Teleoperation Bottlenecks: From Network-Centric Optimization to Human-Centered Design

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***Abstract*—Teleoperation has been a central research topic for over six decades, with envisioned applications in power plants, extreme exploration, surgery, remote driving, industrial maintenance, and care robotics. Despite substantial technological progress, teleoperated systems remain far from ubiquitous deployment. This paper revisits the "teleoperation paradox" – the persistent gap between research maturity and real-world adoption – and investigates where the effective bottlenecks lie. Building on recent analyses of network capabilities and human factors, we argue that for most teleoperation applications, contemporary 5G communication infrastructures can meet key latency and bandwidth requirements under favorable conditions. At the same time, human factors – including situation awareness, cognitive load, expertise, and interface design – increasingly constrain performance, even when basic communication requirements are satisfied. This paper (i) summarizes teleoperation network requirements and compares them to 5G/6G capabilities, (ii) relates network evolution to human perceptual and cognitive limits, and (iii) structures operator limitations. Overall, our results motivate a shift in research emphasis toward human-centered design, operator training, advanced shared control algorithms, and safety-by-design solutions.**

***Index Terms*—Teleoperation, Telepresence, 5G-6G, Human Factors Engineering, Cognitive Load, Sense of Agency, Situation Awareness, Shared Control, Symbiotic Interaction.**

I. INTRODUCTION

Teleoperation and *telepresence* have long promised to radically extend human capabilities by allowing operators to act safely and effectively at a distance, elaborated by Minsky's "Concept of Telepresence" [1]. Proposed use cases span from long-latency planetary telepresence for exploration [2], minimally invasive telesurgery [3], teleoperated driving [4], hazardous maintenance, and assistive care robotics [5], [6]. Classical telerobotics work established the foundations of leader–follower (master–slave) control, transparency, and bilateral haptics, and these ideas have been steadily refined over more than 30 years [7]. Yet, despite decades of research and impressive technological progress, teleoperated systems remain far from ubiquitous [8]–[10].

This discrepancy is sometimes referred to as the "teleoperation paradox": while there are sophisticated robots, high-quality displays, emerging 5G/6G networks, and powerful computation, routine large-scale deployment is rare in many domains [8], [11]–[13]. To understand this contradiction, one shall ask where the true performance and maturity gaps lie.

Historically, the dominant narrative has been that communication networks – their latency, jitter, communication protocol, and bandwidth – are the primary obstacles, [8], [12], [13]. Consequently, major research and standardization efforts have focused on ultra-reliable, low-latency communication (URLLC), deterministic networking, and increasingly higher data rates [14], [15]. The rollout of 5G, and the expectations around 6G, and beyond, have therefore been widely promoted as enabling "real" telepresence for critical applications, particularly telesurgery and remote driving [16].

In this paper, we argue that a purely network-centric perspective is no longer sufficient to explain performance and adoption limitations in teleoperation. While communication constraints have historically been a dominant challenge, recent advances in 5G have substantially reduced latency and increased bandwidth in many scenarios [17]. As a result, human cognitive and perceptual limitations increasingly emerge as critical factors affecting performance, particularly once baseline communication requirements are met. It shall be noted that on a global scale, internet network latencies are highly variable depending on load and infrastructure.

This paper provides the following contributions:

- a consolidated comparison of network requirements versus 5G capabilities across key teleoperation domains, highlighting that communication is not the main limiting factor [8].
- a conceptual mapping of network generations (3G–NG) to human perceptual and cognitive thresholds, illustrating that from 5G onward, further network improvements yield diminishing returns relative to human factors [8].
- a structured analysis of the human bottleneck using Endsley's situation awareness framework, deconstructing cognitive load into five addressable stages and linking them to design variables such as display layout, feedback modalities, and shared autonomy [18].

- a preliminary *da Vinci Research Kit* (dVRK)-based teleoperation case study with qualitative observations on how expertise and task complexity shape operator behavior; quantitative workload and throughput analyses remain future work [19].

II. BACKGROUND AND RELATED WORK

A. *Foundations of Teleoperation and Telepresence*

The conceptual roots of telepresence trace back to Minsky's vision of "being there," which inspired efforts to create remote manipulation systems that can reproduce the sensory and control experience of on-site work [1]. Modern telerobotics research has focused on master–slave architectures, impedance control, transparency, and kinesthetic feedback. The advent of commercial systems like the da Vinci Surgical System further catalyzed interest in telesurgery and remote interventions [20].

A parallel stream of work investigated telepresence and immersive interfaces, including stereoscopic displays, head-mounted displays, and multimodal feedback. The goal has been to reduce the cognitive gap between the operator and the remote environment, thereby improving performance and safety. Recent white papers in telepresence emphasize the persistent difficulty of truly matching human perceptual expectations, despite advances in sensing and rendering technologies [12].

