Grasping Temperature: Thermal Feedback in VR Robot Teleoperation

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ABSTRACT

This paper presents a proof-of-concept of a robotic teleoperation system, that provides the human operator a thermal sense in addition to the visual sense. With a sensor suite comprising a stereo camera, 360° camera and long-wave infra-red camera, our demonstrator pushes the boundaries of virtual-reality situational awareness by bringing not only 3D visual content but also a 360° thermal experience to the operator. The visual channel of our robotic teleoperation system is represented through a head-mounted-display and the thermal channel is displayed through directional heaters in the operator cockpit and a thermal glove. Initial tests showed that an operator successfully experienced a 360° remote environment, correctly distinguished between and interacted with hot and cold objects, and could notice the presence of nearby people outside her direct field-of-view, based on their emitted heat.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; *Haptic devices*; • **Computer systems organization** → Robotic control.

KEYWORDS

Teleoperation, Robotics, Virtual-reality, Thermal-feedback

ACM Reference Format:
Leonor Fermoselle, Alexander Toet, Nirul Hoeba, Jeanine van Bruggen, Nanda van der Stap, Frank B. ter Haar, and Jan van Erp. 2022. Grasping Temperature: Thermal Feedback in VR Robot Teleoperation. In *ACM International Conference on Interactive Media Experiences (IMX '22), June 22–24, 2022, Aveiro, JB, Portugal*. ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3505284.3532969

IMX '22, June 22–24, 2022, Aveiro, JB, Portugal

ACM ISBN 978-1-4503-9212-9/22/06.
https://doi.org/10.1145/3505284.3532969

1 INTRODUCTION

Robot teleoperation refers to systems where the human operator remotely controls a robot to perform certain tasks [13]. It aims to replicate the human senses and physical or social skills over an arbitrary distance to a remote location in an intuitive and transparent way [23]. Applications of telerobotics range from operations in environments that are hazardous or inaccessible for humans such as industrial environments or disaster scenes [13], to home care for elderly [12]. Initial studies have shown that teleoperated robots are also promising tools for mediated social communication [15], [19].

Virtual-reality (VR) is a promising approach within which operators can experience the robotic environment as it offers the operator the opportunity of feeling telepresent in the scene [2], by rendering media in a higher dimensionality than those of 2D displays. Another advantage of using VR as a mediating control layer is the possibility of integrating modalities other than audio and video. Based on the media richness theory [5], it is likely that the perceived quality of a mediated experience will increase with the number of sensory channels that are stimulated [3, 4].

Apart from vision and audition, touch is our primary sensory channel. We use touch to interact, explore and understand our environment. Touch serves to identify and discriminate objects, materials or properties and also contributes to affective experiences. Recent studies have shown that the addition of haptics-enabled interfaces to VR/AR telerobotic systems can significantly enhance the operator's sense of telepresence, by making the interaction with the remote environment and the people in it feel more natural [7]. Similarly, enabling operators to feel the thermal properties of the environment and objects in VR/AR through thermo-haptic and thermo-sensing devices may be particularly effective, not only for natural social interactions, but also for better situational awareness and task performance [14]. For example, in the context of remote robot-assisted care, the correct perception of object temperature is relevant when handing a patient a hot drink, and in a remote emergency response scenario a sense of ambient temperature can help to locate fires.

Given the promising results of the use of teleoperated robots for mediated social communication [15, 19], we expect that extending a VR-based teleoperated robotic platform with thermal sensing capabilities will enhance its value for the operator's social communication, task performance and situational awareness [5, 6].

In this paper we present our ongoing efforts towards adding thermal modality to a robotic teleoperated system, where a remote operator can perceive ambient and object surface temperature alongside with 360° and stereo video.

2 RELATED WORK

Recently, a number of systems have been proposed that can enhance the thermal awareness of end-users about their environment. The main approaches that can be distinguished are (1) seamlessly overlaying live thermal imagery from infrared sensors on (simulated or real-world) visual scenes, and (2) the use of thermo-display devices to render the temperature distribution in real and virtual environments. Both approaches serve to raise the operator's awareness of the state of the represented environment and the objects therein.

