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V-LAP: A Hybrid VR Platform for Laparoscopic Cholecystectomy

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1. Client & Problem Context

Client: Electronics Supplier to the Medical Sector.
Users: PGY 1–2 Surgical Residents (Novice).

The Pain Point:

- Residents struggle with the **"Fulcrum Effect"** and identifying the **Critical View of Safety (CVS)** [1] in Calot's Triangle.
- **Box Trainers** offer haptics but static visuals; **VR** offers visuals but weightless haptics.
- **Impact:** This gap *risks* **Negative Transfer** of motor skills [2], increasing Operating Room (OR) time and bile duct injury potential.

The Goal: Deliver a **cost-effective** Hybrid VR system that reduces senior takeovers by $\geq 20\%$ (validated in cadaver trials, n≈40) and validates "safe-to-cut" decision making [3].

2. Proposed Solution: The V-LAP System

Concept: A **Hybrid VR Simulator** (Physical Task-Trainer + VR Overlays). We combine a physical "box trainer" shell with real instruments that interact with a PC-VR headset.

Novelty: *A cost-effective system combining event-based haptics with VR overlays to address the haptic void in current VR training.*

Figure 1. Bridging the gap: Physical resistance meets VR overlays

2.1 System Components

- **Hardware:** Physical mannequin housing generic resistance gels. Users insert **real laparoscopic trocars**.
- **Visuals:** PC-VR Headset with high-res Pass-through. Users see their real hands, but tool tips/organs are 3D renders.
- **Tracking:** 6-DoF IMU sensors clipped to instrument handles (Latency < 20ms).
- **Safety:** Non-patient educational use only; wipeable antimicrobial surfaces; anonymised analytics.

3. Interaction Flow (Storyboard)

- **Step 1 (Setup):** Trainee inserts real tools into physical ports. Natural fulcrum resistance is felt immediately.
- **Step 2 (Identification):** Trainee dissects virtual tissue to identify the *Critical View of Safety (CVS).*
- **Step 3 (Complication):** VR triggers a "Cystic Artery Bleed." Trainee must apply physical pressure.
- **Step 4 (Feedback):** "Safe Zone" heat maps projected over Calot's Triangle during debrief.

4. Human Factors Rationale

Fidelity Strategy (Task vs. Physical):

- We prioritise **Functional Fidelity** (task behaviour) and **Cognitive Fidelity** (decision-making) over expensive physical realism [4].
- **Event-Based Haptics:** The gel provides constant passive resistance, while audio/visual cues substitute for active force feedback (e.g., "snap" sound when clipping).

Presence & Cybersickness:

- **Sensory Conflict Theory:** Standard VR causes nausea due to visual-vestibular mismatch [5].
- **Mitigation:** Pass-through video anchors the user in the real room (stable horizon) and maintains **Self-Presence** [6].

