2025 IEEE-RAS 24th International Conference on Humanoid Robots (Humanoids)
September 30 – October 2, 2025 | COEX, Seoul, Korea

Preliminary Exploration of Antagonistic Vibrotactile Feedback To Improve Force Regulation in Teleoperated Bimanual Manipulation

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2025 IEEE-RAS 24th International Conference on Humanoid Robots (Humanoids) | 979-8-3315-9869-3/25/$31.00 ©2025 IEEE | DOI: 10.1109/HUMANOIDS65713.2025.11203208

***Abstract*— State of the art robotic systems still struggle to accomplish complex tasks, such as bimanual manipulation, in unpredictable environments due to limitations in sensing, adaptability, and control - leading to artificially restricted autonomous system performance. This research addresses this limitation by introducing a novel metric for quantifying antagonistic internal forces during teleoperated bimanual manipulation, conveyed through minimalistic vibrotactile feedback (VF) to the operator. Experimental tests demonstrated that integrating the proposed metric through VF improved internal force regulation, reducing average internal forces by approximately 39.5% and decreasing force variability by 52.1% compared to trials without feedback. Introducing VF exhibited an increased number of occurrences of payload drops – indicative of operators pushing closer to operational limits. These findings confirm the proposed metric delivered through minimalistic VF substantially enhances teleoperated manipulation, providing a promising avenue for safer, more intuitive robotic operations in dynamic and uncertain environments.**

I. Introduction

The humanoid robotics industry is exploding, growing 40% in the past year [1] – reaching $2.92 Billion [2] – and is projected to increase 6 to 13-fold in the next 10 years [3]. Humanoid teleoperation has grown in importance in this context. Current automated systems perform reliably in predictable environments with well-defined tasks and interactions. However, a significant capability gap emerges when robots encounter atypical situations, such as handling heavier-than-expected payloads, dealing with external disturbances, or manipulating irregularly shaped or delicate objects. These limitations stem from challenges in controls, insufficient instrumentation, and incomplete environmental knowledge. To ensure safety under these constraints, autonomous robotic systems greatly limit their performance, sacrificing flexibility, adaptability, and functional capabilities. We aim to reduce this capability gap through teleoperation of force-controlled proprioceptive hardware while providing a metric – founded in quantifying antagonistic forces exerted between end-effectors during bimanual manipulation – as feedback through a minimally complicated system.

A. Motivation

Awareness of the robotic platform's state, environment, and applied forces is a multifaceted problem – particularly when controlling complex motions between multiple robotic contact points. Bimanual manipulation is a prime example, where each arm moves independently and interacts with the same payload forming a closed loop, where small kinematic errors can cause large internal forces [4].

The work is funded by the National Science Foundation via grants IIS2024775 and CMMI-2043339

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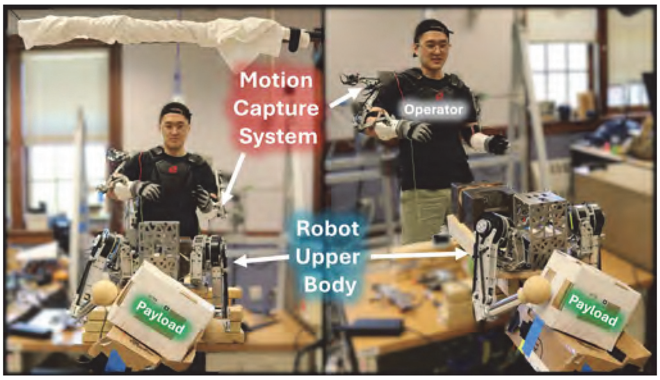

Fig. 1: Experimental setup used in the teleoperated bimanual manipulation tasks. At the top, the white screen is used to block operator view when appropriate. Gloves on the operator contain vibrotactors which deliver vibrotactile feedback.

