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Video and Laser based Augmented Reality Stereoscopic Viewing for Mobile Robot Teleoperation

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Abstract: This paper proposes an augmented reality visualization interface to simultaneously present visual and laser sensors information further enhanced by stereoscopic viewing. The use of augmented layers is proposed to represent laser measurements suitably aligned to video information. This methodology enables an operator to intuitively comprehend object proximity and to respond in an accurate and timely manner. The use of augmented reality to assist teleoperation, sometime discussed in the literature, is here proposed following a systematic approach and developed based on authors' previous work on stereoscopic teleoperation. The approach is experimented on a real telerobotic system where a user operates a mobile robot located thousands kilometers away. The result proved feasibility and simplicity of the proposed methodology and it represents a base for further studies.

Keywords: Teleoperation, Robots for Hazardous Environments, Tele-presence.

1. INTRODUCTION

There are many applications in robotics that requires intervention with unknown, inaccessible, or dangerous environments where unpredictable situations may occur. E.g. in case of industrial robots operating in deep waters, in planetary or volcanos exploration, in applications of safety and prevention, (bomb finding and their deactivation), (1) - (5).

These applications and many more make impossible the use of fully autonomous robotic systems and require direct human (tele-) intervention to resolve issues. These are the cases where human-cognition is irreplaceable because of the high operational accuracy that is required, as well as deep environment understanding and fast decision-making. E.g. to escape deadlock situations, to perform skillful manoeuvring, etc.

Robot teleoperation systems typically rely on 2D displays. These systems suffer of many limitations. Among them: misjudgement of self-motion and spatial localization, limited comprehension of remote ambient layout, object size and shape, etc. These limitations lead to unwanted collisions during navigation, as well as long training periods for an operator. An advantageous alternative to traditional 2D (monoscopic) visualization systems is represented by the use of stereoscopic viewing.

The authors of this paper have proposed in a previous work a mobile robot teleguide based on video images, (6). The use of stereoscopic viewing increased user's sense of presence and improved understanding of the remote scene structure and distance to surrounding objects.

Stereoscopic viewing improved performance on a system relying on the visual sensor only, but there are a number of other sensors a robot can rely on, and those can well complement the visual sensor output, e.g. laser, infrared, odometry, sonars, bumpers, etc. The use of these sensors can significantly improve teleoperation performance because of the additional information they provide. There is however a problem related to contextual visualization of different sensor measurements. This information is often shown to a user independently into the same interface, lacking of coherence and being visualized in a not intuitive manner. Sometime the panel size is also limited despite several information need to be shown.

This paper proposes a method to simultaneously and coherently present both video and proximity information within a stereoscopic augmented reality viewing context. The approach focuses on the use of augmented objects showing (laser-based) information superimposed and integrated with video objects. The proposed approach exploits stereoscopic visualization too.

2. MULTI-SENSOR DATA

Vision being the dominant human sensor modality, large attention has been paid in telerobotics to the use of visual sensors. Video images provide rich and high contrasted information and this comes presented in a way that is intuitive for humans.

There are limitations to the use of visual sensor in teleoperation, e.g. a possible delay in image transmission, (7). The rich information provided by a camera may require a large bandwidth to be transmitted over a network at interactive rates. Furthermore, the captured images come from a constrained viewpoint being a camera typically placed very close to the robot.

Some of the limitations associated to the use of a visual sensor can be reduced by using additional sensors. A laser sensor can be very useful to assist robot navigation and to complement visual information. We find several contributions in the literature proposing the use of camera and laser sensors, e.g. (10). Other sensors like sonars or infrared have also been proposed, e.g. (8), (9).

A laser rangefinder can be very effective in measuring position and orientation of walls and obstacles surrounding a robot, and their distance to the robot. This sensor can provide accurate estimates which has made it suitable for extracting 2D floor-maps of a robot workspace. 3-D spatial information can also be obtained by combining more sensor readings or a by letting the laser device move, (11). Furthermore, it is possible to completely rely on 3D spatial information extrapolated from 2D laser measurements in case of simple structured environments, (12).

The figure 1 shows our robotic system equipped with a stereo camera and laser sensors, and it includes an example of the visual output they may generate.