B. *Network-Centric Teleoperation Research*

The limitations of early communication infrastructures long constrained teleoperation. 3G networks offered limited bandwidth and highly variable latency, often exceeding 300 ms, which made high-quality video, let alone stable haptic feedback, challenging for critical tasks. Research focused on latency compensation, predictive displays, and quality-of-service mechanisms, accordingly.

With 4G/LTE, high-definition (HD) video streaming became feasible, supported by typical data rates in the tens of Mbps and round-trip latencies on the order of tens to low hundreds of milliseconds under real-world conditions [21], [22]. Still, stable bilateral haptics remained difficult, and applications, such as telesurgery and teleoperated driving often relied on dedicated networks. The emergence of 5G, with URLLC modes targeting sub-20 ms latency and significantly higher bandwidths was therefore widely touted as the enabler for mobile, ubiquitous teleoperation [8].

Multiple studies have quantified the network requirements for different teleoperation domains and compared them with 5G/6G capabilities [23]. The overarching conclusion is that for most current application scenarios, 5G or 6G – and often even well-engineered 4G – can meet or exceed the necessary performance. This is particularly true for visual and video-centric tasks, where latencies below 100–200 ms and HD resolutions are sufficient, and for care robotics applications that tolerate up to 500 ms [24], [25].

C. *Human Factors in Teleoperation*

As network parameters improved, human factors attracted increasing attention. Teleoperation inherently imposes an additional cognitive layer: operators must interpret remote sensor data, maintain a mental model of the environment and robot state, and make decisions under uncertainty and delay. Situation awareness – the perception of elements, comprehension of their meaning, and projection of their future status – is a critical determinant of performance [26], [27].

Recent works and reviews highlight that situation awareness and cognitive load remain dominant limitations in teleoperation, even as sensing and displays improve [21], [28]–[30]. Studies show that operator expertise has a strong impact on task performance: experienced operators complete tasks faster, with fewer errors and smoother motions than novices, often independently of moderate variations in network conditions. Interface design also plays a significant role: psychophysics-based overlays and adaptive user interfaces can substantially improve completion rates, reduce collisions, and minimize mode switches [31].

These findings suggest that the bottleneck in many teleoperation systems is no longer the communication infrastructure, but the human operator and the human–machine interface.

III. NETWORK REQUIREMENTS VS. TELEOPERATION DOMAINS

A. *Domain-Specific Technical Requirements*

Teleoperation applications differ in their safety requirements, timing constraints, and sensor modalities, which translate into distinct network requirements. Table I summarizes typical end-to-end (E2E) latency, video resolution, haptic feedback, and uplink bandwidth needs across four key domains, along with an assessment of whether 5G is already capable of meeting these needs and what the primary bottleneck is today.

Table I. shows that, for each domain, 5G meets or exceeds the latency and bandwidth requirements [22], [32]. Even care robotics and some telesurgery scenarios can be supported over high-quality 4G connections. However, the "Key Bottleneck Today" column consistently points to human factors, including operator skill, SA, interface quality, and shared control.

B. *Network Generations vs. Human Perception*

To further clarify this shift, let us consider a conceptual mapping between network generations (3G, 4G/LTE, 5G, 6G, and a notional next-generation "NG") and several dimensions relevant to teleoperation: visual feedback, haptic feedback, E2E latency and jitter, uplink bandwidth, and human cognitive load. Table II summarizes an adaptation of the analysis from [22], [25], [33], [34].

The key insight is that from 5G onward, many technical metrics – including latency, bandwidth, and visual feedback quality – approach levels that are sufficient for a wide range of teleoperation tasks under controlled conditions [22], [32]. However, these improvements do not eliminate performance limitations. Operators may still experience high cognitive load, reduced situation awareness, and increased error rates,

TABLE I: Network requirements and bottlenecks across teleoperation domains

Domain	E2E Latency Requirement	Video Resolution	Haptic Feedback	Uplink BW Needed	5G Capable?	Key Bottleneck Today
Telesurgery	<200 ms ideal <300 ms acceptable	Full HD (1080p stereo)	Required (<10 ms loop)	8–50 Mbps	**Yes**	Surgeon skill, haptic stability
Teleoperated Driving	<100 ms UL <20 ms DL	HD + LiDAR multi-stream	Not typical	20–80 Mbps	**Yes**	Operator SA, tail latency
Care Robotics	<500 ms acceptable	HD sufficient (720p–1080p)	Desirable (not critical)	5–20 Mbps	**Yes (even 4G)**	Interface, training, cost
Industrial Manipulation	<50 ms for precision	HD + depth sensing	Required (force feedback)	10–50 Mbps	**Yes**	Operator skill, shared control

TABLE II: Network generations and performance regarding technical and human factors in teleoperation. "NG" refers to a notional next-generation network beyond 6G.

