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Evaluating Telecollaboration Modalities for the Realization of an Industrial Maintenance Operation in a Constrained Environment

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Abstract. The continuous improvement of reactivity and resilience of the maintenance teams is one of many industrial companies' priorities, especially in the scope of urgent interventions. To save valuable time usually lost travelling, it is possible to mobilize a technician near the defective infrastructure, and an experienced technician to guide him entirely remotely. Teleassistance, or telecollaboration, is a subject whose interest has grown widely in recent years in line with the evolution of digital technologies. Our study brings a new eye towards the current state of the art with an important focus on the industrial aspect of the operation; in terms of constraints but also of tasks to be realized. We present an interface of telecollaboration specially developed for Android tablets in order to evaluate the quality of the communication as well as the performance of an industrial maintenance operation on the operator-assistant format. The raised problematic is related to the methodology for finding the most optimal methods and formats of communication according to the quality of the available Internet network. The results of this study intend to provide relevant information on the use of teleassistance in an industrial environment according to different levels of available Internet speeds, or different work constraints such as noise or the use of safety equipment. Our work proves that it is essential to provide some form of audio communication to the collaborators to ensure the proper execution of the operation; and solutions are presented in the case where it is impossible to do so, depending on the cause, whether it is related to the work environment or connectivity.

Keywords: Telecollaboration · Communication · Maintenance

1 Introduction

Many scientific studies address the use of some form of remote intervention in industry [1–11], such as the use of remotely controlled robots in the nuclear sector [12], collaboration for product design or project review between different teams [13]. Our study focuses on remote assistance for industrial maintenance, on the operator-assistant format in synchronous communication.

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Research on this subject is numerous but generally suffers from at least one of the following two symptoms: the tasks performed are not representative of an industrial maintenance operation or the communication modalities made available do not take into account industrial constraints. If the results show the conditions and modalities according to which communication can be efficient, it seems difficult to transfer these conclusions to a real use case in an industrial context. This paper's main goal is to identify under which circumstances telecollaboration enables a remote assistant to guide an operator on an industrial maintenance task. For industrial usage purposes, this study will focus on telecollaboration using tablets only.

2 State of the Art

Telecollaboration is usually defined as the "remote participation in the realization of a common task". Its purpose is to enable two or more participants to take part in a remote communication enhanced by many sorts of interaction modalities. The availability of these modalities depends on different constraints; may it be hardware or software related, or due to the nature of the task to achieve. Telecollaboration can be used in real time (synchronously), or in delayed time (asynchronously) [6]. Digital interfaces can be varied and different between collaborators (hardware symmetry or asymmetry). The roles of the collaborators can be identical (multiple operators) or different (operator and assistant).

A remote collaboration system relies on two main features. First, the collaborator must have some sort of work environment sharing, like a 3D model of the system on which the task is to be performed. Then, they need to be able to communicate.

Communication. The following communication methods are often employed in scientific studies regarding telecollaboration: audio chat [1, 5, 6, 12] or alternatively a text chat solution, picture exchange [7], drawings [7, 9, 12] and finally spatial markers [6, 7, 9, 12]. Some papers make use of mixed reality tools to further enhance the quality of the communication, for example by representing collaborator's full body avatar, or head and gaze direction [9, 12, 21]. Those modalities require specific hardware to achieve real-time body tracking. Cited work typically address the communication interaction possibilities without any limit regarding hardware usage and invasive equipment; especially for the means of capture and displays (using numerous cameras, body sensors, video projectors, mixed reality interfaces). In this extent, we specifically design our experiment to only rely on the use of one interface: a tablet.

Workspace Sharing. While this work does not aim to study the impact of the choice of the form used to represent the workspace between collaborators, we can expose some technologies that are already used depending on the telecollaboration context. Two main approaches are possible: real time capture of the workspace, or premade models.

