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Development of Mutual Telexistence System using Virtual Projection of Operator's Egocentric Body Images

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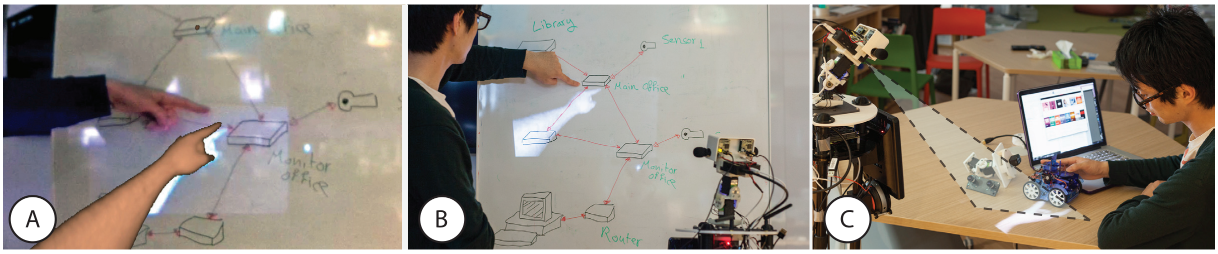

Figure 1: *Our proposed mutual Telexistence system using projected body visuals. (a) user's first person view with his hands being projected on remote place, and (b) a remote participant interacting with user's projected hands. And in (c) the user explaining to a remote participant about several items using the projected hands*

Abstract

In this paper, a mobile telexistence system that provides mutual embodiment of user's body in a remote place is discussed here. In this system, a fully mobile slave robot was designed and developed to deliver visual and motion mapping with user's head and body. The user can access the robot remotely using a Head Mounted Display (HMD) and set of head trackers. This system addresses three main points that are as follows: User's body representation in a remote physical environment, preserving body ownership toward the user during teleoperation, and presenting user's body interactions and visuals into the remote side. These previous three points were addressed using virtual projection of user's body into the egocentric local view, and projecting body visuals remotely. This system is intended to be used for teleconferencing and remote social activities when no physical manipulation is required.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities

1. Introduction

Teleoperated robots have been widely used in several applications related to communication and operation. For communication purposes, we rely not only on what we see, hear and say, but also we utilize our bodies as a way to communicate and embody our internal mental states to the others [BP75]. Telepresence type of systems generally provides mean to navigate and have a mediated video/audio communication over the internet, such as Telepresence robots [TMEHB11, LS*11]. Furthermore, these systems provides minimum representation of user's body state using a display showing user's face. However, the interface of these systems disconnects user's perception of presence in the target remote place. And the user fails to observe his body being immersed in the teleoperated robot side, as well as the remote participants does not have clear awareness of user's body state and actions.

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In contrast with Telepresence systems, Telexistence systems provide the human operator a real-time sensation of being presented at a place different from where he physically located at, and to be able to interact with the remote environment [TMFF12]. These type of systems usually uses a Head Mounted Display (HMD) to deliver the user an immersive, first point of view (FPV) vision of the remote place. In addition, Telexistence in concept enables the observers in the remote environment to see an avatar representation of the operator.

In this paper, we focus on the topic of Telexistence into remote environment using real body captured images. We addressed the following points:

1. User's body representation in a physical environment.
2. Preserving body ownership during teleoperation.
3. Presenting user's body visuals to remote observers.

This paper describes how to accomplish a low-cost mobile Telexistence platform that enables the user to have visual awareness of his real arms and hands in the remote place. Also, the remote observers can understand the intended interactions clearly although the operator does not have physical representation of his arms and hands. Figure 1 shows the different scenarios of using virtual projection of user's body into local and remote surfaces. Figure 1 (A) shows what the user sees in the remote place while using his hands. And in Figure 1 (B), user's hands are projected to remote surfaces making it easy to understand what the user is pointing at. Also it shows in Figure 1 (C) how the remote participants can understand precisely what the user is pointing at.

2. Related Work

Several works addressed the mutual presentation of user's body into remote places. Systems which deploys a tangible representation for user body were proposed [LFOI14,IK92], in this type of systems the remote participants can understand user's hands motion and position using a visual and tangible surface. For teleconferencing and collaborative tasks, [KNK10] uses life-sized video to show user's body being overlaid into a shared display in the remote place. Remote participants can see user's gaze and gestures in their local space. However, these type of systems do not aim for immersive teleoperation. Other type of systems which aims for full scale immersive telecommunication using virtual representation for both local and remote sides has been presented. [STB*12, OSS*13] demonstrated the concept of "Beaming" in which the user can teleoperate into a remote physical space using full 3D representation of that space. The project demonstrates a general framework for such purpose.