Network Generation	Visual Feedback	Haptic Feedback	E2E Latency & Jitter	Uplink Bandwidth	Human Cognitive Load
3G	Low res, high delay	Not feasible	>300 ms, high jitter	<5 Mbps	Overloaded — poor SA, high error
4G / LTE	HD possible 50–150 ms	Marginal stability	50–150 ms mod. jitter	8–50 Mbps	High — latency compensation req.
5G	Full HD+ 20–100 ms	Feasible (URLLC)	10–50 ms low jitter	50–300 Mbps	Still high — interface dependent
6G	4K+ <10 ms	High fidelity sub-ms loop	<2 ms neg. jitter	>10 Gbps	Still high — human limited
NG	Exceeds human perception	Exceeds human perception	Negligible	Unlimited	? — Can better networks help?

indicating that human factors remain a critical constraint even when communication performance is adequate [35].

This observation is further supported by indicative technical thresholds reported in the literature, which provide approximate ranges rather than strict limits [22], [25], [33]–[35]:

- $<$ 200 ms E2E latency is generally considered ideal for telesurgery, and is typically achievable with contemporary 5G infrastructure.
- $\approx$ 40 ms corresponds to the lower bound of human visual reaction time. Further latency reduction below this threshold offers no direct perceptual benefit for many human operator-induced tasks.
- 1080p Full HD video resolution has been found sufficient for surgical teleoperation with RAMIS systems, such as the da Vinci and Avatera.
- Latencies between $\approx$ 40 ms to $\approx$ 100 ms correspond to one frame cycle at 25 fps down to 10 fps, respectively, which is adequate for continuous control in many remote driving scenarios.
- $\approx$ 500 ms is acceptable latency for a large class of care robotics tasks, well within 4G/5G capabilities.

These thresholds suggest that beyond a certain point, further improvements in the communication layer offer diminishing returns compared to improvements in human interface design, training, and shared control [36], [37].

IV. HUMAN-CENTERED CONSIDERATIONS IN TELEOPERATION

A. *Endsley-Based Decomposition of Cognitive Load*

To systematically analyze the human-related bottlenecks, we adopt an Endsley-based situation awareness framework that decomposes teleoperation-related cognitive load into five stages [18]:

1) **Perception:** acquiring visual, auditory, and haptic cues from the remote environment. Key factors include camera field of view, resolution, stereoscopy, depth cues, refresh rate, and feedback modality (e.g., visual, vibrotactile, kinesthetic).

2) **Comprehension:** integrating perceived information into a coherent mental model of the remote scene and system state. Influencing factors include spatial awareness, display layout, information fusion from multiple sensors, and the clarity of system state indicators. However, unfiltered multi-modal feedback often leads to sensory overload, preventing the operator from forming an accurate mental model, despite high data availability.
3) **Projection:** anticipating future states of the environment and the robot(s), and planning actions accordingly. This stage depends on the operator's experience, training level, and the availability of predictive displays or trajectory previews.
4) **Decision:** selecting appropriate control actions under time pressure and uncertainty. Workload, stress, task complexity, and the level of autonomy (LoA) or shared control significantly affect this stage.
5) **Execution:** translating the chosen action into precise control inputs via the master interface. Relevant factors include input device ergonomics, control mapping, scaling, and the quality of haptic guidance or virtual fixtures.

A key observation is that once network performance exceeds the perceptual floor and further latency reductions will not meaningfully improve any of these stages. Instead, improvements must come from better interface design (e.g., augmented reality overlays, multimodal feedback), training and simulation, adaptive automation, and ergonomic input devices.

B. Evidence of Human-Dominated Performance Limits

Empirical studies show that human factors, rather than network parameters, dominate teleoperation performance [8], [38]–[41].

1) Situation Awareness: Rakita *et al.* find that operator situation awareness remains the primary limitation even as additional sensors and views are added [8]. Operators struggle to maintain a coherent mental model of the scene and robot state, especially in cluttered or dynamic environments [31]. Extra raw data streams (e.g., more cameras, LiDAR) can increase cognitive load unless they are carefully integrated.

2) Operator Expertise: Operator expertise introduces substantial and persistent differences in teleoperation performance, including situation awareness and control quality, often comparable in magnitude to system-level factors [37]. This suggests that training and experience are critical for unlocking the potential of teleoperation systems, and that human learning curves may be a more significant bottleneck than network performance once basic thresholds are met.