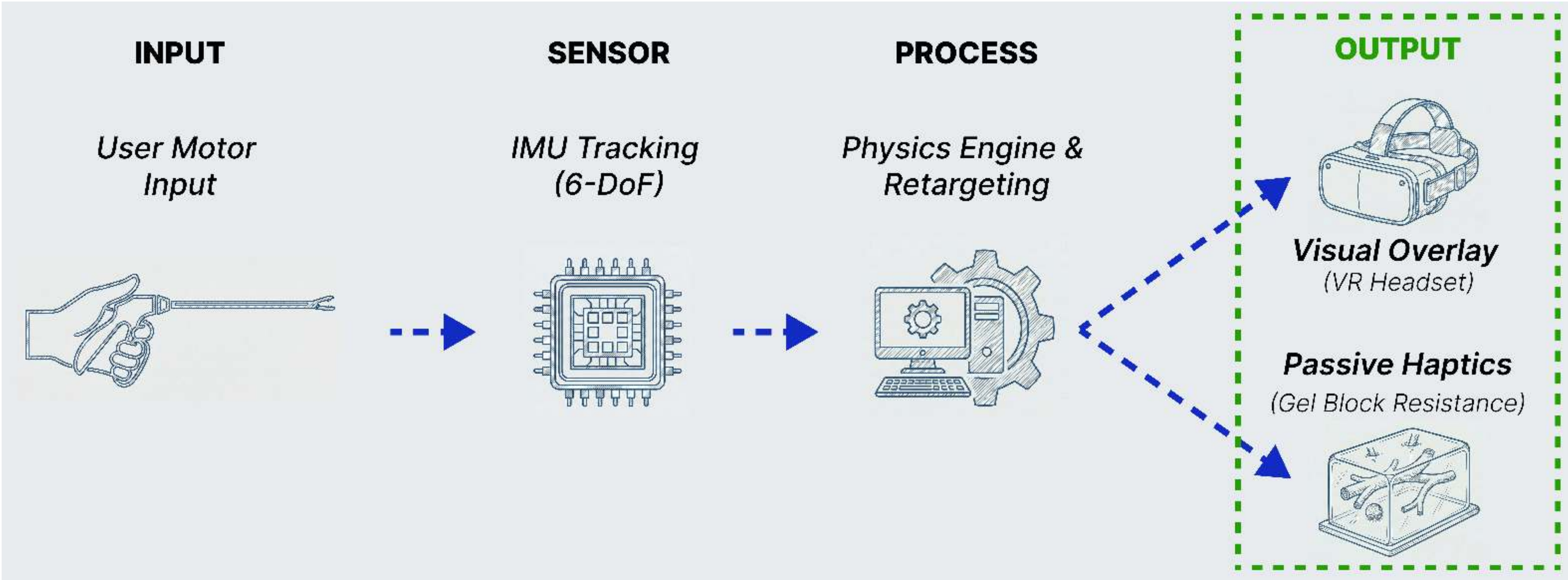

Figure 2. The V-LAP Haptic-Visual Loop

5. Measures of Success (Validation Plan)

Proposed Study: Between-groups randomised trial (n=40; 4x30-min sessions; power target 0.8, $\alpha = 0.05$). Validation Framework per [7].

Validity Type	Metric	Target
Construct	Time to identify CVS (incision to confirm)	Experts 40% faster than Novices
Content	Protocol Adherence (SAGES step list 0/1)	$> 90\%$ steps completed correctly
Predictive	Senior Takeovers*	$\geq 20\%$ reduction vs Control
Predictive	Off-Plane Dissection Events	< 2 events in Transfer Test
Tracking	Path Length Efficiency	$> 30\%$ improvement vs Baseline
Exploratory	Clip Misplacement Count	< 2 errors per session

Table 1. KPIs (*Measured in Cadaver Transfer Test [8] by blinded assessors using OSATS/GOALS)

Safety: SSQ < 15 [9]; Presence (IPQ) $> 4/5$ [10] (Collected post-task).
ROI: TCO per trainee hour $< £50$ (Hardware amortised 5y + faculty time).

6. Advantages vs. Disadvantages

Advantages:

- **Repeatability:** Safe simulation of rare complications (e.g., aberrant anatomy) impossible in box trainers.
- **Objective Assessment:** Analytics replace subjective supervisor ratings.
- **Reduced Negative Transfer:** Real tool weight prevents "gamer" muscle memory.

Disadvantages & Mitigation:

- *Risk:* **Visuo-Haptic Mismatch** (Gel feels static while image moves).
  - *Mitigation:* "Retargeting" algorithms bend the virtual tool slightly to visually match physical limits.
- *Risk:* **Equity/Access** (Visual/Vestibular susceptibility).
  - *Mitigation:* Offer 2D desktop non-HMD module for at-risk users.
- *Risk:* **Calibration & Supply Chain** (Drift and consumables).
  - *Mitigation:* Boot-time 6-DoF tolerance check; standardised replaceable gel cartridges.

References

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