Premade models require to have the CAD or 3D model of the system. There is an issue in using those models that are not real-time acquired: it can be difficult to keep track of the system's evolution, most particularly for a real-time intervention. Being able to get a representation of the system on which the operation is to be performed allow the users to always get an up-to-date state version but requires the operator to perform a scan of the system and may need more performances and network bandwidth.

Photogrammetry may give the best result regarding the quality and fidelity of the model, but also takes the most performances and bandwidth [9]. Furthermore, the collaborator must scan the system in a specific manner to ensure a good result. LIDAR scanning is a more lightweight solution and allows to get 3D models in a surprisingly fast time and a quite good quality [10, 12, 20]; it can be performed in real time by a handled device without the help of a server. If the device used does not support LIDAR, one can use an RGB-camera coupled with the right algorithms to try and recreate a 3D model of the scene [7], however, the results are of a lesser quality than with a depth-camera. Finally, if the use case does not allow for the exchange of 3D models, collaborators can share pictures of the system, which can be presented in a more or less structured way to allow them for virtual navigation between pictures [21].

The articles cited before give some interesting results for communication related operation, although the use case on which the experimentation is conducted usually does not take industrial constraints into consideration. Our goal is to provide clues on how to use remote collaboration for the assistance of an industrial maintenance task. To do so, we first need to define those constraints.

Industrial Maintenance. Based on a bibliographical study coupled with an in-situ observation of various maintenance operations, we specify and characterize the industrial use cases for our experimentation using a certain number of criteria: the type of maintenance [14] either preventive or corrective, the frequency of the operation and the execution time. The level of mobility [4] which represents the range of movement of the operator during the maintenance is also evaluated, along with the difficulty of the task and its sensitivity *i.e.* the risk associated in the event of an error occurring during the intervention, whether it is human or material. Subtasks can be categorized according to the standard classification in three levels. The first level represents tasks planned by the manufacturer such as front-end adjustments or replacements of disposable components (like a fuse), the second level requires an identification of defective parts and a certain knowledge to diagnose the system, where the third level involves replacing or changing parts of the system and sometimes altering the initial functioning.

Moreover, performing a maintenance task requires the operators to wear safety equipments; the nature of which varies according to the field of the operation and must be considered to implement the use of telecollaboration, in the same manner as the following specific constraints: work in high places, confined spaces, in a humid atmosphere, heavy load handling.

3 Scientific Issues

The constraints presented in the state of the art are too numerous to be considered all at once. We will then focus our study on two main industrial constraints. First, the need to wear safety equipments and the environment of the operation do not allow the operator to use certain tools for telecollaboration; for example, it is not possible to have an operator wear an augmented reality headset because he must already wear a hard hat. Wearing a glove requires adaptation of touch-sensitive surfaces. Finally, the quality and availability of telecommunication networks (phone, radio, Internet) is not guaranteed, and it is therefore essential to study degraded cases of functioning where the bandwidth is limited. Our work will address the network quality constraint in a simplified way; for instance, parameters like traffic congestion and packet losses will not be considered. The study will focus on the amount of data that may be exchanged in real time; meaning only the bandwidth quality will be a parameter for our experimentation.

3.1 Question

Our study intends to identify the optimal methods and tools for the use of teleassistance in an industrial environment, considering the operational constraints and the different levels of connectivity that are available. The research objective can be formulated as follows:

> *Evaluation of the quality of the realization of a maintenance task in telecollaboration on the operator-assistant format, according to the industrial conditions and in limited connectivity*

The goal of these results is to identify, for an industrial use case, under low connectivity conditions, the optimal telecollaboration methods. Therefore, we adopt the following research question:

> *To what extent does the use of telecollaboration allow for the assistance of a maintenance operation despite operational constraints and limited connectivity?*

3.2 Hypothesis

In order to formulate our research hypotheses, we subdivided the main research question into elementary sub-questions:

- Does telecollaboration on the operator-assistant format allow to realize a maintenance task that the operator could not realize in autonomy?
- If yes, what are the parameters that influence the quality of the task realization on one hand and the communication on the other hand?
- Can a situation of low connectivity compromise the use of telecollaboration? What are the limitations?