3) Interface Design: Psychophysics-based interfaces with task-relevant overlays, attention guidance, or depth cues significantly improve completion rates, reduce collisions, and decrease mode switches without changing the network [42]. Well-designed interfaces can therefore compensate for human limitations and support situation awareness more effectively than marginal latency reductions. Recent interface-comparison studies further show that objective task performance and subjective workload should be assessed together; for example, Aoki and Itadera compared teleoperation interfaces using both successful task operations and NASA-TLX, revealing task-dependent workload/performance trade-offs [10].

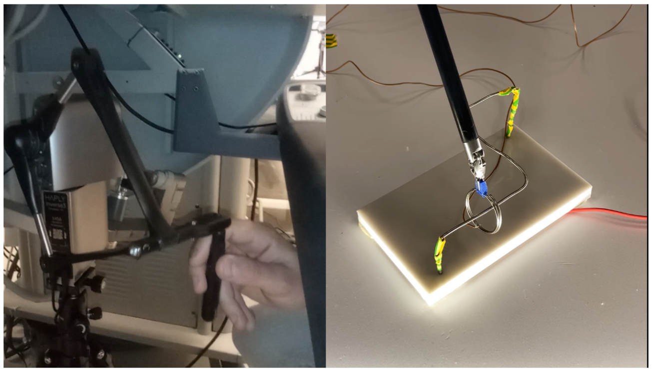

Fig. 1: The dVRK-based teleoperation setup used in the experiment, showing the master console with the Inverse3 haptic device and the patient-side manipulators.

4) Cognitive Frameworks: Cognitive ergonomics work highlights the impact of attention, working memory, and cognitive flexibility on teleoperation performance [39]. High workload and frequent task switching reduce performance under time pressure, with cognitive constraints remaining a key bottleneck even when network conditions are adequate.

Overall, these findings argue for shifting research emphasis from optimizing protocols, bits, and milliseconds to optimizing human interfaces, physiology understanding, and cognitive action.

V. DVRK TELESURGICAL CASE STUDY AND IMPLICATIONS

We conducted a small, illustrative dVRK-based qualitative case study emulating a telesurgical task. The aim was not to quantify workload, but to probe whether expertise and interface-mediated demands remained salient under near-ideal communication.

The setup used a standard dVRK with one patient-side manipulator, stereoscopic endoscopic video on a 3D glass, and a single Inverse3 as the master to guide a loop along a 3D wire without contact (classical hot wire benchmark). Communication used ROS2 with round-trip latency below 20 ms and negligible jitter, comparable to or better than well-provisioned 5G URLLC links [25], with no intentional degradation.

Five participants with varying teleoperation experience repeatedly performed the loop-tracking task after brief familiarization. Even under near-ideal communication, performance varied strongly with prior experience and training. Haptics benefited experienced operators generally but, in the meanwhile increased the cognitive load for novices, who struggled to interpret and integrate force cues. A minimal quantitative extension would pair such observations with NASA-TLX and a simple task-throughput measure, following recent teleoperation interface studies [10].

Overall, once basic network thresholds (e.g., sub-20 ms latency, adequate visual quality) are met, further network optimization provides diminishing returns. Performance is instead driven by:

- **Expertise and training:** systematic curricula, simulators, and staged visual vs. haptic familiarization.
- **Interface design:** adaptive, multimodal displays that support situation awareness without overloading the operator [39].
- **Shared control:** virtual fixtures, motion scaling, and predictive assistance that remain transparent and trustworthy [43].
- **Safety-by-design:** fail-safe behavior, robust error handling, logging, and supporting regulatory frameworks for safety-critical use [12].

These human-centered factors are likely to yield larger gains in teleoperation performance and safety than marginal improvements in already sufficient network metrics.

VI. CONCLUSION AND OUTLOOK

We argue that teleoperation bottlenecks have shifted from network properties to human operator capabilities and interfaces. 5G already meets the latency and bandwidth needs for many applications, making further network gains of limited impact. Instead, cognitive and perceptual factors – such as situation awareness, workload, expertise, and interface design – dominate performance and safety.

Underlining these with some practical experiments, our preliminary dVRK observations are consistent with this interpretation, suggesting effects of expertise, training, and task framing under well-provisioned communication, but they do not yet quantitatively establish workload effects. This suggests that focusing on human-centered and symbiotic system design, adaptive interfaces, shared autonomy, and safety frameworks, with continued experimental work on human-machine control allocation provides more impactful technical advances. Having spent decades attempting to remove the wire, we must now focus on supporting the person at the end of it.

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