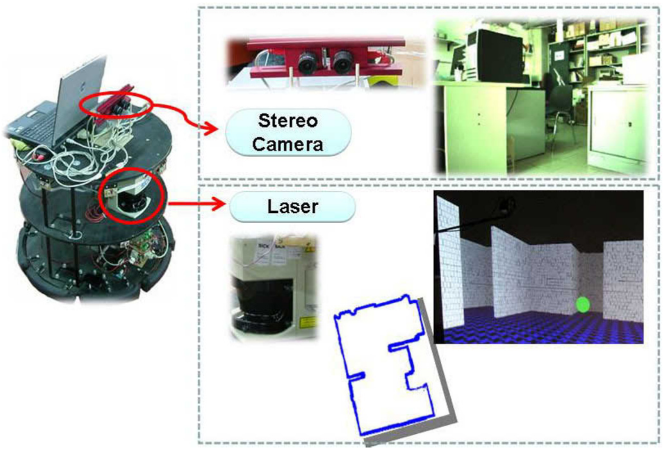

Fig. 1. The stereo camera and laser sensors with an example of the visual output they may generate. An example image of a generated 2-D floor-map reconstructed by the laser, is also shown.

Other sensors that can be exploited to assist robot teleoperation, (and that can typically be transmitted more quickly than video information), are infra-red, odometry, bumpers, and sonars.

3. AUGMENTED REALITY

The different types of information can be directly presented to a user on different displays. Alternatively, a methodology needs to be devised in order to make more effective the use of multi-sensor information.

A relevant issue is related to present proximity measurements to an operator in a way that this can effectively and quickly be understood during tele-intervention. Furthermore, in case a visual input is also present, one wishes to combine both video and laser information in an intuitive and consistent manner.

If the sensory information is provided in a natural and intuitive manner, it paves the way to fast information processing and comprehension by a human. An intuitive visual context is a precondition for immediate and accurate reaction. Therefore a well designed visual interface is a fundamental pre-requisite to improve human-robot interaction.

Augmented reality represents a convenient methodology to present multi-sensor information. Our focus is on visual representations. From when it first appeared, augmented reality has been proposed to robotic systems to assist users, (13). In Rastogi et al. (14), an operator is provided with visual feedback of a virtual wireframe robot superimposed over an actual physical robot. Augmented reality has also been proposed industrially to be used in the programming of painting robots to manipulate a spray gun and to teach a robot how to use it, (15), (16).

The benefits of augmented reality include an increased task-related intuitiveness, which improves users' performance, and make more efficient to train an operator too, (17), (18). Among others, augmented reality has been applied to maintenance applications (18), manual assembly (19), and computer-assisted surgery (20). A number of works, (21) - (24), have shown that augmented reality can be very efficient for sensor fusion and for status information delivery in teleoperation. Nevertheless, an effective and consistent representation of multi-sensor information is also a challenging problem.

4. PROPOSED METHOD

The proposed method aims at representing robot sensors information after three objectives. The sensor information should be presented visually, coherently, and three-dimensionally.

The first objective is to integrate visual and proximity information into the same visual scenario, so to avoid having different displays which compete for operator's attention.

The second objective is to simultaneously present video and laser information in a coherent and intuitive manner. The display is expected to show both video and virtual objects within an augmented reality context.

The third objective is to enhance our augmented reality interface by stereoscopic viewing. An effective 3-D visualization of the environment allows a user to comprehend environment layout, objects shape, and their dimensions, in a way more natural and accurate than using 2-D displays.

To obtain visual consistency of the different sensors measurements we need to calibrate the different sensors. In the literature we find proposals for off-line calibration, e.g. (25), (26). This type of approach requires a number of specific actions before teleoperation takes place. A robot teleoperator needs to be trained for this calibration.

An automatic calibration process would certainly be more desirable. However, automatic calibration is unreliable in practise on many application contexts.

In this work we propose a semi-automatic calibration process. This is expected to take no longer than a couple of minutes. The user follows an interactive procedure to "align" different sensor information in an easy and intuitive manner. The calibration process takes place before starting a teleoperation activity and the initial calibration settings can typically be employed for an entire teleoperation session. The calibration setting can also be stored to be reused on future teleoperation sessions that runs under the same system setup.

The system starts by automatically processing video and laser information and showing the result of the interaction within an augmented reality context. The operator can react to what he/she observes by adjusting the visualization settings, and select different options.

The system will react to operator's adjustments and will re-process sensor measurements based on new sensors information. The new result will be afterwards presented the operator will so be able to provide further input to refine the result as long as he/she wishes. The operator's is expected to be satisfied with suggested setup within very short time and to get acquainted to system functionalities. The possibility for users to immediately see the results of their actions, make the proposed semi-automatic process very effective (human-cognition is directly involved).