For Telexistence type of systems, the topic of mutual telecommunication was addressed in TelesarPHONE system [TKN*08]. TelesarPHONE projects user's body visuals that were captured from external camera into slave robot body. The system uses retro-reflective projection technology (RPT) [IKT03] to provide single point of view image projection to the observer. However, this system requires to view the operator from specific points of view based on the positions of the acquired images in respect to operator's body. In addition, the user does not observe the remote environment from an egocentric position, but observes using set of displays. The work presented by [FFK*12] addressed the physical representation of user's body as an avatar representation, in which the human operator upper body is fully replicated and mapped as a humanoid robot. In this type of systems, the user has an immersive experience of presence in the remote place, with the capability to manipulate objects using the robotics arms. However, in this type of full scale robotic systems, the user fails to see his real body visuals in the robot place, but instead he would see mechanical representation. In addition, the scale of these systems is inconvenient to be used for mobile and telecommunication situations due to the cost and complexity.

To present user's body visuals into a virtual environment, several works investigated the appropriate methods to achieve that. In the work of [YHK96] developed a "What you can see is what you can feel" system, which is used to directly manipulate and touch virtual objects using hands and a video-see-through display. This system requires video keying technique using a distinguishable background color from hands colors, user hands are segmented from the background and superimposed into virtual environment. In this work [BSRH09], egocentric images of user's body are captured using a video-see-through HMD, and superimposed into virtual environment. In this method, the user has to train the system for his skin color in order to be captured effectively. In [TAH12], demonstrated the usage of depth array sensor to capture user's hands interaction and superimpose it remotely for visual guidance applications. Though the hands are captured from a different point of view from user's eyes, the 3D geometric data are reconstructed and matched with his view. A different approach was proposed by [SFF*13] which uses model-based image segmentation. In this method, egocentric body visuals are also captured using a video-see-through HMD, but the images are masked from the background using humanoid virtual body representing the tracked state of user's body. The user is equipped with set of optical trackers and data gloves to track his body, arms and hands posture, and mapped to the virtual mask.

Recent work started to address an important cue for telecommunication, facial expressions and gaze representation. SphereAvatar [OSS12] uses a 360°spherical display to present face visuals of the local user into a remote place. Though the visual representation is the face is mapped into a virtual 3D head, however it helps to identify the user from any viewpoint around the display. Also in [PS14] a cylindrical display is used to project multi-viewpoint captured images of user's head into a remote place, achieving higher realistic visuals of the face and gaze compared with the 3D representation.

A previously proposed mobile, low-cost telexistence system [SFM*14] provides operators own hands visuals by using Computer Generated (CG) hands and overlaid into operator's HMD along with remote avatar vision. However there was no representation of the hands in the avatar robot place. As a result, the remote participants were not capable to understand user's gestures and posture with respect to his avatar body. Therefore, sometimes the remote participants get confused due to lack of visual clues of the operator interactions.

To address these limitations, we propose a mutual virtual embodiment method for lightweight Telexistence robots that lacks physical arms. This method uses virtual hands that are captured from user's side, and present those hands in user's view as superimposed pictures on the remote images. Also, the hands are projected remotely using a small projector mounted on the robot head and aligned with head movement. The virtual hands can be projected onto a physical table, remote user, or to any remote surfaces in order to provide the clue of user's hands interaction and intended actions. These virtual hands also provides the awareness for the user about his body, which are necessary for the sense of body presence.

3. Design Considerations

As described in [BS10, Bio97], three types of presence contribute in user's awareness of being presented in a specific environment: *spatial presence*, *self presence*, and *social presence*. Spatial presence is to be capable to interact with the environment. Self presence can be described as to be able to observe our bodies being presented in the environment, and aware of its posture at any given moment. The social presence is how we observe social interaction with other people within one environment. Figure 2 shows the three points with some examples of the target experience for each.