Teleoperation is a common stepping stone leading to full autonomy, keeping humans in-the-loop during operations, using inherent and contextualized visual understanding and motion planning; however, it also introduces several challenges. Operators cannot visually estimate internal forces, only forces that create motion. Contact between the robot and payload can be non-ideal or imprecise, introducing uncertainty into the foundation of the applied force. Furthermore, unknown collisions, uncertain contact, or interaction with objects of undetermined properties during teleoperation exacerbate these challenges.

There have been many approaches to help maintain Self and Situational Awareness (SaSA), including Heads up Displays, audible indicators, haptic force feedback, etc. However, these approaches require either 1) artificially and substantially limiting system capabilities (speed, lift capacity, etc.) or 2) introducing significant system complexity (additional sensors, more displays, haptics, etc.). Our goal is to find a low-complexity system that enables Internal Force Regulation (IFR) in teleoperated systems.

B. Related Works

1) Teleoperation: Robotic teleoperation is the process by which human operators control systems remotely. The field has progressed rapidly thanks to advancements in communication infrastructure, including high-bandwidth networks and lower-latency protocols, enabling robots to transmit real-time visual and sensor data back to the operator.

Current deployments can largely be categorized into three overlapping motivations. Teleoperation extends human expertise in *distant operations* to remote locations, such as surgeons performing procedures in isolated clinics via telepresence systems [5]–[8]. In *hazardous environments*, robots are increasingly deployed in environments unsafe for humans, such as disaster zones, nuclear facilities, and combat areas, enabling inspection, manipulation, or rescue tasks without risking human life [9]–[11]. Despite technological advances, teleoperated operations benefit from *human intelligence and reasoning*, which utilizes our inherent adaptability and creativity to support real-time control adjustments in unpredictable or unstructured scenarios [5], [8].

Despite its strengths, teleoperation faces challenges, including communication latency, limited sensory feedback, and operator overload due to reliance on vision and complex interfaces. Force feedback remains limited, complicating manipulation of delicate or unpredictable objects [11]. Mapping human to robotic dexterity remains an open problem, as does balancing human/autonomous shared control. Continued progress in these fields will progress teleoperation.

2) Bimanual Manipulation: the simultaneous operation of two robotic arms to handle the same object – offers notable advantages such as increased task efficiency, improved stability through force distribution, and enhanced adaptability for complex operations. It aims to replicate and/or augment the capabilities of human two-handed operations to achieve higher levels of dexterity, adaptability, and autonomy in tasks that demand simultaneous coordination of two robotic arms.

In industrial settings, dual-arm manipulation is used to streamline manufacturing, assembly, and automation processes, often leveraging popular robotic arms [12]. Meanwhile, assistive robotics research focuses on advanced humanoid platforms [13]–[16]. Bimanual robots also demonstrate agility and adaptability in unpredictable scenarios [17].

3) Vibrotactile Feedback: (VF) conveys information through vibrations, targeting human's touch sense instead of visual or auditory channels, which are generally prioritized. Varying the vibration's amplitude, frequency, or binary state has been shown to alert operators to events and guide them through complex tasks. However, choosing *what* information to convey and *how* to represent it remains.

VF has been used in several different applications, with varying degrees of success: directional cues [18]–[22], providing alerts to operators[21]–[30], teaching motions to mirror or achieve an instructor's body position [31]–[33], signaling vehicle slippage, etc. In some cases, VF greatly increases performance, in others it proved detrimental.

a) Detrimental Vibrotactile Feedback: Experiments showing worsened performance with VF included those which required pattern recognition [19], [24], [34], non-intuitive encoding [19], [22], [24], excessive and/or dense stimulation (either too many stimuli, similar to excessively loud/similar noises) [23], [29], [31], [34]. Here, operators struggled to decipher ambiguous or unintuitive patterns, particularly when multiple vibrotactors were activated simultaneously. Humans have difficulty determining directionality of high-frequency vibrations, making representation of high-dimensional data (e.g., spelling, complex patterns) without causing confusion problematic [20], [24], [31], [32], [34], [35]. Too many stimuli in close proximity can lead to overlap in perceived sensations, compounding the difficulty in interpretation [22], [27], [36].