A visual overlay of thermal information over a visual scene has several practical applications. Using AR in computer-assisted assembly manufacturing, the projection of thermal information registered to the 3D representation of industrial components enables workers to assess whether variations in surface temperature are within nominal values [1]. Using a VR simulation, it was recently shown how blending infra-red information (radiated heat) into our visually perceived environment may help to detect and locate phenomena and object properties in our daily environment that are otherwise invisible to the human eye, such as heat leaks, hidden stove pipes, etc. [22].

The display of thermal information in addition to visual imagery may enhance the user's sense of immersion and realism in VR/AR [14]. Various systems that provide users a sense of touch in VR/AR are already commercially available. Thermo-sensing and thermo-haptic devices that can sense and render the temperature distribution of remote objects and environments are also becoming increasingly available. A recent study used a wireless thermal display glove, with flexible actuators capable of rendering hot and cold temperatures, to present participants with thermal information about objects in a simulated 2D environment [10]. When interacting with virtual objects in the screen, the participants experienced the simulation as significantly more realistic when thermal feedback was provided even though the visual input relied on a 2D screen.

3 MULTIMODAL ROBOT TELEOPERATION DEMONSTRATOR

In this paper we present a prototype of a VR teleoperated robotic system. The operator perceives the robot's environment through a mediating VR control layer that integrates 360° view, stereo vision and thermal feedback. Heat emitted by objects in the robot's environment is displayed (1) as a thermal overlay on the visual scene, (2) on the operator's hand through a thermal glove and (3) through infrared heating panels in the walls of the operator station. Our main contribution lies in the addition of a thermal modality, perceived while teleoperating the robot.

The architecture of our demonstrator is illustrated in figure 1. The hardware setup of our demonstrator has the robot side sensor suite connected to a laptop computer running Windows 10, with NVIDIA GeForce RTX 2080 Super Max-Q graphics card, Intel® Core™ i9 processor and 32GB RAM, that is responsible for processing and transmitting the captured data. The operator can view the remote environment by wearing a HTC Vive Pro Eye VR head-mounted-display (HMD), which is connected to the rendering computer running Windows 10, with NVIDIA GeForce RTX 3080 graphics card, Intel® Core™ i9 processor and 64GB RAM. The thermal modality is rendered on the operator's hand through ThermoReal® glove, a temperature haptic feedback device from TegWay [21] (referred to as thermal glove), and through the universal control-pod from Sensiks [18] (referred to as POD) with the heaters. The thermal glove is connected to the rendering computer via Bluetooth, and the POD through a usb-connection.

When touching a hot object with his/her hand in VR, the operator perceives its temperature, besides its 3D visual representation. Also, the heat emitted by a person who walks by in the vicinity of the remote robot is displayed through the directional heaters installed inside the POD, thus providing the operator with additional situational awareness about the presence and location of a moving heat-emitting object in the robot's immediate environment (even when outside the operator's direct field-of-view). The steps to achieve this are described further in this section.

3.1 Robot side

The robot's environment is essentially represented by its sensor suite, illustrated in figure 2 which consists of three different sensors placed in a fixed frame structure.

A Zed2i stereo camera from StereoLabs [9] is used to capture stereo color images giving the feeling of depth to the operator, necessary to manipulate objects in VR. For a live representation of the robot's environment, we rely on a 360° camera Theta Ricoh Z1 [11]. Finally, for the detection of object temperatures, we rely on a long-wave infra-red (LWIR) camera A655sc from FLIR [8], with a 45° field-of-view lens.

Our demonstrator for robot teleoperation was designed for implementation on two robots: EVE from Halodi robotics [17], and ALMA from ETH Zurich [24]. However, for the purpose of our proof-of-concept, the integration of the entire sensor suite in both robots is not relevant. In the future, the robot viewing direction will be linked to the operator head direction.

