operator. The most advanced recent mobile robots for telemanipulation have been explored in the context of disaster response e.g. [30]–[32]. These systems enable a remote user to navigate through unstructured environments and manipulate physical objects.

These solutions are useful for inaccessible environments, but the research question of how remote guidance and telemanipulation could be combined in a collaborative setup remains unanswered.

III. REMOTE ASSISTANCE STUDY

In this study, we propose and test a remote assistance system which consists of two main parts. On the local workspace site, a camera-equipped handheld robot with 5-DoF motion capabilities (displayed in figure 2) is carried by a local user. A remote user accesses the robot through a remote interface, which allows them to control the robot for inspection, manipulation and gesturing. We investigate the collaborative interaction between the three agents involved in the task that is the remote user, the local user and the handheld robot. Our main focus lies on the effect of the robot’s semi-autonomous assistance features on the collaborative task performance and communication strategies. Figure 1 shows an overview of the experiment setup.

A. Study Design

For our experiments we use a within-participant design to compare the performance of the remote user and local user pairs using our proposed remote assistance system in two different conditions:

1) Non-Assisted: The remote user has to request information about the task state and steers the robot manually.

2) Assisted: The remote user can select an object to interact with and then the robot assists through locally fulfilling the task within its workspace (detailed description in section III-C).

The setup is a semi-simulated pipe system, which we use as an example for a collaborative maintenance task. Solutions for solving this task requires elements of common real-world assistance problems, such as inspection, diagnosing, instructing and manipulation.
B. Hypotheses

Concerning the effect of the robot’s assistance features on performance and collaboration, we hypothesise that with those features enabled:

H1 The time to complete the task would be reduced.
H2 The robot’s task knowledge and autonomy change the required amount and balance of verbal communication.
H3 The perceived workload of both users would decrease.
H4 The users’ rating of the system’s usability would be increased.

C. Participants

20 participants (4 females, $m_{age} = 30$, $SD = 5$) were recruited and split into two groups for the role of the remote user ($N = 5$) and the local user ($N = 15$). We decided to rerun experiments with participants from the remote user group as the introduction to the remote interface is a time-consuming process. The volunteers were staff and students from our department, however, no technical knowledge was required for either of the roles. There was no benefit or financial compensation in exchange for the participation, however, they were happy to volunteer, presumably because most found the experiment entertaining.

D. Collaborative Setup

The task setup consists of two main areas, the local workspace site and the remote workstation (cf. figure 1). For the experiment, remote and local users were located in the same room, however, a visual barrier prevented them from direct interaction. They were allowed to speak to each other as if they were on a phone call.

For the experiment, we used the handheld robot reported in [9], of which the mechanical design is publicly available on our research website [33]. As it can be seen in figure 2, it features a 5-DoF actuated tip and two cameras. One camera is fixed to the robot’s frame and delivers an overview of the current workspace. A second camera is positioned close to the tooltip so that it can be directed for exploration, whilst allowing a detailed view on tooltip operations.

The remote user was seated at a desk equipped with the remote interface, which allows the perception of the robots’ workspace and features a 5-DoF input for the remote control, as well as information about the system and its required goal states. The local user is located in the workspace where the physical task has to be completed. The user holds the robot in place for inspection and helps the remote user to reach objects for manipulation and diagnosis. A demonstration of the task is shown in the supplementary video of this paper that can also be found on our website [33].

E. Experiment Task

The experiment task simulates the maintenance of a pipe system, which consists of a network of pipes, valves and gauges. While the pipes are a physical system, the valves are simulated through a display in the background of the pipe system (cf. figure 3). The gauges are also simulated, but on a separate screen two meters away from the pipe system. That way, the remote user cannot look at the gauges while carrying out work on the pipes. The value of the gauges depends on the state of the valves. There are two different kinds of valves, the first kind has only two discrete states i.e. open and closed while the wheel-shaped valves are continuous. Each valve has a specific contribution to a gauge in the open state. The system contains 8 discrete valves, 2 continuous valves and 3 gauges.

The experiment consists of two main tasks, adjusting the valves in the first place and checking the pipes for cracks. For the first task, the valves need to be changed so that the gauges get to a predefined target value. The remote user holds the knowledge about the target values of the gauges and the contributions of the respective valves and consequently knows what changes need to be done. However, initially, the remote user does not know the pipe system’s current state i.e. valve states and the readings of the gauges. Retrieving this information requires either a visual exploration of the work scene or verbal requests.

When the soft tooltip of the robot touches the valve, the remote user can press an activation key to turn it open or close. This manipulation is simulated through a 2D animation of the valve handle/wheel in the screen and the associated gauge value changes accordingly. For simulation purposes, the touch of the robot’s tip is registered using motion capturing, which enables the 3D localisation of the handheld robot and the screen surface.