To address the first key point "spatial presence" the user should have direct access to the environment as if he is located there, with the freedom to move and navigate via an alternative representation of his body. The user should be able to move freely and independently his head and body, and according to that, the slave robot should follow and update user's visuals of the remote place. We avoid using any physical or tangible controller (such as a joystick or keyboard) to control motion and rotation speed of the slave robot. This is important because if the user is aware of the presence of a physical controller, then the coherence between the local and remote place will break. So an intuitive and natural interface is required to maintain spatial coherence. To move and navigate in virtual environments, locomotion interfaces

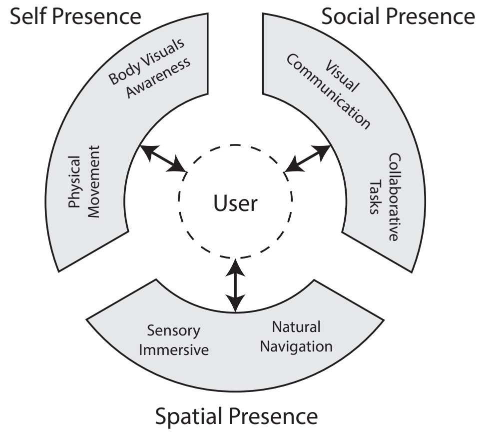

Figure 2: *Three main factors for sense of presence.*

such as [IF96] usually uses treadmill floor to allow the users to walk infinitely by constraining his body position. Other type of navigation in virtual environments was suggested by [LJFKZ01] in which the user decides the moving vector by leaning his body. The latter method in comparison with the former one has less fatigue effect on the user when the system is used for long period since the user can navigate while on seat.

The second point "self presence" is the fact the user should have physical awareness of his body's presence. The user validates his existence in a specific place by observing his body's visuals as he expects, maintaining the ownership relation with his body. Several works addressed the representation of our bodies in virtual/physical environments as listed in the previous section, mainly two types were discussed: physical robotic representation, and image-based representation. In this work, we found that observing body visuals is an effective factor to maintain the seamless sense of presence for the user, so image-based method is developed which captures egocentric images of user's body visuals, and superimpose it into the remote place.

The final point we addressed in this paper is "social presence". In order for the user to communicate effectively with other people in a different location, mutual communication between both sides should be maintained. As in "spatial presence" the user is aware of the surroundings and people around, those people should be capable to understand what the user wants in return. It is commonly to user an LCD panel only to show user's body, however this method is not capable to provide spatial interaction in the 3D space. As an alternative, we propose to project user's body visuals in robot side, so the user can visually affect in the remote place, allowing remote observers to visualize his body.

4. System Implementation

4.1. System Overview

The developed system is divided into a Master-Slave Telexistence systems as described in Figure 3 . The master side is the operating side where the user is located, and it contains a set of tracking tools that are used to capture user's head movement integrated with a wide angle HMD (Model No: Oculus Rift DK2). The HMD was customized to contain a front Infrared (IR) Camera to capture user's egocentric images, more specifically hands images. The IR Camera used is part of a commercially available product (Model No: Leapmotion). User's cockpit communicates with Robot avatar over wireless network 5.8 Ghz band, which handles real-time stereo-images video streaming from robot side, as well as control commands from user's side.

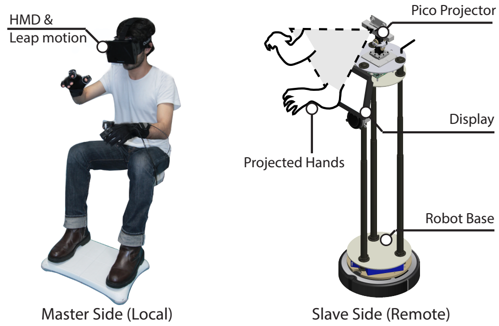

Figure 3: *Proposed system overview.*

In the robot side (slave), a 3D printed 3 Degrees of Freedom (DOF) head was designed to physically map user's head rotational motion at the remote place. HD stereo cameras and binaural microphones are used to enable bidirectional visual and auditory communication to the user from robot side. The robot provides to the remote participants user's video and voice using a LCD display and a speaker mounted on the front side of the robot. The robot also contains a pico projector to display user's hands projection.The robot designed with fully wireless and mobile platform that allows free motion in remote places.

Table 1 summarizes the current setup for the cameras and projector in the robot side, as well as user's HMD and IR camera. Because its not always possible to maintain the same FoV for all the components, image size correction needs to take place. Further details about correction method will follow in the next sections.

