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Intuitive Virtual Reality Human-Robot Interface with Volumetric Tele-presence, Visual Haptics and Audio

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I. Introduction

Teleoperation provides the ability for a user to operate a robot in remote locations; it enables interactions with the robot's environment and the ability to perform physical tasks [1]. During teleoperation, the operator's efficiency and performance are susceptible to various factors such as limited network bandwidth, time lags, frame rates, lack of perception, frame of reference, two-dimensional views, attention switches, and motion effects [2]. Thus, the interface between the user and the robot plays a crucial role in the teleoperation.

Virtual Reality (VR) teleoperation is increasingly being used within industries such as nuclear decommissioning [3], robotic construction [4] and space robotics [5] due to the potential for offering greater situational awareness, accurate sense of depth and multiple viewing orientations for complex physical operations [6].

Advanced Mechanics Assistance System (AMAS) from **Extend Robotics** is a special VR based commercially available interface that can be used to connect and operate physical robots using intuitive gestures. It provides 3D perception of physical robot's environment. This VR-based human robot interface (HRI) software allows non-robotic experts to intuitively teleoperate or tele-program the robot over a network (local or global). This interface utilizes commercial off the shelf VR equipment instead of custom hardwares required in traditional teleoperation solution. AMAS system creates a 3D virtual world from the 3D sensors data located in the remote robot location. The 3D information is streamed and rendered in realtime. This reduces the task load for the operator compared to traditional 2D interfaces [7].

II. AMAS System Design

The AMAS system architecture and data flow is presented in Figure 2. AMAS system includes following sub-systems to provide the real time control, manipulation capabilities, 3D telepresence and bidirectional audio communication.

A. AMAS VR App

The AMAS VR app is the HRI software which renders the VR environment using consumer grade VR headsets. The AMAS VR app supports both Oculus (Standalone or PC version) and HTC Vive VR Head Mounted Devices (HMD) and uses OpenXR for the backend processing of the inputs from the VR hand controllers.

Key features of the AMAS VR App:

- **Volumetric Telepresence**, achieved by providing real-time reconstruction of the remote workspace, rendered using 3D textured volumetric data typically captured by RGB-D acquisition devices/sensors.
- **Interactive Digital Twin**, renders interactable 3D holographic digital twin of supported robot arm overlaid onto the real arm visualization rendered from captured 3D data. The manipulation of the real arm is done using the interaction of digital twin with the VR hand controller.
- **Tele-programming**, allows programming a robot remotely using AMAS VR app by recording the users motion while performing a task in the VR environment. The recorded motion may be replayed in a loop such that the robot performs the exact same task repeatedly.
- **Visual Haptics**, AMAS uses a displacement based visual representation to indicate 3-axis force and 3-axis torque at the end effector of the robot arm. The visualisation uses a reference object showing zero force and torque, and another object which displaces and rotates based on the force and torque.

Visual haptics, audio feedback and other experimental features impact on user experience is currently under evaluation. An example of the current AMAS app is shown in Figure 1, highlighting the immersive 3D perception, digital twin as well as experimental features.

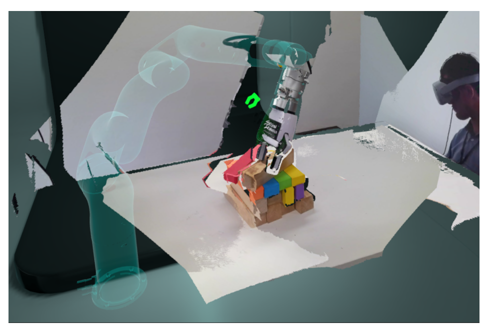

Fig. 1. View of the AMAS VR App performing teleoperation with the Digital Twin, Volumetric Rendering from 2 SenseKits and Visual Haptics

B. RoboKit

RoboKit is the peripheral computing device used for the control of the robot. AMAS VR app sends target pose for the end effector and any other additional target link of the robot. RoboKit computes the Inverse Kinematics in real time, enabling real time manipulation of the robot.

