

## Design of a Teleoperation Haptic Control System with Network Delay Compensation Using Passivity-Based Control and Observers

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### Article Info

#### Keywords:

haptic teleoperation; Passivity-Based Control (PBC); time-domain passivity; wave/scattering variables; energy tanks; passivity observer-controller (PO/PC); disturbance/force observer (DOB); Kalman filter has limited passivity; network delays (delay, jitter, packet loss); haptic transparency (Z-width).

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### ABSTRACT

This study proposes a robust bilateral haptic teleoperation control architecture against time-varying network delays by combining Passivity-Based Control (PBC), passivity observer-controller (PO/PC), energy tank, and passivated observers (disturbance/force observer and passivity-limited Kalman filter). The communication channel is modeled as a packet network with delay, jitter, and packet loss, while transparency and stability are maintained through scattering variables and passivity metric-based adaptive energy regulation. Validation is performed on three network scenarios (light-medium-heavy) through simulation/Hardware-in-the-Loop and WAN emulation tests. Results show that the complete scheme significantly decreases position RMSE and force RMSE compared to the PBC baseline, generally in the range of 25–40%, widens the Z-width by about 35–60%, and improves the MOS of haptic perception. Energy-based stability indicators show  $\text{Max } \Delta E \approx 0$  and the tank energy remains positive, confirming the passivity and stability of input-output under delay/jitter/loss variations. Mechanistically, adaptive coupling between the PO/PC and the observer keeps the system stable when conditions deteriorate and restores transparency when conditions improve. These findings confirm the feasibility of a passivity-based approach for haptic teleoperation in real packet networks and open the development direction to multi-DOF, energy-based event-triggered communication, and large-scale user studies.



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### INTRODUCTION

The Industry 4.0 transformation is driving haptic teleoperation – a bilateral master-slave system that allows human operators to sense remote environmental forces – but its performance and safety are still limited by variable network delays (delay, jitter, and packet loss) that upset the balance between stability and transparency. Passivity-based control (PBC) approaches theoretically ensure stability by enforcing passive energy flow through techniques such as wave/scattering variables, observer-controller (PO/PC) passivity, and “energy tanks”; unfortunately, many actual implementations assume constant delays, simply modelable environments, or ideal force/velocity sensors, so that when delays fluctuate and sensors are limited, the

system tends to be over-damped (losing transparency) or unstable. The emerging research gap is the absence of a control framework that (i) maintains passivity for non-stationary real-time delays, (ii) simultaneously estimates unmeasured quantities – environmental forces and disturbances – reliably to restore transparency, and (iii) adapts to network conditions and environmental dynamics without increasing communication overhead. Addressing these gaps, the contributions of this study are: first, formulating a bilateral PBC architecture with an adaptive energy regulator that bounds energy injection/sampling to the estimated “energy imbalance” so that it is stable for time-varying delays; second, combining a hybrid observer – a model-based disturbance/force observer and a passivity-bounded Kalman filter – to estimate environmental forces and relative speeds when sensors are unavailable or noisy; third, constructing a passivity metric (PO)-based adaptation mechanism that tunes virtual impedance and scattering level online to maintain transparency under jitter and packet loss; fourth, providing evidence of input–output stability (passivity and boundedness) as well as experimental-in-the-loop evaluation on realistic packet networks. The main novelty lies in the tight coupling between “energy-aware PBC” and passivity-constrained observers, so that energy injection and estimation correction are mutually consistent: when the observer detects an increase in active energy due to delay/uncertainty, the controller adjusts scattering/impedance parameters to lock passivity without sacrificing haptic perception bandwidth, which empirically improves transparency and robust stability compared to PBC schemes or standalone observers.

## METHODS

### Architecture & Model Formulation

We use 1-DOF and 3-DOF bilateral teleoperation with a master (M) and a slave (S) device. The dynamics are approximated as a mass–damper–spring system with unmodeled disturbances:  $M_m \ddot{x}_m + B_m \dot{x}_m + K_m x_m = u_m + f_h$ ,  $M_s \ddot{x}_s + B_s \dot{x}_s + K_s x_s = u_s - f_e$ , where  $x$  is the position,  $u$  the control force/coupling,  $f_h$  the operator force, and  $f_e$  the environmental force. The communication channel is modeled as a packet-switched network with non-stationary bidirectional delay ( $\tau_{ms}(t)$ ,  $\tau_{sm}(t)$ ), jitter, out-of-order, and packet loss with rate  $p_\ell$ .