b) Beneficial Vibrotactile Feedback Incorporation: Many examples show introducing VF greatly improved performance, including alerting teleoperating drivers that they were approaching the limit of balancing capabilities while picking up heavy payloads [21], [28], [37]; warning of proximity, collisions, or slippage [22], [24]–[27], [29], [30]; and travel direction [19], [20], [22]. Other examples include astronauts recognizing gravity vector during flight operations [38], in rehabilitation motion teaching operations [33]; Center of Pressure balancing feedback on exoskeletons during disruption tasks [21], [37], [39], obstacle avoidance navigating cluttered environments [18], [22], [24], [30], or contact sensing [26], [30]. Many works show improvements when pairing VF feedback with visual/audio feedback [19], [23], [24], [27], [29], [32].

c) Principles for Effective Vibrotactile Systems: Effective VF shares three features: low cognitive load, meaningful information, and ergonomic design. VF interface and signals should not require intense mental effort to decode. Single dimensions (such as a single vibrotactor ramping in intensity [23], [31]) or simple mappings (e.g. vibrotactors encircling the operator conveying angle [18]–[22]) tend to be understood more readily than patterns requiring classification (e.g. spelling or abstract decoding) [19], [22], [24], [34]. VF has been shown to work best when conveying a signal corresponding logically to a *single* dimension (e.g., distance to an obstacle, tilt angle, force magnitude, etc). Complex or multi-dimensional data can work if clearly partitioned, either through separate sensory channels (e.g., different body regions) or vibrotactor arrays. However, one should avoid confusing signal superimposition [23], [29], [31], [34].

C. Approach and Contributions

This paper aims to explore and improve Internal Force Regulation (IFR) during teleoperated bimanual manipulation through simple and accessible sensory augmentation. We propose that IFR during bimanual manipulation can be improved by introducing VF representing a novel minimal metric representing the antagonistic portion of applied forces, in contrast to the trend in teleoperation feedback systems where increasingly large volumes of data are conveyed through increasingly complicated systems, such as placing several vibrotactors in patterns or rings to indicate directions, letters, or patterns as discussed above. Further, we propose 3D force data during bimanual manipulation can be conveyed implicitly through the operator's proprioception paired with a single dimensional metric, allowing a single vibrotactor to provide sufficient SaSA for an operator to effectively regulate internal forces when operating a humanoid form-factor robotic platform with force-controlled actuators.

The contributions are as follows. 1) introduction of a novel and computationally light metric designed to quantify the antagonistic forces exerted between end effectors during teleoperated bimanual manipulation for improving IFR by reducing a rich high-dimensional full data stream to axes identified as important in bimanual manipulation tasks and further condensed that into a single-dimensional, minimal metric. 2) Validation of the metric's effectiveness in IFR, through experimentally demonstrating performance difference, finding the feedback reduced the applied antagonistic internal forces and the amplitude of the varying internal forces by 39.5% and 52.1% respectively. 3) ascertaining if VF alone—without complex visual displays or haptic interfaces—is sufficient for enabling effective IFR during teleoperated bimanual manipulation.

II. Methodology

A. Research Platform

This research uses the upper body of the Semi Anthropomorphic Teleoperated dYnamical Rolling Robot (SATYRR) platform, a humanoid robot with powered wheels on its feet [40] shown in Fig. 2. SATYRR was designed to improve model-robot accuracy and for use with intuitive teleoperation capabilities (especially with bimanual manipulation and whole-body teleoperation) with the goal of using the operator's body to control movements directly.

1) Design Principles: SATYRR's design mirrors the design philosophy seen in quadruped systems like those in [41] and further abstracted in [42]–[44]; it has been shown to support responsive, safe interaction with objects and humans during real-time dynamic interaction. The design philosophy's core tenants are: proximal placement of backdrivable proprioceptive actuators, low-inertia limbs, and force control.

