Shadow-Based Depth Perception with Adaptive Motion Scaling for Safe Teleoperated Retinal Surgery

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INTRODUCTION

Retinal microsurgery demands extreme precision, with tool positioning tolerances often within tens of micrometres to avoid damaging delicate tissue. In teleoperated retinal surgery, network latency and the absence of stereoscopic cues can compromise safety. Surgeons traditionally rely on naturally occurring shadows of instruments on the retina to infer depth when using a microscope. We leverage these shadows to quantitatively estimate tool-retina distance in real time, while integrating latency-aware motion scaling to enhance safety and intuitiveness in long-distance teleoperation.

MATERIALS AND METHODS

A transatlantic teleoperation system was established between a 3D Systems Touch haptic input device in Canada and a custom-built ophthalmic microsurgery robot in Germany (Fig 1). Operator motions were transmitted via a ROS2 connection, with rotational inputs mapped directly and z-axis translation controlled through stylus buttons.

To mitigate overshoot risks under latency, we implemented an adaptive velocity scaling algorithm. The scaling factor was dynamically adjusted based on both measured round-trip delay and real-time tool-to-retina distance, estimated from instrument shadows in the microscope video. When the latency was high or the tool neared the retina, motion slowed smoothly; if thresholds were exceeded, z-motion froze.

A graphical user interface showed live video, network latency, the active z-scaling factor, and a virtual side-view of tool proximity.

We validated the system in a user study where six participants in Edmonton performed retinal puncture tasks on a phantom eye model in Munich under three control modes: unassisted, depth-only scaling, and combined depth-latency scaling.

RESULTS AND DISCUSSION

In a transatlantic user study, six participants performed retinal puncture tasks under three control modes: unassisted, depth-only scaling, and combined depth-latency scaling. The adaptive method (depth-latency scaling) achieved the lowest and most consistent contact forces, significantly reducing overshoots compared to unassisted control. Importantly, while forces increased by approximately 30% under high latency for the other modes, they rose by only 3.4% with our adaptive method (Table 1). This safety improvement was achieved with a deliberate but acceptable increase in task time, reflecting a favourable safety-efficiency trade-off.

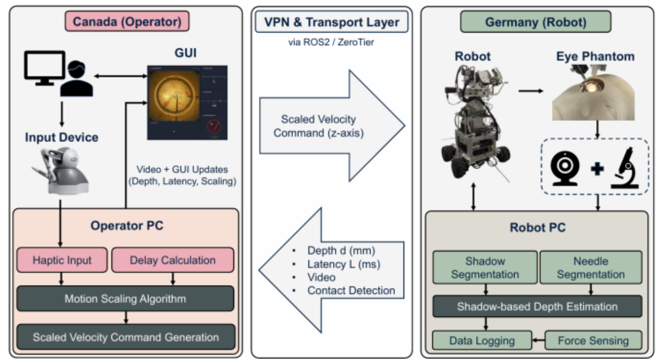

Fig 1 Closed-loop architecture of the teleoperated system.

CONCLUSIONS

We present a teleoperation framework that integrates shadow-based depth estimation with adaptive motion scaling to enhance safety in long-distance retinal surgery. Our transatlantic user study demonstrated that dynamically scaling tool velocity based on both depth and latency significantly reduced excessive contact forces while maintaining intuitive control. This safety improvement comes at the cost of a modest, intentional increase in task time – a trade-off participants valued for the added sense of safety. These results highlight the potential of our approach to enable reliable and clinically viable remote microsurgery.

REFERENCES

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Table 1: MEAN PUNCTUATION FORCE UNDER LOW AND HIGH LATENCY CONDITIONS.

	Low Latency [mN]	High Latency [mN]	*Increase [%]*
Constant Scaling	71.6 ± 17.7	93.7 ± 50.8	*30.8*
Linear Scaling	59.7 ± 15.7	76.5 ± 11.8	*28.2*
Adaptive Scaling	59.9 ± 10.5	61.9 ± 21.6	*3.4*