We then state the following research hypotheses:

- H0: Telecollaboration allows the remote assistance of an operator for the realization of a maintenance intervention.
- H1: The availability of a diverse number of communication modalities enhances the quality of the communication. This hypothesis has already been proven by the related works, but we want to ensure its validity in an industrial use case.
- H2: The effectiveness of telecollaboration (in terms of execution and communication) depends on the level of available connectivity.

4 Experimentation

4.1 Participants

Pairs of participants take on the role of operator and assistant and must carry out an industrial maintenance operation that the operator does not know. The candidates are chosen among students registered in higher education in industrial maintenance or in engineering school in order to homogenize the profiles and to ensure the basic knowledge in maintenance.

4.2 Setup

The candidates are set in representative conditions of an industrial use case, in separate rooms to simulate distance and prevent natural communication. The following Fig. 1. Presents the setup for the experiment.

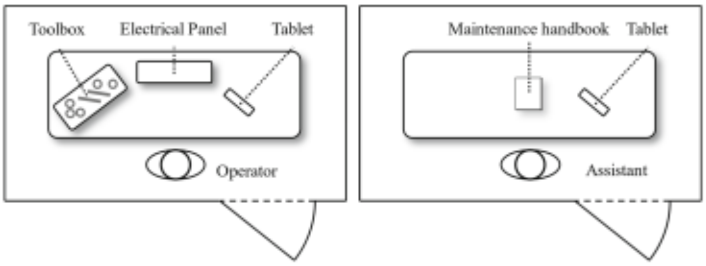

Fig. 1. Experimentation setup

In their respective rooms, the candidates are seated at a table with the necessary equipment for the operation:

- The operator (OP) has on his table a model of an industrial electrical panel (on which he has to perform the maintenance task), the standard intervention tools as well as a tablet on which the telecollaboration application is installed.
- The assistant (AS) has on his table a tablet with the same telecollaboration application, as well as a manual detailing the maintenance procedure.

The maintenance operation that the operator has to perform concerns an industrial electrical cabinet (Fig. 2) allowing to realize a star-delta starting of a three-phase motor. The model presents failures and defects according to three levels of maintenance (standard classification):

- Level I: front panel adjustments and verification of component caliber;
- Level II: verification of the components' normal functioning;
- Level III: replacement of a defective component.

For safety reasons, the operation is carried out without power. The following situation was presented to the candidates in order to reinforce the implication: *After a failure of a* *hydraulic pump, a first quick diagnosis involved the motor control panel. It was removed from the system and taken to the workshop where you will perform an in-depth analysis.* **The telecollaboration application** (Fig. 2) was developed specifically for the experiment, using Unity (version 2022.2) and running on Samsung Galaxy Tab S7 + 5G (Android 13). This application provides five communication metaphors:

- Audio chat;
- Written chat: useful in the case where audio is not available, or to share a precise information without ambiguity in pronunciation or listening (standard, setting value, name of a component).
- Drawings and plots [7]: a canvas on which it is possible to freehand draw, with a choice of colors and pencil thickness. Can be used for example to share an electrical or kinematic diagram.
- Photos: take a photo with a choice of camera to use, and upload utility and interface to browse all shared photos.
- 3D markers [7]: the user can place a marker by pointing on the 3D model to highlight a zone or a precise element of the working environment or of a component. Different models are available (colored circle, multimeter probe, screwdriver, danger sign, standard components: buttons, potentiometers…).

The 3D model of the system has been made on Blender for the experimentation; and it can be explored by the user of the application with standard interactions (pinch to zoom, one finger to turn the model, two fingers to move). The application connects the tablets via Internet and synchronizes the metaphors introduced earlier.

[redacted]

PROTOCOLE D'INTERVENTION :
AUTOMATE DE CONTRÔLE DE
MOTEUR DE POMPE

Fig. 2. From left to right: **1.** The electrical panel on which the maintenance operation is to be performed. **2.** The telecollaboration application on the Tab S7 + 5G tablet. **3.** The manual detailing the maintenance procedure.