3.2 Sensor feed processing and transmission

The data streams from the three sensors are used simultaneously in different processes. The transmission of these data streams to the VR rendering computer, together with the results of the following processing modules, is performed through a custom-made, shared memory block named Remote Data Access (RDA). This module,

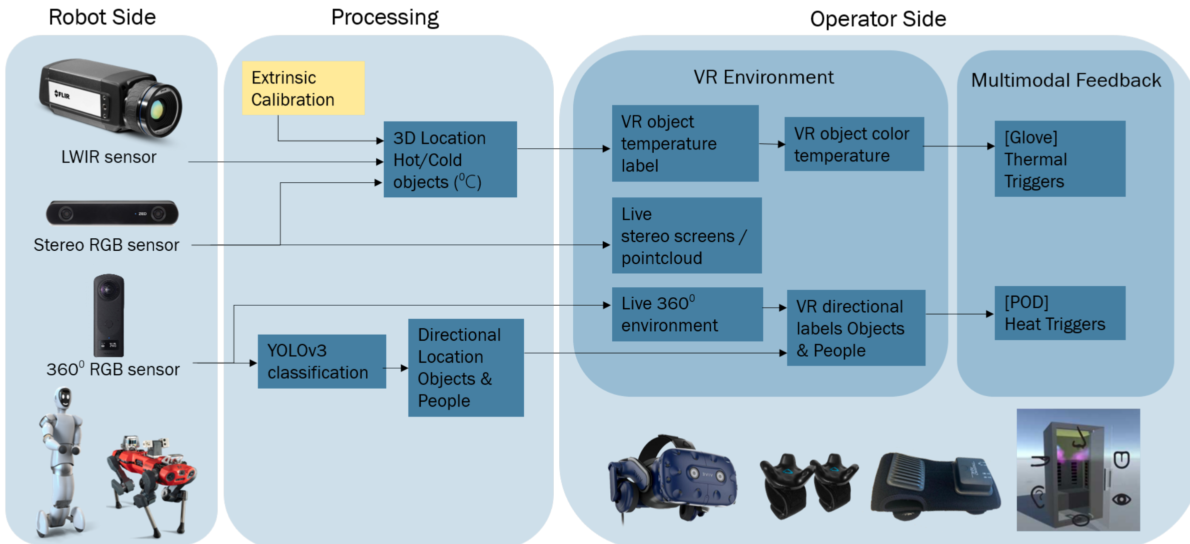

Figure 1: System architecture diagram. The robot side is represented by its sensor suite and the operator side by the different rendering modalities.

implemented as a cyclic buffer, can be viewed as a data-bridge between the robot side and the operator side, and is responsible for the data transmission between the two computers (robot and operator) on the same network.

3.2.1 Sensor calibration. Prior to live processing and streaming, a spatial registration between the LWIR sensor and the stereo sensor is performed. This calibration is a one-time offline procedure, represented in the system architecture figure 1 as a yellow block. A homography matrix that registers the LWIR and stereo sensor (left camera) is estimated from 6 corresponding points in both image, indicated by a human. This matrix is applied to wrap the LWIR

Figure 2: Fixed frame sensor suite including long-wave infrared sensor with 45° lens from FLIR, 360° Theta Ricoh Z1 camera from Ricoh, and stereo camera Zed2i from StereoLabs

image feed in realtime (see figure 3) to the stereo sensor coordinate frame.

3.2.2 3D Temperature detection. This process is responsible for the detection and 3D localization of relatively high and low temperature sources in the robot environment.

The LWIR image stream contains 16-bit per pixel and measures the temperature linearly. From the LWIR sensor's documentation, a conversion from pixel values to degrees Celcius can be obtained. The 16-bit image is thresholded for hot and cold sources according to predefined temperature values (hot objects from 40° C to 150° C, cold objects from -20° C to 15° C). The thresholded areas are considered hot or cold detections if the perimeter of the bounding-box around them is larger than 15 pixels.