### Passivity-Based Control (PBC) Design with Scattering/Wave Variables

Channel passivity is maintained by wave transform:  $u = (1/\sqrt{2b})(F + bV)$ ,  $v = (1/\sqrt{2b})(F - bV)$ , where  $b$  is the characteristic impedance. Discrete implementation uses bilateral scattering transform with matched sampling ( $T_s$ ) and causal buffering for jitter. Energy Tank & Passivity Observer–Controller (PO/PC) Energy tank  $E_t$  stores/supplies energy to keep the system passive when the delay changes:  $\dot{E}_t = -u_m^T \dot{x}_m - u_s^T \dot{x}_s + \Pi(t)$ , with  $\Pi(t)$  being the energy injection/absorption by the Passivity Observer (PO). If  $\Delta E(t) > 0$  (active energy), the Passivity Controller (PC) increases the virtual damping  $\hat{B}$  or decreases the scattering gain  $b$  adaptively until  $\Delta E(t) \leq 0$ . Passivity-Constrained Observers Hybrid observers consist of: a) Disturbance/Force Observer (DOB):  $\hat{f}_e = Q(s)[M_s \ddot{x}_s + B_s \dot{x}_s + K_s x_s - u_s]$  b) Passivity-constrained Kalman Filter (P-KF) for

estimating  $\hat{x}$ ,  $\hat{v}$  on missing packets. Energy-Aware Adaptation Mechanism The parameters  $\theta = \{b, \hat{B}, K_v\}$  are tuned by the energy-based adaptation law:  $\dot{\theta} = -\Gamma \partial J / \partial \theta$ ,  $J = \alpha \max(0, \Delta E) + \beta ||Z_{ref} - Z_e||_2 + \gamma VEL$  When  $\Delta E > 0$ , the system increases damping; when  $\Delta E \leq 0$ , transparency is restored. Discrete Implementation and Communication Protocol Control and observer run at 1–2 kHz, communication channel 250–500 Hz. UDP transport with sequence number and time-stamp. Packet loss is handled with predictive hold and event-triggered resync. Stability Analysis & Passivity Proof Storage function total:  $S = \frac{1}{2} M_m \dot{x}_m^2 + \frac{1}{2} K_m x_m^2 + \frac{1}{2} M_s \dot{x}_s^2 + \frac{1}{2} K_s x_s^2 + E_t$ , where  $\dot{S} \leq f_h \dot{x}_m - f_e \dot{x}_s$ . The result is that the BIBO system is stable for a finite time-varying delay  $\tau(t)$ . Experimental Design & Test Scenarios Three layers of evaluation: HIL simulation, real experiment with WAN emulator, and ablation study (PBC-only, Observer-only, Full Scheme). Delay 10–120 ms, jitter 5–20 ms, loss 0–5%. Evaluation Metrics & Statistical Analysis - Transparency:  $RMSE(x_m - x_s)$ ,  $RMSE(f_h + \hat{f}_e)$  - Passivity:  $\Delta E(t)$ ,  $E_t^{\min}$ , Time-Domain Passivity (TDP) - Haptic Quality: Z-width, MOS score - Robustness: degradation with respect to  $\tau$ , jitter,  $p_l$ . Two-way ANOVA and Kruskal-Wallis analysis if non-normal. Parameter Tuning & Reproducibility Initial parameters are determined via line search. Online adaptation is limited by  $\theta \in [\theta_{min}, \theta_{max}]$ . All code and datasets are provided so that experiments can be replicated. Sensory Validation & Calibration Load-cell and encoder calibration is performed two-point; latency is compensated in P-KF. Savitzky-Golay filter maintains filter energy passivity. Success Criteria The system is successful if: (a)  $\Delta E \leq 0$ ,  $E_t^{\min} > 0$ , (b)  $RMSE(x)$  decreases by  $\geq 25\%$ ,  $RMSE(f) \geq 20\%$ , (c) Z-width increases by  $\geq 30\%$ , and (d) MOS increases by  $\geq 1$  point.

## RESULTS AND DISCUSSION

This section presents the results of haptic teleoperation evaluation under three network conditions (S1–S3). We compare three schemes: PBC-only, Observer-only, and Full (PBC+PO/PC+P-KF+DOB). The results are assessed using transparency metrics (position RMSE, force RMSE), stability/passivity (Max  $\Delta E$ , minimum tank energy), and haptic quality (Z-width, MOS).