The captured Hands movement and visuals are used to provide visual feedback to user's side, as well as to be projected in the robot's side. The user observe his own hands motion over robot's vision. To present user's hands in the remote place, the captured egocentric images are first segmented to isolate the hands from the background, then superimposed on the visual stream from the robot side, so the user can have visual awareness of his hands presence. The position and size of the captured hands are preserved in the FPV with his real hands, so the pointing remains natural. In the robot side, Those hands are sent and projected using the pico projector. The projected hands serves as a shadow of user's hands which follows its motion and gestures.

Table 1: *Robot/IR Cameras, HMD, and Projector's FoV and Resolution*

	Horizontal FoV	Resolution
HMD	100°	1920x1080
Robot Camera	75°	1280x720 (per eye)
IR Camera	135°	640x240 (per eye)
Pico Projector	45°	1280x720

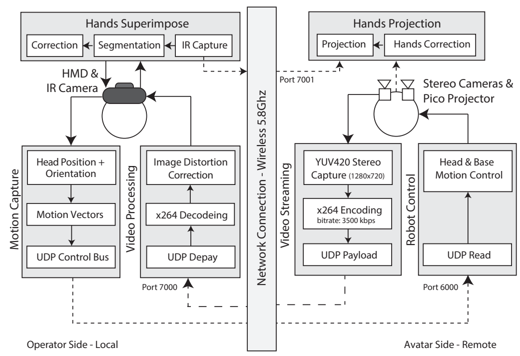

Figure 4: *System data flow diagram. Main components of Mutual Telexistence System.*

The overall data flow and main components of the system are described in Figure 4. Stereo images are captured from the robot side, stitched to one image and encoded together on a single stream. This is important to ensure the synchronization between both eyes even if some frames dropped depending on network's reliability. The stream is encoded using H264 video encoder with a bit-rate of 3500 kilobits per second (kbps). The video stream is sent over a UDP channel to the user side. On the user's side, video stream is decoded and visually corrected to match HMD's Field of view (Fov), then displayed inside the HMD. For media encoding and encapsulation, we used an open source library "GStreamer 1.0".

For hands displaying and projection, the hands are captured from user's FPV, and processed locally to be displayed over the remote images. Also those images are sent to the remote side using H264 encoding (similar to the previous). The robot side handles those images, and correct the size and distortion of the images, and project them using the pico projector. Further details will follow in the next subsections.

4.2. User's Side Overview

4.2.1. Hands Capturing and Segmentation

In the user side, the hands are captured using an IR camera mounted on the front of the HMD. The camera provides 110°field of view which covers HMD FoV, and thus it is possible to capture user hands with no cropped areas. Though the resolution of the cameras are relatively low (640x240), up sampling step is necessary to smooth out the edges. The advantages of using IR camera compared with RGB camera is the possibility to capture objects close to the camera using the returned intensity, in our case we capture hand visuals effectively. However there is a resulting noise from the background. We apply a nonlinear filtering function on the captured images, this function removes the pixels which color intensity are below a certain threshold:

$$Filter(P) = \begin{cases} P^{\frac{1}{Gamma}}, & \text{if } P^{\frac{1}{Gamma}} \geq threshold \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

$$P \in [0,1]$$

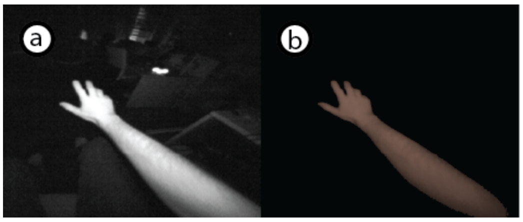

Figure 5: *Captured hands IR images before (a) and after (b) applying the filter.*

The procedure of applying the filter is implemented in the GPU using shader language. The results of applying the filter can be seen in Figure 5.

4.2.2. Avatar Robot Motion Control

To enable the motion in the remote place, the control mechanism should avoid any explicit controllers. A hand-free control was implemented to fulfill this condition using body as a joystick. The user controls robot motion by leaning or rotating his body to move forward or rotate to left and right. Figure 6 outlines the motion vectors relative to user's head.

User's motion is captured using Oculus DK2 tracker, which outputs 3D position H_{pos} and head Euler angles H_{ang}. When the user connects to the robot, H_{pos} and head panning values are calibrated to zero. While connected, H_{ang} directly controls robot's head angles (Tilt, Pan, Roll), so the user head rotation is mapped 1:1 with robot's head.