Finally, the center pixel of this detection is used to provide the depth value of the hot/cold object. Through the stereo sensor's intrinsic parameters, the center point of the temperature source detection is projected into 3D-space using the classic 3D camera projection equations.

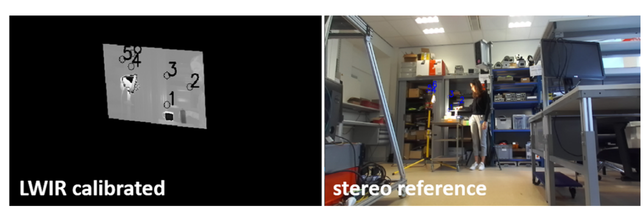

Figure 3: Left: LWIR image warped according to estimated homography matrix, through six correspondences between LWIR and stereo images. Right: Reference left stereo image with the six established correspondences.

Figure 4: Left: Operator sitting inside the Sensiks POD, surrounded with six built-in heaters of which four are visible (black panels), and wearing a virtual-reality head-mounted display and a thermal glove. Right: The operator's hand wearing the ThermoReal glove with a Vive tracker for hand tracking.

3.2.3 Relevant object classification. For enhancing the operator's situational awareness of the remote environment, the 360° sensor stream is fed into a object classification network, YOLOv3 [16].

The detections from the 360° sensor activate the direction-specific ambient heaters installed in the POD. In our demonstrator, only "person" detections are considered to be ambient heat sources. A "person" detection is represented to the operator by activating one or more of the spatial heaters installed in the POD with an angular direction (relative to operator) corresponding to the angular direction of the object (relative to robot).

3.3 Operator side

The operator side of our demonstrator renders the robot's different modalities to the remote operator (visual and thermal), to provide the operator a sense of being present in the remote environment. Figure 4 illustrates the operator setup. The operator sits in the middle of the POD, surrounded by six spatial heaters, and wearing an HMD. For perceiving the temperature of objects in VR, the operator wears a thermal glove on his/her hand coupled with a VR-tracker for hand pose tracking in VR.

3.3.1 Virtual-Reality Environment. The VR environment renders the visual streams to the operator. It was developed with the Unity™ game engine [20], with SteamVR plug-in ensuring the connection between the virtual environment and the VR hardware used by the operator (HMD and VR-tracker). The VR scene contains the live feeds from the 360° sensor projected onto a skybox around the operator, and the stereo camera feed rendered as two stereo-screens (in each of the HMD displays) with an option to toggle between a 3D colored pointcloud, computed with Unity VFX shader (see figure 8). The detections of high and low temperature sources (subsection 3.2.2) are visually rendered in the scene, both with their corresponding temperature values as text-labels and with a color-coded sphere (ranging from blue to red, representing low to high temperatures) overlayed on the rendering of the stereo sensor feed (see figure 7). The object classification results (subsection 3.2.3) are visually rendered as text-labels placed in the corresponding angular direction, within the 360° skybox rendering.

3.3.2 Thermal Rendering. The thermal glove from TegWay is used to render the temperature of VR objects to the operator's hand.

The thermal glove is controlled by bHaptics plug-in. When the operator's VR hand-model, tracked by the VR-tracker on the operator's hand, collides in VR with one of the detected hot/cold objects the thermal glove renders a hot or cold sensation with an intensity corresponding to the temperature label from the detection. The temperature feedback intensity is scaled and adjusted within safe limits to prevent harming the operator.

The built-in heaters in the POD render the ambient heat from the 360° detections (subsection 3.2.3). The POD is controlled through Sensiks proprietary software. The ambient heat is rendered through six directional heaters installed and distributed in the POD which are actuated based on the direction of the heat source detection on the VR environment.

4 TESTS

This section describes some initial tests performed its functionalities and associated feelings of the operator. In response to a personal invitation, two colleagues of the authors volunteered to participate and provided oral consent.