The assistant is provided with a maintenance manual (Fig. 2) detailing the step-by-step procedure in the clearest possible way. In the case of industrial use, the assistant does not necessarily have such a tool; it is used in our experimentation to simulate the perfect knowledge of the assistant concerning the maintenance operation to be performed. In this regard, the assistant is not allowed to send pictures of the manual to the operator.

4.3 Telecollaboration Scenarios

In conformity with the presented research issue, we want to evaluate the relevance of the use of telecollaboration in an industrial context, depending on the connectivity conditions, *i.e.*, depending on the available bandwidth. Our experimentation takes place in a local network laboratory, where the available bandwidth is maximum. We have therefore designed two telecollaboration scenarios according to the bandwidth requirements of each communication mode.

A preliminary theoretical study allowed us to evaluate the bandwidth needs for each modality. The audio, marker and text needs in terms of data are evaluated theoretically given their implementation in our application. The drawing's weight depends on its complexity, starting at 0KB for no drawing at all going to 100KB or more for a very complex one. This number can be brought down significantly using another way of compressing and synthetizing the data.

The weight of a picture depends on numerous parameters that make it impossible to establish a constant size beforehand; the most influential ones being the subject of the picture and the compression algorithm used, as seen in the following Fig. 3. A picture of the system studied in our experimentation in 480p resolution (720*480 pixels) weighs between 50 and 250KB once compressed in jpeg format. This format has been chosen for its performance in terms of speed and compression rate.

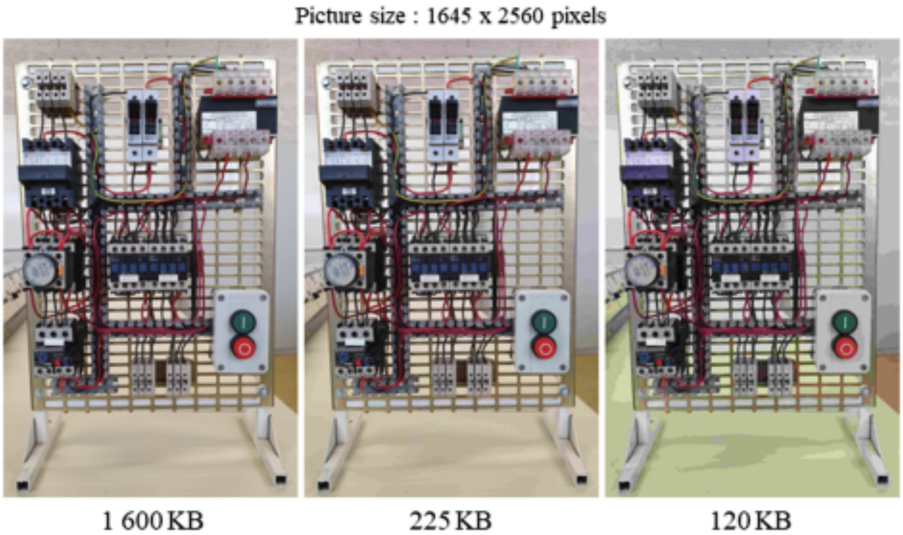

Fig. 3. The weight of a picture depends on the subject as well as the compression rate.

The results from our preliminary analyses are synthetized in Table 1 below.

These results were then used to define two telecollaboration scenarios presented in the following Table 2. As stated in the introduction, we only address the constraint of low connectivity level only in terms of amount of data that is exchanged in real time.

Table 1. Bandwidth requirement for each communication modality

Modality name	Amount of transmitted data
Audio	200 KB per seconds of audio
Picture	50 KB to 500 KB (depending on quality and subject)
Drawing	10 KB to 100 KB
Marker	12 Bytes
Text	2 Bytes per character

Table 2. Telecollaboration scenarios

Scenario	Name	Available communication modalities	Bandwitdh
S0	Degraded	Text, picture, drawing, marker	50 Ko/s
S1	Nominal	**Audio**, text, picture, drawing, marker	250 Ko/s

4.4 Measures

Numerous metrics have been identified to evaluate the realization of the maintenance task and the quality and fluidity of the communication.