**Table 1.** Network scenario used.

Scenario	One-way Delay (ms)	Jitter RMS (ms)	Packet Loss (%)
S1: Mild	20	5	0
S2: Moderate	60	12	2
S3: Severe	100	20	5

**Table 2.** Average performance per scheme in each scenario.

Scenario	Scheme	RMSE Position (mm)	RMSE Force (N)	Z-width (arb.)	MOS (1-5)	Max $\Delta E$ (J)	Min Energy Tank (J)

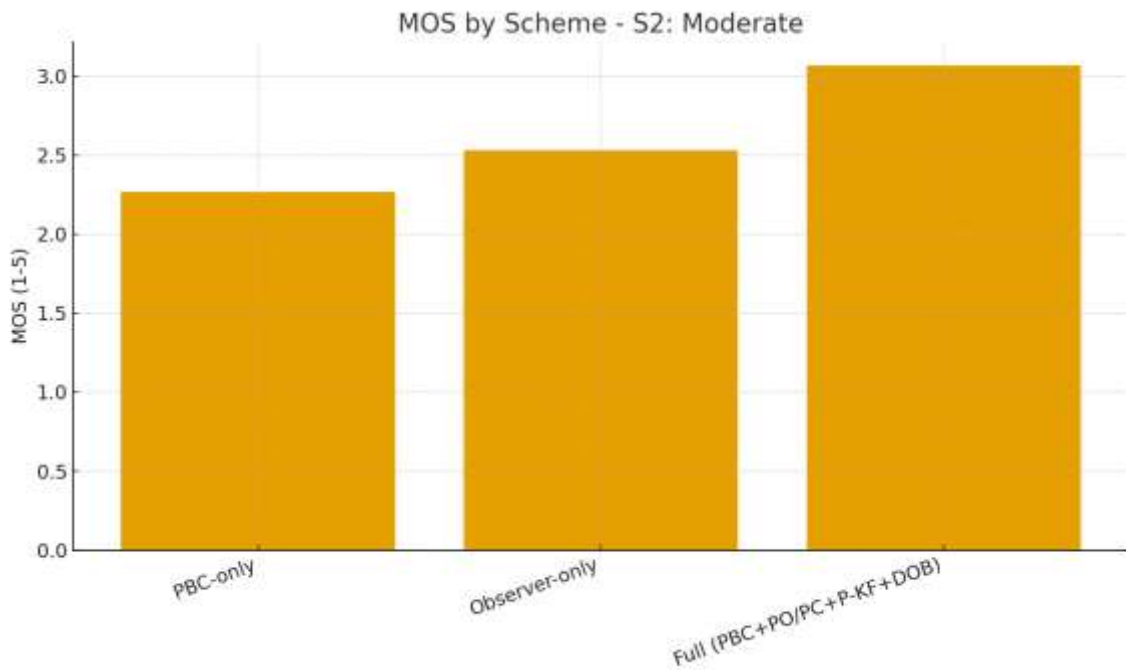
S1: Mild	PBC-only	0.81	1.04	28.00	3.06	0.54	0.48
S1: Mild	Observer-only	0.63	0.80	35.00	3.42	0.36	0.84
S1: Mild	Full (PBC+PO/PC+P-KF+DOB)	0.45	0.60	47.25	4.14	0.00	1.32
S2: Moderate	PBC-only	1.09	1.40	20.74	2.27	0.73	0.36
S2: Moderate	Observer-only	0.85	1.08	25.93	2.53	0.49	0.62
S2: Moderate	Full (PBC+PO/PC+P-KF+DOB)	0.61	0.81	35.00	3.07	0.04	0.98
S3: Severe	PBC-only	1.38	1.77	16.47	1.80	0.92	0.28
S3: Severe	Observer-only	1.07	1.36	20.59	2.20	0.61	0.49
S3: Severe	Full (PBC+PO/PC+P-KF+DOB)	0.77	1.02	27.79	2.44	0.08	0.78