The test setup consisted of a fixed table placed in front of the sensor suite frame with a variety of different temperature objects, illustrated in figure 5. Since we used a fixed sensor suite setup in our demonstrator (figure 2), the table was placed within arm-reach of the operator in VR such that the operator could easily interact with the remote objects in VR. The objects included a construction lamp, generally over 80° C, two visually indistinguishable hot or cold pads, one at room temperature and the other heated up to 80° C, and some beverages, either at room temperature or cooled to 14° C. Furthermore, in order to assess the ambient multi-sensory awareness, one participant volunteered to walk around the setup in the remote room.

Figure 5: Remote test setup containing both hot and cold objects.

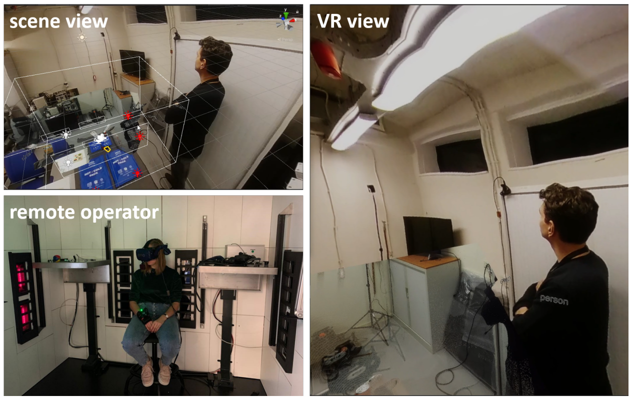

Figure 6: Testing ambient temperature perception with a recipient standing at the left of the robot's sensor suite and the corresponding leftmost POD heater activated. Classification label ('person') is visually rendered in VR

4.1 Remote dynamic temperature perception

Operators viewed the remote environment from a central viewpoint through the live 360° feed presented on the HMD. Objects and people moving real-time had their respective predicted labels rendered next to them, as can be seen in figures 6 and 7, where the labels "person" and "cup" are displayed in VR.

For a preliminary ambient temperature functionality test we associated the predicted class "person" as a source of ambient heat, which triggered the corresponding directional heater inside the POD. Figure 6 shows a situation in which a remote person stood left of the robot's sensor suite. When asked if she could feel any temperature difference, the operator responded "I can feel high-temperature to my left".

This test confirms that the perception of ambient temperature through VR robot teleoperation can enhance multimodal situational awareness, and that it can potentially increase the feeling of telepresence in the remote environment.

4.2 Remote object temperature perception

To how the operator experiences hot and cold objects two cooling-heating pads were used. Since the visual appearance of the pads is independent of their temperature, the operator can only distinguish a hot from a cold pad through thermal rendering in the thermal glove, or through visual overlay of temperature estimate. The visual overlay consisted of a coloured-sphere at the object's location (color-scale related to the temperature), accompanied by a temperature label rendered on top of the sphere, see figure 7. We also investigated the interaction of the operator with hot and cold objects with a remote person handing the robot a cup of hot water (see figure 8).

The operator could distinguish the hot pad from the other pad through visual overlay, and she clearly perceived the hot sensation on the palm of her hand when reaching to touch the pad in VR, making her experience immersive and coherent with her visual input. When the operator reached in VR to grasp the the warm tea cup handed to her, the warm sensation in her hand actually gave her the feeling that she was sharing it with the remote person.

We noted that hot or cold temperature rendering in the thermal glove had no perceivable latency associated, which made grasping and releasing of hot or cold objects in VR feel natural to the operator.

5 DISCUSSION AND FUTURE WORK

In this paper, we describe the design and initial functionality tests of a robotic teleoperation proof-of-concept demonstrator. Our main contribution lies in realizing a teleoperation system where a human operator can perceive thermal information through visual and thermal sensations, to enhance telepresence and situational awareness in social interaction scenarios.