An interactive semi-automatic approach to system calibration has been proposed in the past in different research areas. It has for example been responsible for successful applications in the area of vision-based 3-D reconstruction (an area where fully automatically processing had been sought for several years). A good example is the successful work of Debevec et al. (27). We believe that a semi-automatic calibration and interaction in a multi-sensors based teleoperation using augmented reality, can make the proposed methodology popular in teleoperation interfaces.

5. THE ALGORITHM

The proposed algorithm for multi-sensor viewing generates colored surfaces and draw them into the image plane overlaid to the projection of environment objects. Each overlay is meant to be a visual aid for distance estimation, e.g. to detect potential obstacles. The shape and position of the colored overlays are estimated by the proposed algorithm exploiting laser and visual sensors data. Data from both sensors are combined when they are acquired at approximately the same time. The 2-D laser scans the horizontal plane in front of the robot at sensor height providing a number of distance measurements with an angular resolution of one degree, ranging from -90 and +90 degrees. The figure 2 illustrates the video and laser field of views.

At the beginning of the navigation maximum and minimum distance values are set within the laser data range. The particular values depend on the application and on the characteristics of the environment. A color look-up table is consequently generated, where the color "red" represents the smallest range value (closest distance) and

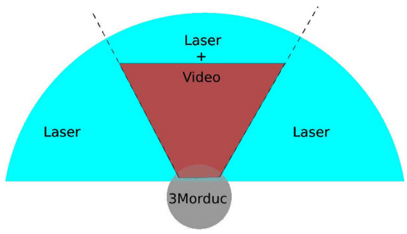

Fig. 2. A top-view representation of the laser and video sensors visibility related to robot frontal area.

the color green represents the largest range value (farthest distance). Figure 3 shows a simple example. Each distance value lying in-between these two extremes is mapped to a color ranging between red and green.

Fig. 3. A simple example of a video image (left) and the colors associated to laser measurements (right).

The main processing steps of the proposed algorithm are illustrated in the diagram of figure 4. They are:

- Augmented Layers
- Semi-automatic Calibration
- Edge Detection
- Stereo Matching
- AR-Image Generation

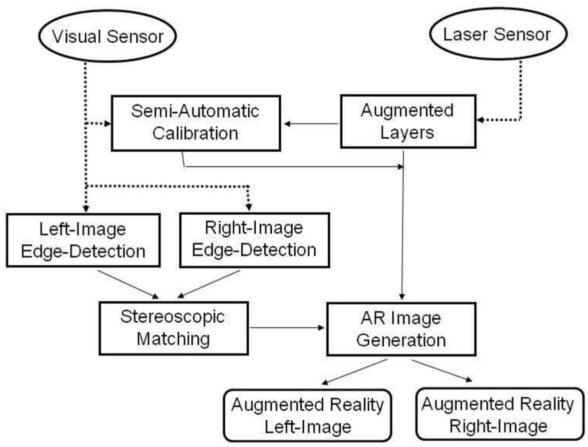

Fig. 4. The main processing steps of the proposed algorithm.

5.1 Augmented Layers

During this phase, semi-transparent colored overlays are generated based on laser measurements. The degree of transparency of the overlays can be adjusted according to the operator preferences. The augmented layers used in our work are of three types:

- *Proximity Planes*. Flat surfaces are generated from 2-D (horizontal) laser values. In particular, lines are drawn on the horizontal plane to connect neighbor laser values. The surfaces are then obtained by elevating those lines. The generated surfaces are colored, made transparent, and visualized superimposed to the video images incoming from the robot cameras. The generated augmented layers are color mapped according to the detected proximity values so that operators can visually associate a color to a distance value and get immediate understanding of possible hazards. The layers are computed at pixel resolution. The transparent effect is obtained by manipulating the original intensity values according to the color wished for the augmented layer. The intensity values can be adapted to current video context (e.g. illumination, background color, distance to the object). The figure 5 shows an example of proximity planes of different colors superimposed on different environment objects.

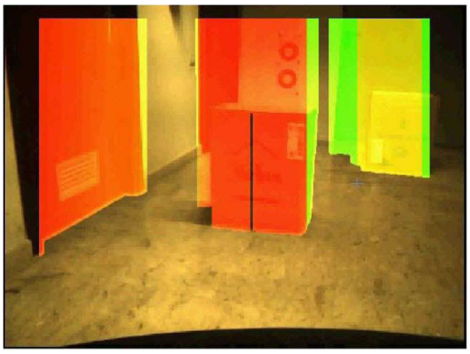

Fig. 5. Proximity planes of different colors superimposed to different environment objects.