Realization of the Maintenance Task: the metrics concerning the operation are relatively standard [2], [16], [17]. Their purpose is to measure the quality of the intervention: maintenance time, number of errors, number of corrected errors, number of completed tasks. We define a completion rate expressed as a percentage of the total completion and defined by the following relation (1):

$$\tau_{completion} = \frac{N_{accomplished\_tasks} - N_{errors}}{N_{total\_tasks}} \tag{1}$$

The total number of tasks and the number of errors are weighted by coefficients according to the difficulty of the task: level I: coef. 1, level II: coef. 2, level III: coef. 9. The maintenance protocol to be performed is composed of 40 tasks, (I: 7, II: 32; III: 1) for a weighted total of 80 tasks.

Quality of the Communication: we quantify the use of each communication metaphor featured by the application. Moreover, we perform a distinction of the transmitted messages [5] for each scenario:

- OP and AS: question asked;
- OP: proactive or reactive description;
- OP and AS: confirmation;
- AS: proactive or reactive instruction;
- OP and AS: clarification.

This differentiation, especially for proactive/reactive messages, makes it possible to qualify the fluidity of a communication and the impact that each interlocutor brings to the common effort.

We also asked each candidate after the experimentation his level of agreement (5-choice Likert) on four propositions: “my statements were clear for my interlocutor”, “the statements of my interlocutor were clear for me”, “the application seems to allow me to express myself correctly”, “the application seems to allow my interlocutor to express himself correctly”. Comparing the perception of the interlocutor’s comprehension with one’s own perception can reveal the quality of the communication; for instance, in some cases, there is a large dissonance within a pair, which reflects the poor quality of the communication.

Telecollaboration Interface: We proposed a reduced version of the SUS questionnaire to the candidates, composed of 7 items concerning the usability of the application. This allows us to have feedback on the ergonomy of our application, but also to put into perspective some results such as the difficulty or the ease to communicate. The goal is not to have an objective measure of the usability of our telecollaboration system, but rather to get qualitative feedback from the users.

The cognitive load of the candidates was evaluated according to the Nasa TLX questionnaire in order to determine the involvement of the candidates as well as the effects of the communication possibilities on the workload.

5 Results

A total of 22 candidates aged 18 to 22 took part in the experimentation *i.e.*, 11 pairs; 5 for scenario S0, 6 for scenario S1.

The results are clear: none of the pairs deprived of the audio discussion (S0) succeeded in completing the whole operation, despite a much higher average maintenance time: 58(±15) minutes for the S0 scenario against 28(±6) minutes for the S1 scenario. The S0 pairs ended the experiment by declaring that they had completed the protocol, but tasks were forgotten, and errors were made. S1 pairs almost all passed the experiment completely, except for one group that made an error on a Level II task ($\tau = 98\%$).

The statistical analysis employed is a two-sample t-test; for which we confirm the following assumptions: the observations are independent and the candidates were assigned a scenario randomly. Finally, the normal distribution on such a small sample size is difficult to prove but the two sample t-test is robust against non-normal distribution (in a certain extent) especially in small sample size scenarios. The normal distribution hypothesis is not to be rejected, given the results of the test.

The completion rates are summarized in Fig. 4. The difference in completion rate is highly significant ($p < 0.01$), so is the difference in experimental duration ($p < 0.01$).

Beyond the failure of the S0 pairs to perform the maintenance operation, we observe an augmentation of the mental load with a Task Load Index of 11.4(±1.9) against 7.7(±3.3) for the S1 pairs ($p < 0.05$). However, further observation by classifying the results by scenario and role, shows a difference of smaller magnitude (Fig. 5).