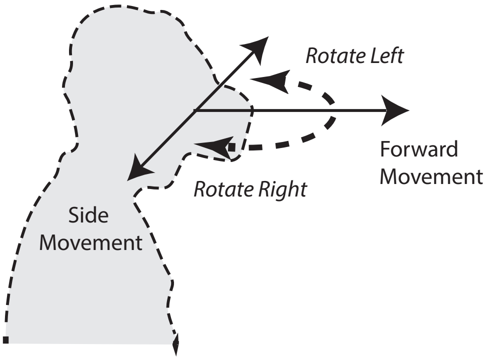

Figure 6: *Body as a joystick for motion control.*

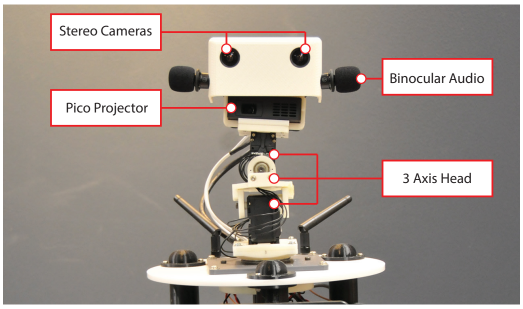

Figure 7: *Top/Side views of camera/projector FoV and projection size.*

4.3. Avatar Robot Overview

4.3.1. Head Design

Robot's head provide the user spatial mapping using a 3 DOF part to control (Roll,Pan,Tilt) rotation based on user's head movement. High torque servo motors used in this design (Model No: HerkuleX DRS-0201). Visual mapping is done using stereo HD cameras (Model No: See3CAM CU130) with a fixed interpupillary distance (65mm). The camera outputs images at resolution 1280x720@50 Frames per seconds (FPS) using YUV420 format. To provide egocentric images of user's body into robot side, a pico projector (Model No: Lumex Beampod MX-65) is used to project user's hands remotely. The projector is aligned with the eyes movement so the relative distance between eyes-hands remains the same as in the user. Head components alignment can be seen in Figure 7.

4.3.2. Projector Calibration

Due to the displacement between the projector position and the camera position in the robot side, and the difference between both fields of view, the projection of the hands directly will result mismatch scale and position when observed by the operator from the FPV. Thus it is necessary to measure this displacement and scale by calibrating the projector with respect to one of the cameras. The goal of the calibration process is to determine the amount of displacement (dx,dy) between the projected image and camera's captured region. Also to extract the relative scale between the projected image and the field of view of the camera (Rw,Rh). This process is done at a projection distance (D). Figure 8 shows an illustration of the top and side views of calibration setup. The parameters (Wp,Hp), (Wc,Hc) represents the size of projection and capture for the projector and the camera respectively. An automated process is done to extract those parameters by projecting a chessboard image into a specific distance (D) which is set to 100 cm as representation of hands reach. The relative scale of the projected images (Rw,Rh) is calculated as the ratio between (Wp,Hp) and (Wc,Hc). This ratio is used as a cropping factor for the projected hands, and the displacement (dx,dy) is used to shift the cropping region of hands images.

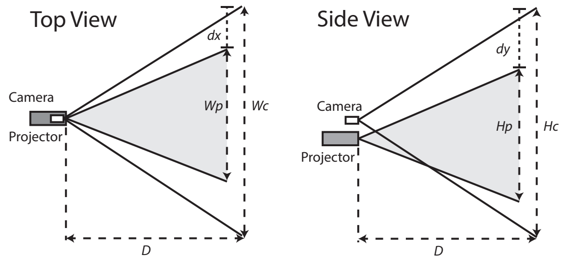

Figure 8: *Top/Side views of camera/projector FoV and projection size.*

This calibration gives matching results for images projected at the calibrated distance (D). However it is affected when the images are projected at different plane, resulting mismatching size and shift of hands position. This behavior is intended as a shadow of the hands, so even though the user can see the projected hands, he still understands this acts as a precise pointing interface in the remote place.

4.4. Hands Presentation

4.4.1. Presenting to User

The processed hands are used locally in the user side by superimposing them over the remote visuals of the robot side. By doing this, the user remains aware of his body though there is no physical representation in the remote side. Also, since the hands are image-based captured from his FPV, the user knows that the presented hands are his own, thus preserving his body ownership sensation. Figure 9 shows what the user sees from his FPV when he uses his hands.

Since of the captured images FoV can be different from HMD's FoV (depending on IR camera's FoV), hands size will be different from the size of our observed real hands.