For the pipe checking task, a sonar sensor is simulated. The procedure of taking a measurement is inspired by [27] where a sensor tip is placed on a machine part for a short duration to check the condition of the material e.g. for crack detection. Similarly, here, the robot’s tip needs to be in contact with a pipe to be checked for a few seconds while the remote user activates the sensor reading.

1 OptiTrack: optitrack.com
There is no predefined order in which valves have to be opened or closed and pipes to be checked. In that way, the remote user has to come up with her/his own strategy for a solution, which brings the task closer to real-world problems. The maintenance task is completed when all gauges display the desired target values and a predefined set of pipes is successfully checked with the sensor.

F. Remote Interface

The workstation of the remote user consists of three main units: the robot control system, a display with the robot states and another one containing task system information. This design of the visual interface is in essence derived from solutions reported in several remote assistance studies e.g. [1], [5], [17], while the positioning of the cameras and the spacial input is inspired by work about remote manipulation [29]. An overview can be seen in figure 4.

The main part of the control unit is the 5-DoF input, which is realised through a wand, which is tracked through motion capturing. Its relative position and pose to the base socket is replicated by the robot arm with respect to its local reference frame. To account for the limits of the robot’s workspace, the wand is attached to the base. The initial position allows the remote user to either reach out or retreat as demonstrated in figure 5. Tooltip operations such as manipulation and sensor activation can be triggered by pressing the space bar of a keyboard.

G. Robot Assistance Condition

When the robot is in the assisted condition, a set of features are enabled which incorporate task knowledge and navigation capabilities. In this state, the remote user is no longer required to complete detail motion. Instead, he/she selects an object to interact with and the robot aims for it when he/she presses the activation key. For example, the remote user could roughly direct the local user to a valve, activate the assistant and the robot completes the manipulation. The robot has knowledge about the gauges target values and can, for example, turn open the continuous valves until the associated gauge matches the required value. Similarly, the robot helps with a world-stabilised positioning of the sensor on the pipes’ surface during crack detection and retreats when the measurement is complete.

H. Experiment Procedure and Data Collection

Before the start of the experiment, the participants were given an introduction to the system. Both robot conditions were practised with the experimenter taking over the role of the matching team member until the participant felt confident. The 5 participants of the remote user group were matched with 3 unique participants of the local user group. For each of the 15 remote-local user pairs, the experiment task was executed one time for each of the conditions non-assisted and assisted, which were counterbalanced across the trials. The initial state of the valves, the gauges’ target values and which pipes would require checking were randomised in such a way that the number of actions
required to solve the task remains constant for each trial.

The trials were followed by the completion of a NASA Task Load Index (TLX) form [34] and a System Usability Score questionnaire (SUS) [35] by both participants and for each condition. Furthermore, the required time to complete the task was recorded as well as voice recordings. The audio material was later transcribed to derive word counts for the analysis. Furthermore, video recordings were taken to a qualitative assessment. The complete dataset contains 30 data points.

IV. Results

The analysis of the experiment data is divided into two parts, a quantitative and a qualitative assessment.

A. Quantitative Analysis

To assess the effect of the robot’s condition on the task performance and collaboration, we compare completion time and dialogue word count as well as the TLX and SUS results between the two condition groups. Due to the hierarchical design of the study, it is necessary to take into account the variance introduced by the repeated participation of remote users [36]. Therefore, we apply a series of two-way ANOVA with the robot’s mode, the remote user identifier and their interaction as independent factors and the time to complete, word counts, TLX and SUS, respectively, as dependent variables. The results are summarised in table 1.

Concerning task performance, a significant 24% decrease of the mean completion time, from 191.5 s (SD = 60.4 s) to 145.6 s (SD = 32.0 s), is observed when the robot is in the assisted mode compared to the non-assisted mode (cf. figure 6a). Furthermore, the remote user has a significant influence while no significant interaction is observed between the mode and the remote user. These results are also true for the word count of the remote user, of the local user (cf. figure 6b, 6c) and the total word count. No significant influence of either the condition, the remote user or their interaction was found for the word count ratio, calculated as remote user word count over total word count (cf. figure 6d).

In terms of the participants’ perceived workload, the robot’s assistance significantly decreases the TLX score for the remote user while no significant effect is identified for the TLX score of the local user (cf. figure 6e and 6f). In both cases, there is a significant influence of the remote user as a factor and no significant interaction between the remote user and the robot’s condition.

The overall system usability is rated significantly higher by the remote users when the robot is in the assisted condition. However, there is a significant interaction between the condition and the remote user. None of the independent variables has a significant effect on the SUS ratings by the local user. The SUS results are summarised in figure 6g and 6h.