- *Ray Casting*. As alternative or addition to proximity planes, we propose a "ray effect" that can be superimposed to incoming video images. The rays depart from camera (assumed) position, i.e. from approximately the center of the onboard stereo-camera system, and they reach the closest object on the specific direction. The rays are emitted for a subset of directions. Typically those related to closest objects. The rays are colored based on the look-up table values as previously described. The figures 9 and 11 show examples.
- *Distance Values*. The estimated distance values between robot and objects can be superimposed to the video image. This type of information can be useful when accurate quantification of the estimated distances is required, e.g. during very slow careful motion. The numbers displayed can be colored while their size and thickness can be adjusted (manually or automatically) depending on navigation context. e.g. the figure size can be inverse proportional to robot speed. The figure 9 shows an example.

5.2 Semi-Automatic Calibration

The self-calibration phase is to align visual and proximity information. The result is a function that maps each laser measurement to an image pixel. We know the camera and laser field-of-views, and we have a rough estimate of the relative position between camera and laser. We assume the camera is oriented such that its axes is parallel to that of the laser.

Based on the above knowledge, the horizontal image coordinate corresponding to each laser measurement will be estimated from the input given by the operator. In particular, the operator observes laser measurements projected onto the video-image. Each subset of adjacent laser measurements with similar values is superimposed to the video image as a colored transparent region (see figure 6). This process provides an operator with clear visual feedback of sensors alignment.

The operator observes possible misalignments between the transparent layers and the visualized environment objects, and he/she will consequently fix them by manually adjusting the calibration parameters present in the visual interface. While doing this, the operator gets immediate feedback on the consequence of his/her actions and he/she is expected to complete the calibration process within a couple of minutes. It will be possible to refine sensor alignment at a later stage during robot teleguide.

The input provided by the operator during the proposed self-calibration process allows the system to estimate camera focal-length and its horizontal offset to the laser position. Assuming less priori knowledge, we could have a more general model. This would however increase the number of configurable parameters, therefore this option has not been considered. We want to keep the calibration simple and we think the proposed assumption is sufficient for several applications.

The left and right images are also aligned during the calibration phase. This avoids that possible inaccuracies in camera positions or differences in the location of their principal points may cause vertical disparity which reduce depth sensation. The horizontal disparity offset can be on the other hand tuned to make stereoscopic viewing comfortable and suitable to current application context.

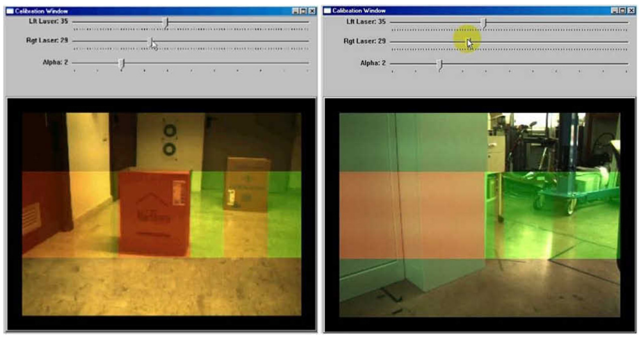

Fig. 6. Images from the calibration phase. The different transparent colored layers should superimpose on corresponding video objects.

5.3 Edge Detection

The objective of this phase is to detect reliable edges. These allow augmented layers to be correctly placed in the image-plane. Furthermore, the edge detection procedure allows for detecting obstacles unseen by the laser sensor. The proposed image processing runs independently on both left and right camera images. The main computational steps are:

(1) *Contrast Stretching.* The aim for this step is to discard edges in image regions that are not relevant to aid navigation, e.g. those representing floors and ceilings; and to enhance edges in otherwise relevant areas, e.g. those representing obstacles. To achieve this result the input image is converted to greyscale and a contrast stretching procedure is applied. The result is a new image where intensity contrast among pixels is reduced in regions with very low or high intensity, and increased in the other regions.
(2) *Canny's Algorithm.* This popular edge detector is implemented using the OpenCV framework, (28). It starts by running the Sobel operator to the image and then a non-maximum suppression is executed, (31), (30). An example result in shown in figure 7.

Fig. 7. The result of image processing (right) applied to a camera image (left).