Our system has several technical limitations for being successfully used in social interaction scenarios. To provide the operator a proper sense of immersion and embodiment during robotic teleoperation, the architecture and the its associated sensor suite should be integrated in a robotics system. During the preliminary system functionality tests, the operator reported to have enhanced situational awareness regarding the presence of remote people, both from the visual 360° feed and from the ambient heaters. Moreover, it was clear that the experience of sharing a hot beverage in VR with a

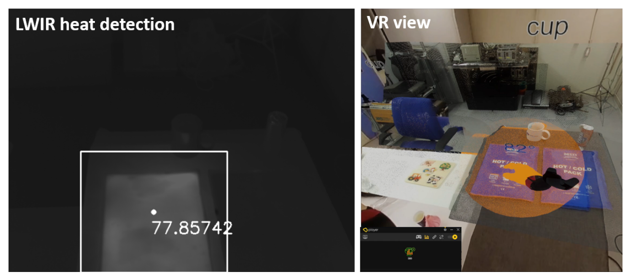

Figure 7: Left: Detection of high-temperature object from LWIR frame. Right: 3D VR rendering of the high-temperature object as a pointcloud from stereo feed, and as a heat-sphere, through LWIR-stereo camera calibration with accurate temperature label display (77°C). Operator's hand is colliding with the sphere in VR to grasp the high-temperature object and the corresponding temperature is rendered through bHaptics interface on ThermoReal glove.

Figure 8: Left: VR operator grasping hot beverage cup with human recipient (visual rendering as pointcloud) and perceiving its temperature. Right: VR grasping a cold beverage from the testing table (visual rendering as stereo screens) perceiving its temperature.

remote human person while perceiving both visual and temperature feedback was quite appreciated by the remote operator.

Both from literature and from our preliminary system tests, we are confident that the addition of a thermal modality to robotic teleoperation systems will positively influence and enhance the operator performance and experience. Future user studies should be performed to assess the feelings of telepresence, embodiment and situational awareness which our demonstrator can elicit. With this system, we have laid the ground-work for studying the benefits of adding thermal modality to a VR robot teleoperation system for social interactions.

REFERENCES

[1] Jonathan Boisvert, Marc-Antoine Drouin, Guy Godin, and Michel Picard. 2020. Augmented reality, 3D measurement, and thermal imagery for computer-assisted manufacturing. In *Emerging Digital Micromirror Device Based Systems and Applications XII*, Vol. 11294. International Society for Optics and Photonics, SPIE Digital Library, United States, 112940L.

[2] Carlos Coelho, JG Tichon, Trevor J Hine, GM Wallis, and Giuseppe Riva. 2006. Media presence and inner presence: the sense of presence in virtual reality technologies. In *From communication to presence: Cognition, emotions and culture towards the ultimate communicative experience*. IOS Press, Amsterdam, Amsterdam, Netherlands, 25–45.

[3] I. Comsa, R. Trestian, and G. Ghinea. 2018. 360° Mulsemedia experience over next generation wireless networks - A reinforcement learning approach. In *2018 Tenth International Conference on Quality of Multimedia Experience (QoMEX)*. IEEE, United States, 1–6. https://doi.org/10.1109/QoMEX.2018.8463409

[4] I. Comşa, E. B. Saleme, A. Covaci, G. M. Assres, R. Trestian, C. A. S. Santos, and G. Ghinea. 2020. Do I Smell Coffee? The Tale of a 360° Mulsemedia Experience. *IEEE MultiMedia* 27, 1 (2020), 27–36. https://doi.org/10.1109/MMUL.2019.2954405

[5] Richard L. Daft and Robert H. Lengel. 1986. Organizational information requirements, media richness and structural design. *Management Science* 32, 5 (1986), 554–571. https://doi.org/10.1287/mnsc.32.5.554

[6] Richard L Daft, Robert H Lengel, and Linda Klebe Trevino. 1987. Message equivocality, media selection, and manager performance: Implications for information systems. *MIS quarterly* 11 (1987), 355–366.