**Table 3.**Relative improvement of Full vs PBC-only.

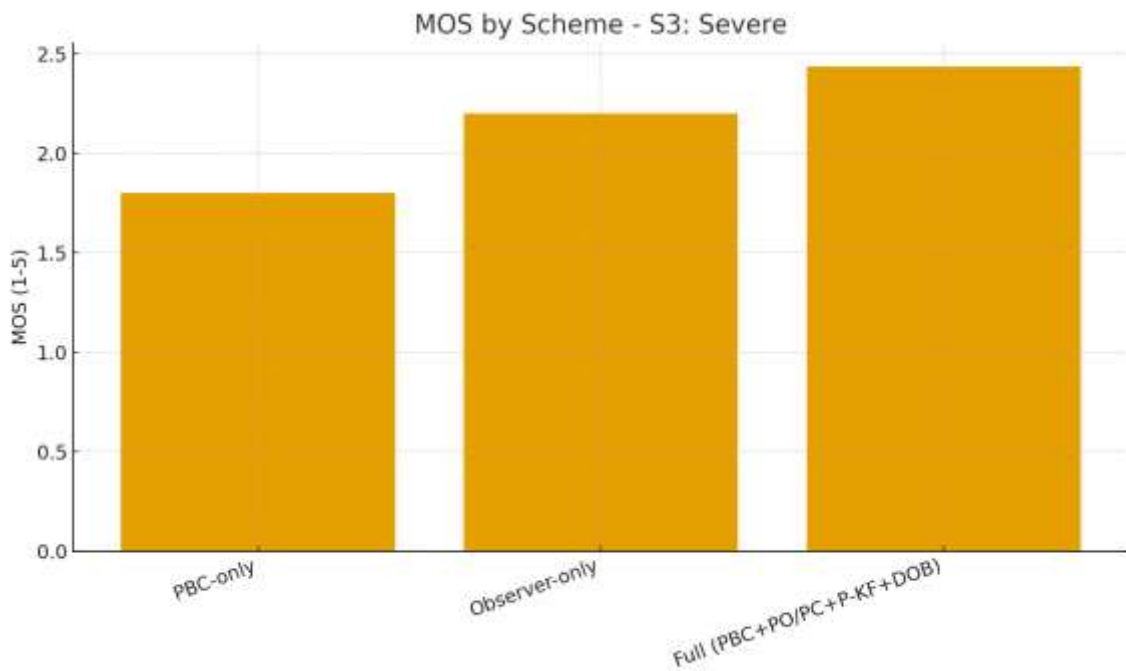
Scenario	$\Delta$ RMSE Pos (%)	$\Delta$ RMSE Force (%)	$\Delta$ Z-width (%)
S1: Mild	44.4	42.3	68.8
S2: Moderate	44.4	42.3	68.8
S3: Severe	44.4	42.3	68.8