(3) *Invisible Obstacle Enhancement.* The obstacles outside laser visible range can be discovered and their lower edges highlighted in the incoming images so to get operator's attention on them. This result is possible by comparing the position of each estimated edge-pixel and the position of the pixel corresponding to each laser measurement. If an edge-pixel is located in the image-plane below the pixel corresponding to laser measurement an obstacle may have been detected, which is highlighted in the image-plane. The figure 8 illustrates the process through an example situation.

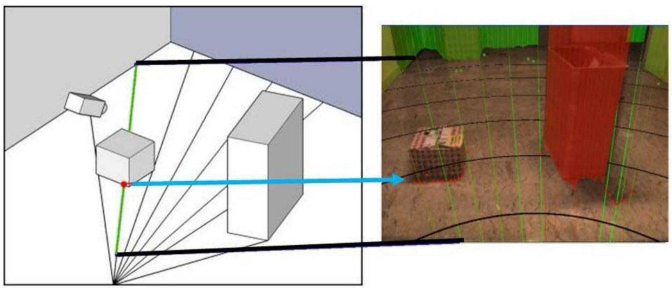

Fig. 8. An example of object invisible to our laser highlighted by the proposed Edge Detection. The left image represents the environment. The right image shows the camera view with the laser invisible object highlighted

5.4 Stereo Matching

False edges generated by image artifacts could represent a challenge for our system. A technique is then proposed to cope with this issue, which exploits correspondences between stereo images.

The corresponding pairs of stereo images (left and right) that are captured by the onboard cameras and sent through the network, are very similar but not identical. They differ by the stereoscopic view difference (image are taken slightly apart from each other), This image difference is what causes an observer to appreciate the 3-D effect, (29).

The consequence of having not identical images is that the same image processing may lead to (slightly) different results. An algorithm is then proposed to only select edges that can be matched in a stereo-image couple. The algorithm classifies edges as "corresponding" and "non-corresponding". In particular:

- *Corresponding Edges.* The edges detected represent the same environment feature in corresponding stereo-images. In other words, the same part of the same object is detected on both the left and right image. Please note that the detected edges may not be located in the same image-pixel on corresponding left and right images.
- *Non-Corresponding Edges.* The edges detected represent different environment features in corresponding stereo-images. This is especially the case for features appearing close to image borders, but it also happens for some other features, e.g. when they are "weakly" represented.

The proposed algorithm is applied to each pair of stereo-images (left and right) and it follows the procedure below.

- For each image within a stereo pair, each detected edge is assigned the corresponding laser measure. This will depend on edge position within the image and the result of the self-calibration.
- If the two assigned laser measures for a stereo-pair have different values, then that edge is classified as "Non-Corresponding Edges". In this case at least one of the two edges is likely an image artifact;
- If the two assigned laser measures for a stereo-pair have the same value, then that edges are classified as "Corresponding Edges". To be classified as "corresponding" we also require that the edges' highest point (on the image vertical axis) is lower than a set threshold.

Figure 9 illustrates examples of corresponding (green circles) and non-corresponding edges (white circles).

5.5 AR-Image Generation

The *Corresponding Edges* will generate augmented layers that will be aligned to the detected edges, therefore producing the final augmented reality image. In case a pair of corresponding edges has a disparity value above a pre-determined threshold, the augmented layer position is estimated as the average of the two edge positions.

Fig. 9. An example where Stereo Alignment is needed. The green circles show correspondent features while the white circles show undetected features.

The *Non-Corresponding Edges* are considered outliers and will not generate augmented layers. In fact, these edges may lead to the generation of isolated augmented layers causing uncomfortable viewing to an operator when an augmented scene is observed in stereo.

6. SYSTEM SETUP AND TEST TRIALS

The proposed method is tested on a real telerobotic system which allows users to operate a robot located approximately 2,500 kilometers apart from them. The robot operates in the Robotics Lab at the University of Catania, Italy, while the operator is sitting in the 3D Visualization and Robotics Lab at the University of Hertfordshire, United Kingdom. Figure 10 shows a schematization of the system setup.

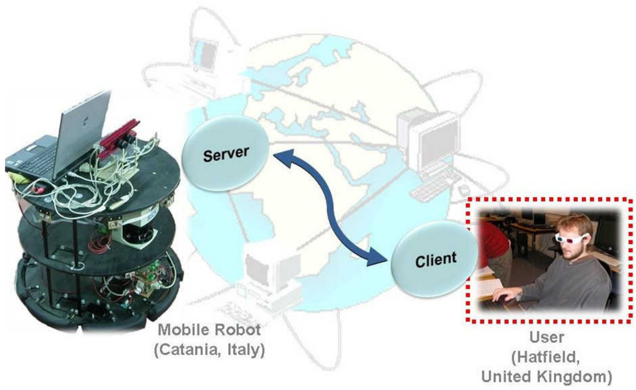

Fig. 10. A schematization of the system setup.