As for the application and more specifically the usability evaluated through an adapted System Usability Scale, the difference between the two groups is not significant: 14.9(±2.1) for S0 and 16.3(±1.9) for S1 ($p > 0.3$). However, when classifying the candidates by scenario and role, we observe a slight improvement in usability between the S0 and S1 assistants (Fig. 6).

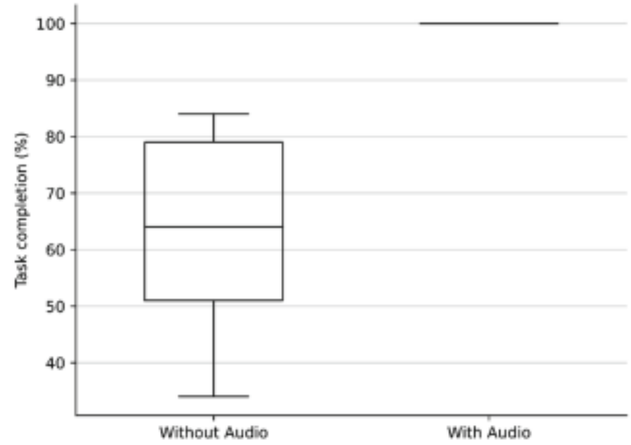

Fig. 4. Task completion for S0 and S1

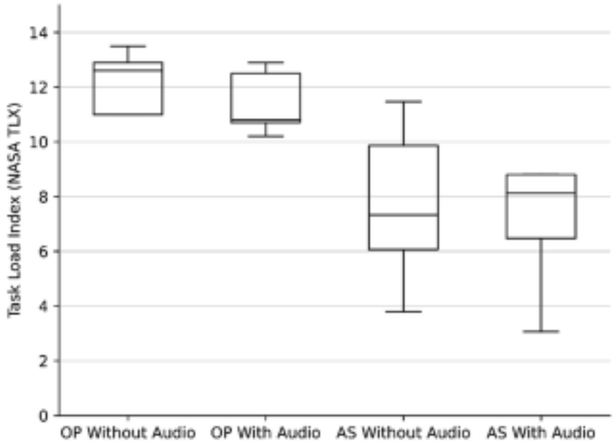

Fig. 5. Nasa's Task Load Index by scenario and by role

The perception of comprehension does not show a significant difference ($p > 0.4$).

Finally, we note a clear improvement in the number of proactive messages: 29 %(±4) for S0 versus 41%(±5) for S1, ($p < 0.01$). The share of reactive messages thus decreased from 18 %(±4) for S0 and 11%(±2) for S1 (Fig. 6).

6 Discussion

In the case where it is possible to make audio communication available in real time, the results show that the operation takes place in very good conditions, and the interlocutors manage to carry out the operation, communicating proactively and smoothly. This validates our hypothesis H0 (Fig. 7).