Robokit contains the drivers for the robot. It sends trajectory or velocity commands to execute the motion. It receives the robot's state and error alerts. This feedback is shared with the AMAS VR app. RoboKit also has various safety

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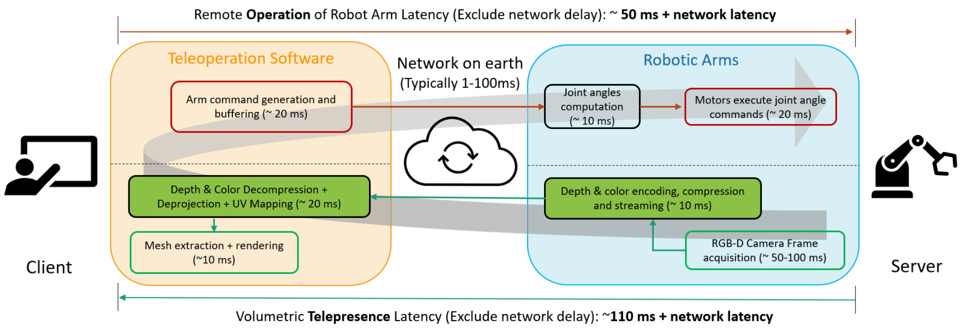

Fig. 2. AMAS System Architecture and Data Flow Diagram

protocols implemented to prevent any random or sudden motion of the robot and minimize risks during teleoperation.

C. SenseKit

SenseKit is the peripheral computing device with a 3D sensor which facilitates the realtime Volumetric Telepresence in the AMAS VR app. SenseKit perceives the remote environment of the robot, encodes and sends the volumetric data. Data includes compressed depth, RGB and mathematical models of the sensors. AMAS VR app receives the data, decodes and renders in the VR environment. The key features of the SenseKit are:

- **Statistically Lossless Depth Compression** provides real-time compression of depth data exploiting the accuracy-range curve of the sensor.
- **Hardware Accelerated RGB Compression** leverages hardware support for industry standard video compression providing low latency, bandwidth and quality
- **Low Latency** <150 ms glass-to-glass delay 3D volumetric streaming independent from HMD motion update
- **Low Bandwidth** requires 20Mbps for streaming 1280x720 RGB and 640x576 depth 3D data at 30 Hz.

D. AudioKit

AudioKit is a software which enables low-latency and low bandwidth bidirectional audio communication between operator and robot. Typically 100 kb/s order bandwidth per link (uplink/downlink) is used.

AudioKit is based on industry standard Real-time Transport Protocol (RTP) / Real Time Streaming Protocol (RTSP). It benefits from open, royalty-free and versatile OPUS Codec applicable from narrowband to fullband stereo scenarios.

AudioKit may be used as a standalone module using a peripheral computing device connected to a speaker and a microphone, or may be part of the SenseKit when using 3D camera with either microphone or speaker or both.

The AMAS system helps in mitigating communication latency and bandwidth limitations in the following ways:

- The Digital Twin of the robot performs local simulation in parallel at low latency (< 20 ms) independent from the streaming, control and network latency (round trip motion-to-motion latency < 150 ms). This reduces the impact of latency by allowing user to observe the motion the arm would make.
- The 3D volumetric streaming allows local rendering of 3D object with typical 100 ms order glass-to-glass latency. This is decoupled from the VR headset frame update response to the movement of the headset (Motion-to-photon latency), which could cause motion sickness. The motion-to-photon latency is minimised with local VR rendering and decoupling prevents streaming latency causing motion sickness.
- Depth and RGB resolutions are decoupled in the 3D data streaming and visualization pipelines supporting limited bandwidth scenarios.
- Dropping the noise component from the data helps in efficient compression which saves the bandwidth.

III. Conclusion

This work summarises the key features and benefits along with primary components and processes of the state-of-the-art VR teleoperation system AMAS by Extend Robotics.

The AMAS system has the potential to enable remote operation in a diverse range of applications. AMAS has been used for the experimental control during Robotic assisted docking in Space environments performed at Surrey University STAR-LAB Orbital Robotics Testbed facilities [8], shown in Figure 3. The AMAS system achieved improved reliability and flexibility with a 95 % success rate.

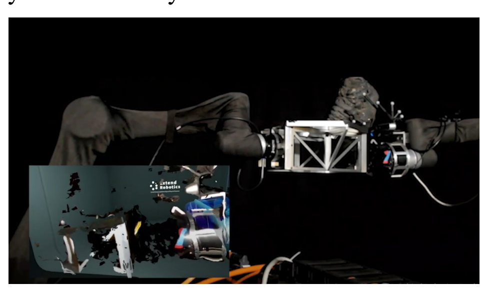

Fig. 3. AMAS system being used to perform satellite docking

Other applications for the AMAS system revolve around hazardous environments such as nuclear decommissioning, explosive ordinance disposal and construction to reduce risk to operator safety [9] and provides cost savings by reducing travel and in-person human intervention, creating opportunities in logistics, manufacturing, offshore maintenance, etc.

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Appendix I
AMAS Components Interaction Architecture