2) Arm Actuation: SATYRR's arms have four Degrees of Freedom (DoF), while humans' have about seven [45]. To use the human operator's body as a control reference, there must be some mapping (motion retargeting) between the operator and the robot. Additional mapping details can be found in [40]. The robot kinematic model assumes a serial

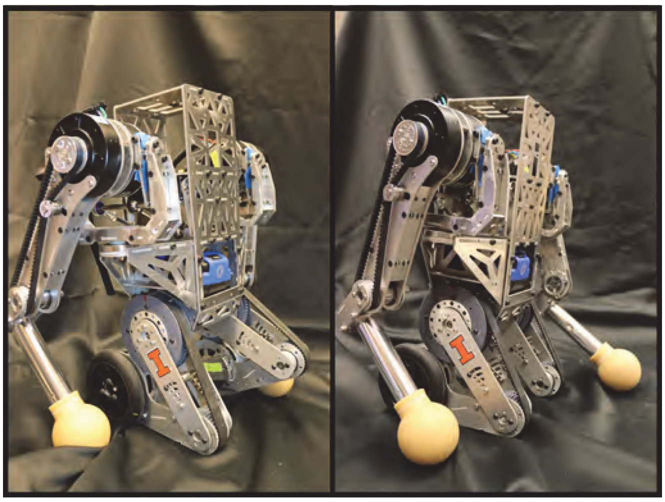

Fig. 2: SATYRR humanoid robotic platform's whole body shown kneeling.

chain configuration but a parallel mechanism actuates the shoulder. This makes its forward kinematics complex and computationally expensive to analytically solve. To bypass this, a surface mapped to the inverse kinematics over the entire workspace was found for each motor/topological angle. For mathematical simplicity, a polynomial surface fit approximated each function. These equations, relating motor angles θ to joint angles ϕ, are shown in Eqs. 1.

$$\begin{aligned} \phi_1 &= f(\theta_1, \theta_2) \\ \phi_2 &= f(\theta_1, \theta_2) \\ \theta_1 &= f(\phi_1, \phi_2) \\ \theta_2 &= f(\phi_1, \phi_2) \end{aligned} \tag{1}$$

The mapping converts between angle-spaces; however, it does not link motor current and applied forces. This mapping based on the manipulator Jacobian can be approximated using the derivative of the positional mappings previously derived. Surfaces had an acceptable average and maximum error of $4.6e^{-4}$ and $2.64e^{-2}$ deg respectively.

$$[\phi] = \begin{bmatrix} \text{yaw}_{\text{shoulder}} \\ \text{roll}_{\text{shoulder}} \\ \text{pitch}_{\text{shoulder}} \\ \text{pitch}_{\text{elbow}} \end{bmatrix} = \begin{bmatrix} f_{\phi_1}(\theta_1, \theta_2) \\ f_{\phi_2}(\theta_1, \theta_2) \\ \phi_3 \\ \phi_4 \end{bmatrix} = F_{\text{ang}}(\theta) \tag{2}$$

The function, F_{map}, represents the mapping between motor and joint spaces. Differentiating produces J_{Force}, the desired Jacobian linking current and force spaces, thus allowing joints to be controlled with feed-forward current control in topological space.

$$\phi = F_{map}(\theta) \tag{3}$$

$$\dot{\phi} = F'_{map}(\theta)\dot{\theta} = J_{Force}(\theta)\dot{\theta} \tag{4}$$

B. Mechanical Motion Capture System for Human Arms

A wearable hard-wired and high-bandwidth motion capture system is employed in experiments. A more detailed overview is available in [40], although the hardware, control features, and joint mappings have been updated.

Achieving safe and accurate dynamic operation in robotics often requires high control rates, where measurement speed, precision, and environmental robustness are critical [41], [42]. Hardline systems reliably support sample high rates, with added hardware complexity and inertial load on the operator. Our wired-encoder mechanical motion measurement system is shown in Fig. 1, 3 and 4.

C. Metric: Antagonistic Force Mapping

The central concept in the proposed VF is to quantify the antagonistic forces exerted between the robot's hands during bimanual manipulation. This involves computing the component of the hands' forces that oppose each other. The robot's exerted effort is linearly related to external interaction forces, assuming that there are no other collisions, the robot remains away from singularity, it remains stable, and it conforms to the proprioceptive actuation design philosophy.