The overall user perception measured by the mean TLX and SUS scores of the proposed system, i.e. in the assisted mode, is summarised in table 2. It shows that there is a low task load score while the usability score is high for the responses of the remote user as well as for the local user.

B. Qualitative Analysis

The major novelty of our proposed remote assistance system is the ability of the remote user to physically interact with the workspace environment. This introduces new solution strategies and behaviours which are reflected in the collected video material.

Across the different participant pairs, a general problem-solving strategy could be observed, which consists of four phases: scene exploration, spacial guidance, local task solving and retreating. During scene exploration, the remote user uses both camera views to diagnose a problem. Once the problem is identified, the local user is guided to a scene object through tooltip gestures and verbal instructions. The ratios between the usage of those two communication means vary strongly between remote users. While some participants gave many verbal instructions, notably, one remote user participant was able to guide the local user through the pipe checking task through manipulator gestures only and without saying a single word. Another observation is that in this phase the remote user can, in some instances, control the motion speed of the local user by the amount of tip deflection.

After the object of interest is reached, there is a transition from shared control over the robot to remote user control as the local user holds the robot in place during manipulation. After a subtask is solved, the local user retreats away from the workspace to give the remote user another chance of exploration and the working cycle starts over again.

V. Discussion

In terms of task performance, we found that the handheld robot’s autonomy and task knowledge contributes to a more efficient collaboration as it reduces the time to complete the task, which confirms [H1]. This is independent of the interaction between the robot’s condition and the remote user i.e. independent of user preferences. Regarding the communication between the remote user and the local user, the qualitative results show that the remote control of the robot’s tip extends the means of communication as it can be used for deictic gestures. [H2] is partially confirmed as the robot’s assistance features reduces the volume of verbal communication required to solve the task. We suggest that the reason for this observation is that the robot’s aiming feature replaces the remote user’s instructions for low scale motion and the task knowledge makes the request for information partially unnecessary. As the introduction
TABLE 1: Two-way ANOVA results for the analysis of the effect of the robot’s condition on completion time, users’ communication word count and their respective perceived task load (TLX) and system usability (SUS) ratings.

| Condition | Remote User | Local User | Total | Ratio | Remote User | Local User | Remote User | Local User |
|-----------|-------------|------------|-------|-------|-------------|------------|-------------|------------|
| Remote User | p = .001 ** | p < .001 *** | p = .049 * | p < .001 *** | p = .712 | p = .015 * | p = .624 | p < .001 *** | p = .971 |
| Interaction | p = .556 | p = .507 | p = .996 | p = .611 | p = .954 | p = .375 | p = .934 | p = .001 *** | p = .887 |

Fig. 6: Diagrams of mean completion time, word counts, TLX and SUS scores for the assisted and non-assisted condition of the robot. Starred samples yield a significant difference due to the robot’s condition without a significant interaction between the mode used and the remote user as a factor (cf. table 1).

TABLE 2: Perceived task load and usability ratings for the case where the assisted mode is enabled.

| TLX | Remote User | Local User | Remote User | Local User |
|-----|-------------|------------|-------------|------------|
| Mean | 28.2 | 28.2 | 83.2 | 78.8 |
| SD  | 16.2 | 16.2 | 13.7 | 13.6 |

In terms of the robot’s effect on collaboration quality, we argue that a collaborative robot should be characterised by reducing workload and high usability. While this is confirmed by the overall TLX and SUS results for both users, improvement through the robot’s assistance feature could only be found for the perceived task load of the remote user. This might be rooted in the fact that the aiming feature takes away task load from the remote user while it does not make a notable difference for the local user whether the tip is controlled by the remote user or through the robot’s assistance.

This is also true for the system’s usability, however, the SUS result is not generalisable as the effect of the interaction between remote users and the robot’s condition implies a possible existence of distortions through individual preferences. More testing is required for a clear answer. Therefore, H3 and H4 are only partially confirmed and we conclude that the assisted mode mainly facilitates the work of the remote user.

VI. CONCLUSION AND FUTURE WORK

In this work, we investigate the use of a handheld robot in our proposed collaborative remote assistance setup within a helper-worker scenario. Our studies show that a handheld robot can mediate task information and physical interaction in collaborative assistance and that the robot’s partial autonomy improves task performance in terms of time efficiency and regarding the remote user’s perceived workload and required verbal communication.

Object manipulations and setup were simulated in this study, thus future work should consider evaluating accuracy and errors in a real setting. Additionally, our findings demonstrate how fully trained remote users benefit from the robot’s assistance. However, it would also be of interest to explore how this setup benefits the training of novice remote users who transition from the local user role.

This study is a first attempt to evaluate handheld collaborative robots in a remote assistance scenario, a setup that can leverage current robot constraints such as incomplete task knowledge and motion competences with the already well-established communication technologies.

Acknowledgements and Data Access

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