Toward efficient under-ice exploration of ocean worlds using distributed autonomy and 3D workspace reconstruction presented in VR for intuitive understanding

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Abstract: Exploration of Europa and Enceladus are currently limited to satellite flybys (Greenberg, Hoppa et al. 1999, Matson, Castillo et al. 2007, Soderlund, Schmidt et al. 2013, Iess, Stevenson et al. 2014, Sohl, Solomonidou et al. 2014), but in-situ observation underneath their icy surface would greatly expand our ability to search for life. Semiautonomous exploration using robotic manipulators equipped with in-situ probes such as an X-Ray Fluorescence (XRF) sensor, similar to PIXL onboard Perseverance (Allwood, Hurowitz et al. 2021), could provide us with an understanding of the subsurface chemistry that is currently unobservable. Conventional robotic underwater intervention operations here on Earth require a high-bandwidth, low-latency connection to support direct teleoperation by pilots. However, interplanetary operations convey severe bandwidth constraints and substantial latency that render low-level teleoperation infeasible.

We present a distributed shared autonomy framework that streamlines the planning and execution of robotic manipulation operations by automating motion planning and task execution. Through a virtual reality (VR) interface (Fig. 1), multiple scientists working in parallel can independently identify sites of interest and plan science tasks using a shared 3D scene understanding, then visualize proposed plans to ensure their viability. This allows science teams to consider factors such as reachability, while enabling collaborators to view the proposed motion from different perspectives. Laboratory tests using this framework demonstrate a reduction in the time required for task planning and execution from ~10 minutes (Bowen, Jakuba et al. 2013) to less than 10 seconds.

In September 2021, we demonstrated our framework's ability to enable precision manipulation tasks in the presence of a low-bandwidth, high-latency connection by taking the first-known underwater in-situ XRF measurement collected by a remote scientist. During these demonstrations we were able to parallelize XRF and pushcore sample site selection and trajectory planning, enabling visualization and validation of the pushcore sampling plan while the XRF measurement was still being collected. This approach increased the science sampling plan's operational tempo while minimizing the required bandwidth between the robot and the science team. This framework shows promise for space flight systems requiring under-ice operations on other ocean worlds.

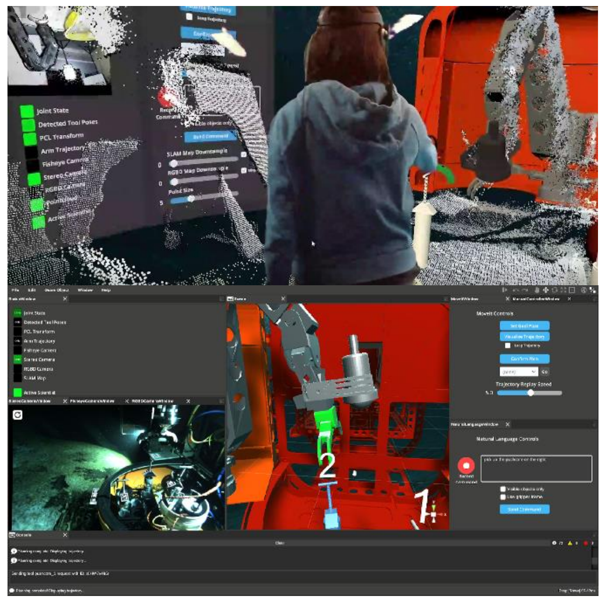

Figure 1: The VR (top) and desktop (bottom) interfaces enabled remote scientists to collect an XRF and pushcore sample during sea trials in September 2021.

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