The robot is equipped with a stereoscopic video camera (Videre Design sth-mdcs2-var-c) and a bi-dimensional laser rangefinder (Sick LMS). The telerobotic system is an evolution of the system adopted in previous work by the authors, (6), but this time the system features a new operational setup and processing scheme because of the different sensors information being simultaneously processed and displayed. The processing phases illustrated in figure 4 take place at operator's site. We use C++ programming language and the OpenCV libraries.

The proposed pilot test aims at assessing performance and reliability of the proposed augmented reality visual interface. The focus is on testing effectiveness of the algorithm for image processing and information alignment. We settled for typical robot movements such as forward translation and rotation parallel to floor. A simple working environment is proposed which is suitable for laser detection. Our laser system has nonetheless been proven reliable also on more articulated setups, (12).

We ran five pilot trials with the aim of proving: the simplicity and effectiveness of the semi-automatic calibration; the reliability of image processing and stereo matching; the support provided by the different options of the augmented layer processing and the stereoscopic viewing. Figure 11 shows snapshots of different output as they appear to our operator during a test trial.

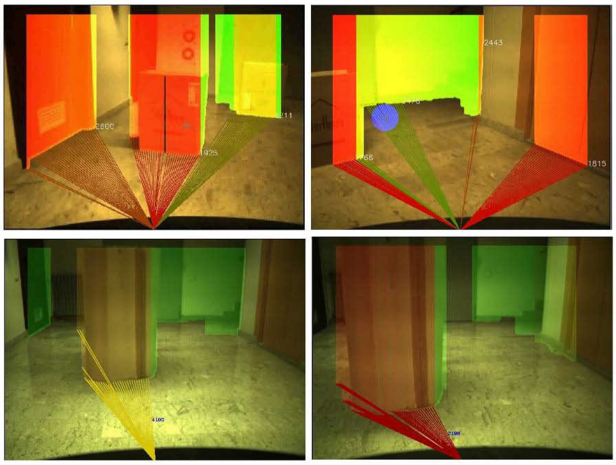

Fig. 11. Snapshots of the different processing phases as they appear to our operator during one of our pilot trial.

The results proved feasibility and reliability of the proposed methodology. The edge detection worked well with the robot movements. It allowed for detecting reliable edges for most relevant objects and correct visualization of augmented layers (proximity planes, ray casting, and distance values). The *Invisible Objects Enhancement* (part of the Edge Detection) works very well because true edges appear grouped along a line while false pixels are isolated therefore not attracting operator's attention.

The general limit of the proposed procedure is the complexity of the environment. Nonetheless, a simple factory-like environment represents many applications. The effectiveness of calibration process depends on the initial view. If this represents a very simple environment there may be a need for re-calibration during navigation. The bottom-right image in figure 11 shows for example a misalignment between environment objects and augmented layers. This can be solved with a second calibration phase or by a better choice of the initial view (with objects at different distances from the robot).

The stereoscopic matching needs careful tuning on the type of the expected environment to effectively recognize outliers and to allow for comfortable stereo viewing. The performed pilot test provided very useful insight about how to prepare and run a more thorough system evaluation (a formal test), and it represents the base for further developments of the proposed methodology.

7. CONCLUSION

This paper presented a new methodology for robot teleoperation based on augmented reality visualization further enhanced by 3D stereoscopic viewing. The aim was a users observation accurate and timely.

A method was described which included a strategy for semi-automatic calibration and a coherent way to visually represent video and laser information. An algorithm was proposed and implemented on a real telerobotic systems. The results proved feasibility and simplicity of the proposed method. The system worked well on a simple working environment that represents many applications. The edge detection was robust and augmented layers were correctly superimposed to video information. The stereoscopic visualization worked well on video images and most outliers were detected.

We are now working on a more precise self-calibration procedure and on a more extensive testing. A wider and more challenging workspace will also be included.

The presented work relies on previous successful experimentation proposing stereoscopic visualization for mobile robots teleguide. The use of augmented reality visualization is considered by the authors the natural step forward for telerobotic systems, and will certaintly become very popular in the near future.

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