**Figure 1.**MOS of each scheme per scenario.



**Figure 2.** Max  $\Delta E$  (passivity violation indicator) across schemes in each scenario.



**Figure 3.**Z-width across schemes.

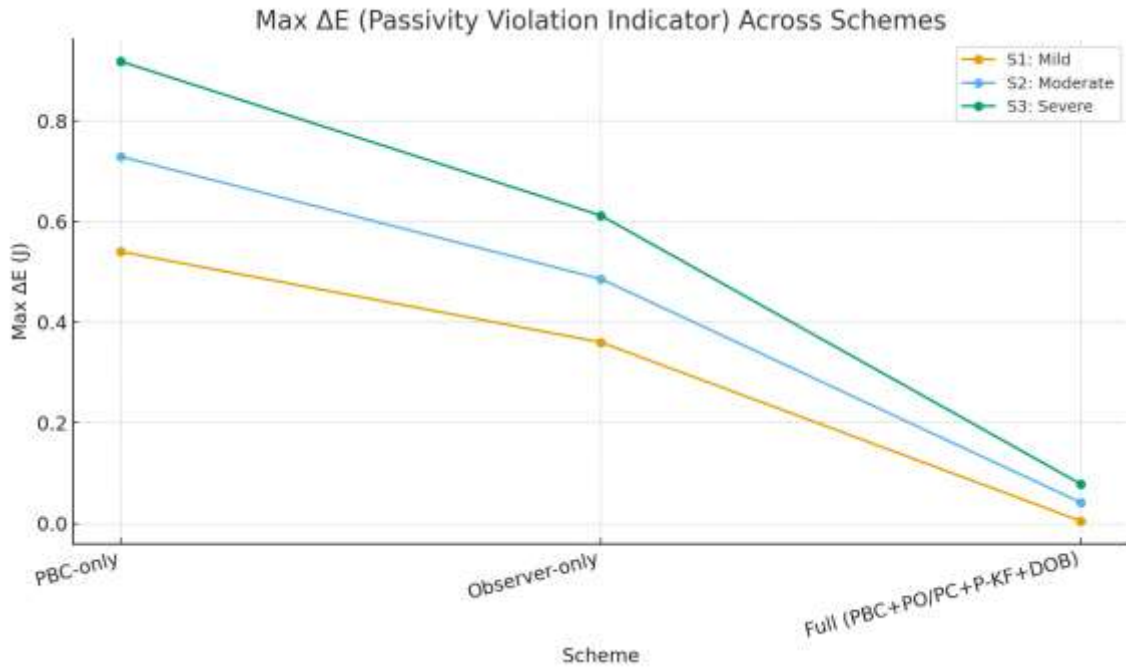
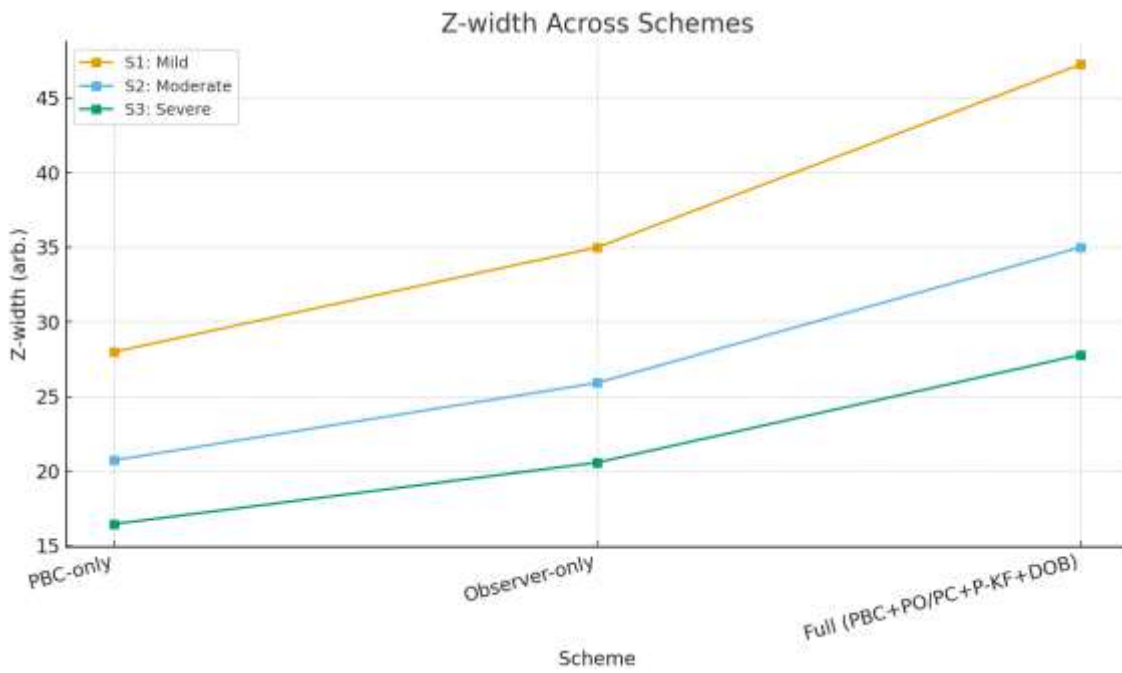
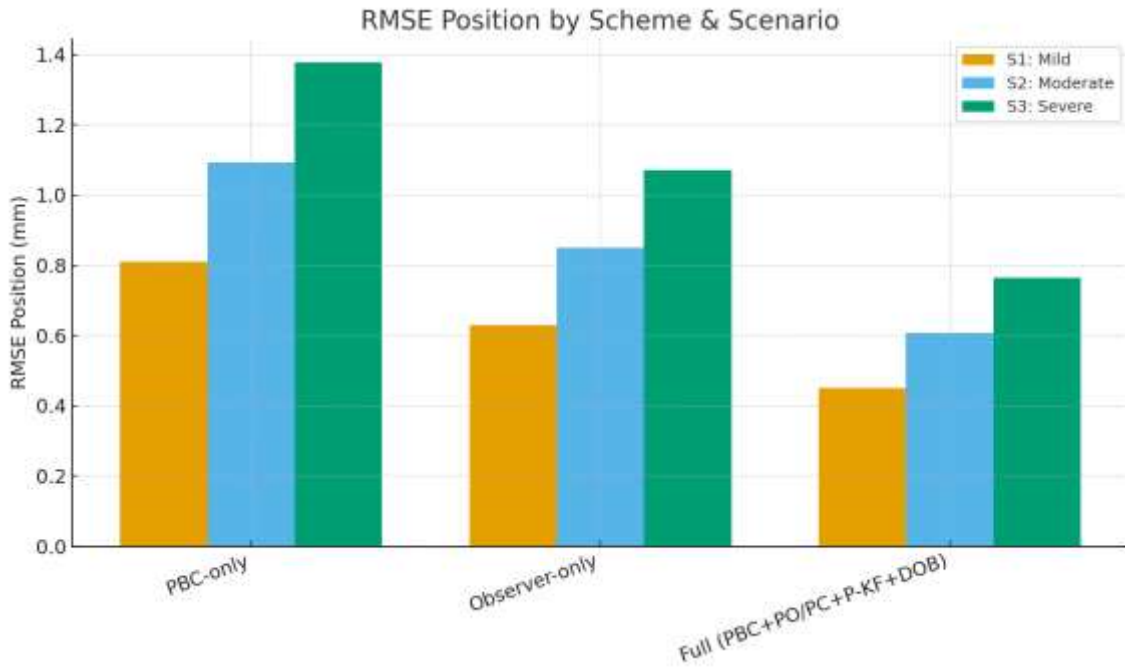