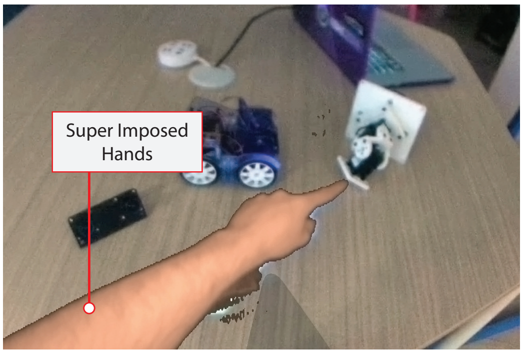

Figure 9: *User's hands being super imposed locally.*

This would results the user to fail to determine the visual distance of his hands. To correct this distortion, simple trigonometry is used to calculate the scaling factor:

$$HandScale = \frac{\tan\left(\frac{FoV_{IR}}{2}\right)}{\tan\left(\frac{FoV_{HMD}}{2}\right)} \tag{2}$$

Because of the hands are being captured, processed, and superimposed locally, the speed of interaction of the hands is not affected by any network delays or packet drops. For example, when latency occurs from robot side (mechanical or visual stream), the user would remain able to see his hands follows his body regardless of the robot side. This helped to reduce the sense of time delay and visual sickness when the network become unstable for some reason.

4.4.2. Presenting to remote participants

User hand images are streamed remotely to robot side, and are projected from robot's point of view using a pico projector mounted on its head. Those hands are aligned with user hands position and motion, and allows the remote participants to see the gesture of his hands. Figure 10 shows the hands being projected on a trivial surface, where user hand gesture can be seen remotely. Depending on projector's lumens, the hands might be difficult to see in a well lit room. In the current implementation, we are using a 65 lumen projector to render the hands.

4.5. Technical Evaluation

Evaluating the speed of transmission in any telexistence system is necessary to be known before conducting user evaluation for it. The two main concerns regarding the latency are: body perception latency, and remote visual feedback latency. Those two factors are necessary to be minimized to an acceptable level. âĂIJAcceptable levelâĂİ has two cases, one for each of the previous:

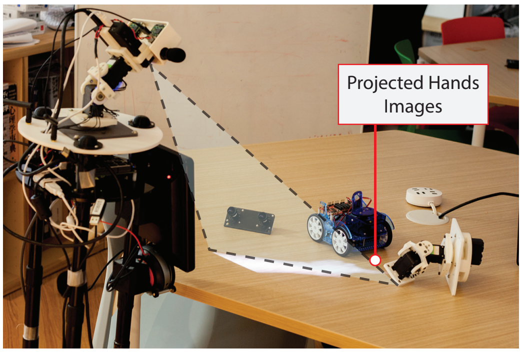

Figure 10: *Illustration of the projected hands into a physical table at robot's side.*

- The first factor related to body perception affects user's kinaesthesia, which is the awareness of his body position in respect to the motion. When user experience latency towards the presented body, the level of presence is reduced accordingly.
- Visual feedback latency mainly affects the operation efficiency of the robot (navigating for example), and also the motion sickness the user would experience if the visual feedback did not match his motion head motion.

For body perception related latency, the processing of body and hands visuals are entirely done locally, no network is involved in this process. The measured speed of capturing the hands images, filtering them and rendering them is within the range 15-20ms (60-50 FPS).

Regarding visual feedback latency, the video stream from the robot to user is passed over IP network, so process of encoding, payloading over network, and decoding the images will add significant overhead. In an ideal system, latency does not exceed one frame (15ms) however due to encoder's requirements, extra frames are needed to do encoding. H264 video encoder is used in this system which handles image size 1280x720@60FPS at bitrate 3500 kbps. The measured Capture-to-Display (CTD) latency was 100±20ms.

5. Conclusion

In this paper, we proposed a mutual Telexistence mobile system which uses virtual projection of egocentric body visuals into local and remote sides. The user maintains the sense of ownership of his body while operating in a different location by superimposing his FPV body visuals on top of remote environment's visuals. Body visuals are also presented remotely by projecting the captured egocentric images into remote space using a pico projector mounted on robot's head. To provide spatial mobility in the remote place, we designed and developed a lightweight Telexistence platform with a 3 DOF head and mobile base. The user controls robot's navigation and speed using his body motion by leaning or rotating, no tangible controllers were used. The robot communicates with the user over an IP network, and a low-latency video stream from robot side is sent to the user over this network. Using this method, it is possible for the participants to understand where the user is pointing at or what the user is intended to do with his hands in the remote environment.

6. Acknowledgement

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