[7] Leonor Fermoselle, Simon Gunkel, Frank ter ter Haar, Sylvie Dijkstra-Soudarissanane, Alexander Toet, Omar Niamut, and Nanda van van der Stap. 2020. Let's Get in Touch! Adding Haptics to Social VR. In *ACM International Conference on Interactive Media Experiences*. ACM, New York, NY, USA, 174–179.

[8] FLIR. 2022. FLIR A655sc High-Resolution Science Grade LWIR Camera. https://www.flir.eu/products/a655sc/ Accessed: 2022-03-09.

[9] Stereolabs Inc. 2022. ZED 2i - Industrial AI Stereo Camera. https://www.stereolabs.com/zed-2i/ Accessed: 2022-03-09.

[10] Seung-Won Kim, Sung Hee Kim, Choong Sun Kim, Kyoungsoo Yi, Jun-Sik Kim, Byung Jin Cho, and Youngsu Cha. 2020. Thermal display glove for interacting with virtual reality. *Scientific Reports* 10, 1 (2020), 1–12.

[11] Ricoh Company Ltd. 2022. Ricoh Theta Z1. https://theta360.com/en/about/theta/z1.html Accessed: 2022-03-09.

[12] Honghao Lv, Geng Yang, Huiying Zhou, Xiaoyan Huang, Huayong Yang, and Zhibo Pang. 2020. Teleoperation of collaborative robot for remote dementia care in home environments. *IEEE Journal of Translational Engineering in Health and Medicine* 8 (2020), 1–10. https://doi.org/10.1109/JTEHM.2020.3002384

[13] Günter Niemeyer, Carsten Preusche, Stefano Stramigioli, and Dongjun Lee. 2016. *Telerobotics*. Springer International Publishing, Cham, Switzerland, 1085–1108. https://doi.org/10.1007/978-3-319-32552-1_43

[14] Kaushik Parida, Hyunwoo Bark, and Pooi See Lee. 2021. Emerging thermal technology enabled augmented reality. *Advanced Functional Materials* 31, 39 (2021), 2007952.

[15] Denis Peña and Fumihide Tanaka. 2020. Human perception of social robot's emotional states via facial and thermal expressions. *ACM Transactions on Human-Robot Interaction* 9, 4 (2020), Article 26. https://doi.org/10.1145/3388469

[16] Joseph Redmon and Ali Farhadi. 2018. YOLOv3: An Incremental Improvement.

[17] Halodi Robotics. 2022. Eve Robot. https://www.halodi.com/ Accessed: 2022-03-09.

[18] Sensiks. 2022. Sensiks Sensory Reality Pods & Platform. https://www.sensiks.com Accessed: 2022-03-09.

[19] Kazuaki Tanaka, Hideyuki Nakanishi, and Hiroshi Ishiguro. 2015. Physical embodiment can produce robot operator's pseudo presence. *Frontiers in ICT* 2, 8 (2015), 1–12. https://doi.org/10.3389/fict.2015.00008

[20] Unity Technologies. 2022. Unity Real-time Development Platform. https://unity.com/ Accessed: 2022-03-09.

[21] TEGway. 2022. ThermoReal, TEGway. http://tegway.co/tegway/ Accessed: 2022-03-09.

[22] ©FLIR. 2018. Try the FLIR Virtual Reality Experience! https://www.flir.in/news-center/corporate-news/try-the-flir-virtual-reality-experience/ Accessed: 2021-08-03.

[23] Alexander Toet, Irene A. Kuling, Bouke N. Krom, and Jan B. F. van Erp. 2020. Toward enhanced teleoperation through embodiment. *Frontiers in Robotics and AI* 7, 14 (2020), 1–22. https://doi.org/10.3389/frobt.2020.00014

[24] ETH Zurich. 2022. ALMA - Robotic Systems Lab, ETH Zurich. https://rsl.ethz.ch/robots-media/alma.html Accessed: 2022-03-09.