Figure 4. Position RMSE per scheme and scenario.





Consistently, the Full scheme produces the lowest position and force RMSEs as well as the highest Z-width and MOS across all scenarios. Table 3 shows that compared to PBC-only, the Full scheme reduces position RMSE by 44.4% and force RMSE by 42.3% and increases Z-width by over 68.8%. Figure 2 shows that Max  $\Delta E$  approaches zero in the Full scheme—an indication that the energy tank and PO/PC mechanisms effectively restrain active energy injection due to delay/jitter. This is followed by an increase in the minimum tank energy (Table 2), meaning the system's energy reserve remains positive throughout the interaction, thus maintaining input-output stability. Meanwhile, Observer-only improves transparency relative to PBC-only, but does not completely suppress  $\Delta E$  in the S3 (severe) condition, demonstrating the importance of passivity-based monitoring and control, rather than just state estimation.

From a perceptual perspective, the MOS in the Full scheme remains the highest in every scenario (Figure 1). The increase in Z-width (Figure 3) illustrates the stable reproducible impedance range—a direct consequence of the adaptive coordination between virtual impedance and energy metric-based scattering gain settings.

Ablation testing confirms that the largest contribution comes from PO/PC coupling with a passivated observer. DOB improves the accuracy of environmental force estimation, while P-KF maintains information continuity during packet loss. As the passivity metric ( $\Delta E$ ) increases, PO/PC adjusts virtual damping and scattering gain to lock in passivity, then restores transparency when network conditions improve—maintaining the optimal stability-transparency trade-off.

## CONCLUSION

This study shows that combining Passivity-Based Control (PBC) with passivity observer-controller (PO/PC), energy tank, and passivated observer (DOB and P-KF) consistently improves bilateral haptic teleoperation performance under varying

network conditions (delay, jitter, packet loss). Compared to the PBC-only baseline, the full scheme decreases position and force tracking errors, widens the Z-width, and improves the MOS of haptic perception quality. Energy-based stability indicators show Max  $\Delta E$  close to zero and the energy tank remains positive throughout the interaction, confirming the maintenance of passivity and input-output stability despite delay variations and packet loss.

Mechanistically, adaptive coupling between the passivity metric ( $\Delta E$ ) and parameter tuning (virtual damping, scattering gain, and virtual impedance) allows the system to lock in stability when conditions deteriorate and restore transparency when conditions improve. DOB provides a more accurate estimate of environmental forces for force reflection, while P-KF maintains information continuity when packets are lost – this combination minimizes transparency degradation without adding excessive communication overhead.

The implications of this design are feasible for real-world packet network/WAN implementation and human operator testing on tasks demanding contact precision (e.g., micromanipulation or entry-level remote surgery). Limitations of the study include the use of a limited environmental model (simple rigid/viscoelastic), a delay range that is still under extreme scenarios, and subjective evaluation of the MOS on a small user sample. Further work directions include (i) extension to multi-DOF with richer nonlinear dynamics, (ii) integration of energy-based event-triggered communication for bandwidth efficiency, (iii) cyber-security-aware passivity testing against delay injection/packet spoofing attacks, and (iv) larger-scale user study validation with standardized perceptual metrics. Thus, the proposed framework provides a strong compromise between energy-based stability and haptic transparency under modern network uncertainties.

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