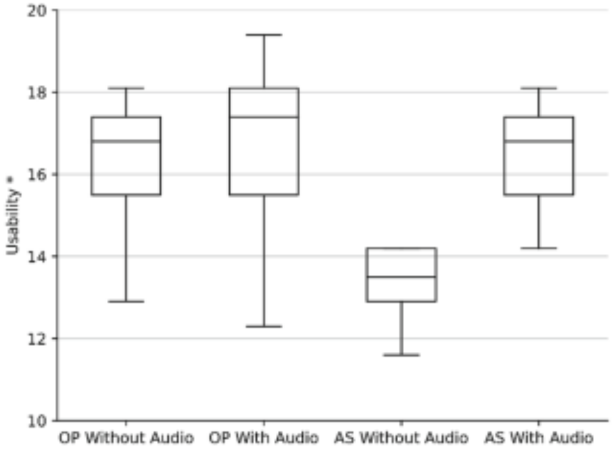

Fig. 6. Adapted SUS by scenario and by role

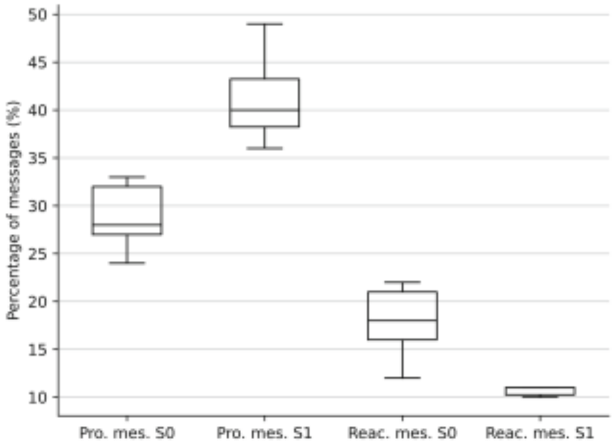

Fig. 7. Percentage of proactive and reactive messages in each scenario

Regarding the telecollaboration interface that we have developed, some interaction metaphors are clearly less used than others (pictures, diagrams). However, these metaphors are essential in some cases. For example, the candidates sent few photos (one per group on average), but they were useful for clearing up ambiguities when the spoken language did not provide a sufficient depiction of the work environment. In this sense, hypothesis H1 is validated insofar as making a larger number of tools available improves the quality of communication.

Finally, our results show that there is indeed a strong link between the telecollaboration interface used and the possibility to perform a maintenance task. It would seem, as it is, that it is not possible to carry out a telecollaboration operation on the operator-assistant format if the collaborators cannot discuss orally. These results are in line with existing work [6] and increase the scope for industrial uses. This impossibility can have two main causes: either the connectivity is too limited and the available bandwidth does not allow the exchange of an audio stream in real time; or the operator evolves in a noisy environment, preventing the use of a microphone. Hypothesis H2 is then validated: the quality of telecollaboration depends strongly on the level of connectivity available.

7 Conclusion

Our work adds to the scientific literature concerning the use of telecollaboration for industrial maintenance assistance by providing a new perspective oriented towards the use case by proposing a specifically designed experimentation. Our results are in line with some previous articles and show that a telecollaboration interface can be used to perform a maintenance operation on the operator-assistant format, but it must be comprehensive and ergonomic. However, there is a limit to the use of telecollaboration: as a matter of fact, our study proves that it is not possible to perform the maintenance operation if the collaborators cannot discuss orally; specific solutions must then be used in case of too weak connectivity.

We can then answer our initial research problem: it is possible to carry out a maintenance operation in industrial conditions by means of telecollaboration, and this with a reduced level of connectivity; however there is a limit below which the quality of the communication is impacted so much that the intervention becomes unachievable if the bandwidth or the stability of the connection becomes too low.

8 Perspectives

If audio communication cannot be provided, solutions are possible: in the case of a noisy environment, acoustic treatment algorithms can reduce the noise enough (to a certain extent) to allow the transmission of a signal representative of the operator's speech. In the case of limited bandwitdth, it is possible to work around the problem: one can use an asynchronous audio communication, with full detailed instructions, and the use of written chat for synchronous communication. Another more elegant solution involves the use of speech recognition technologies: it can be possible to capture the operator's voice, use a speech-to-text algorithm to send the speech as text (which is much less bandwidth intensive) and propose it either in written form or using a text-to-speech algorithm for the interlocutor. This solution may be of great interest in a use case where bandwidth is highly limited and could be the subject of an in-depth study.

The telecollaboration interface can be further enriched compared to the application we have developed. For example, it is possible to display avatars that represent the collaborators, as well as the direction of their gaze in the shared work environment [12, 19]; this allows to bring back some forms of non-verbal communication over the distance.

A very important point to underline is that telecollaboration requires a representation of the workspace, in our case a model designed for this purpose before the experimentation. In an industrial context, it is not always possible to have a 3D model of each of the systems that may undergo a maintenance operation. In this case, there are a certain number of solutions that we would like to study in future works dedicated to the sharing of the work environment, such as 3D scanning (LIDAR) [21], photogrammetry, or more basic solutions such as a set of photos located in space [21].

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