The generic equations governing the manipulation dynamics are encapsulated in equation 5, where H, C, G, and J

Fig. 3: Human motion capture system with back-plate, vest mounting, and two arms attached to the human with the white forearm braces allowing hands-free operator measurement.

denote the inertia, Coriolis, Gravity, and Jacobian Matrices respectively, while τ_f, τ, and F denote the frictional torque, applied torque, and external force vectors respectively.

$$H\ddot{q} + C\dot{q} + G + \tau_f = \tau + J^T F \tag{5}$$

Following the previously discussed design philosophy enables assumptions that facilitate controller simplification.

With proximally concentrated minimal-inertia limbs, external forces dominate over Coriolis and inertia effects ($H\ddot{q} \approx 0, C\dot{q} \approx 0$). Efficient transmissions and joints allow friction to be neglected ($\tau_f \approx 0$). Pairing proprioceptive actuation with low friction transmissions produces a close to linear relationship between torque (τ) and current (i) with some coefficient ($\tau_j = k_{t,j}$) - generally the j'th motor's torque constant. This further allows current to stand in for torque in control. These assumptions have been experimentally validated in prior literature [41], [42], [44], [46]. The resulting simplified relationship becomes:

$$-J^T F = k_t i \tag{6}$$

The robot can thus use open-loop torque control to accurately control interaction forces.

Quantifying the applied interaction forces shifts the focus from the motor space (tied to specific motors in SATYRR's arms) to the arms' four topological (serial joint) angles: a spherical shoulder joint and simple rotational elbow joint. The angles depicted in Fig. 4 are in order: shoulder yaw, shoulder pitch, shoulder roll, and elbow. This change of basis clarifies the derivation and does not change the core concepts or approach. Subscripts L and R denote the Left and Right hands respectively.

Starting from the applied Torques (T), gravitation effects (G) are removed from each arm, giving the effective topological torques (T_{topo}). Converting this to the forces exerted on the right (F_R) and left (F_L) hands in Cartesian space by

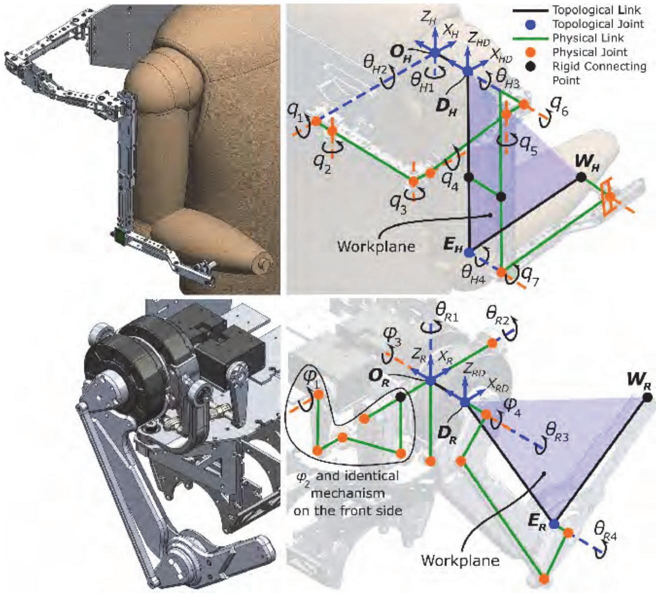

Fig. 4: Actual and topological angle arm models of the human (subscript H) and robot (subscript R). Human operator's arms 7 DoF are mapped to the 4DoF robotic arm angles. Proportional limb link lengths differ. The following words are indicated by their respective letters: Origins(O), deltoid (D), elbow (E), and wrist (W). This figure is based on [40].

using each arm's Jacobian:

$$T = T_{\text{topo}} - G \tag{7}$$

$$F_R = J^{-T}_{Force,R} T_{R,topo}, \quad F_L = J^{-T}_{Force,L} T_{L,topo} \tag{8}$$

The difference between these forces yields the component that represents the degree of opposition between the hands. F_{diff}, or the difference in forces applied between the hands in Cartesian space, is defined as follows:

$$F_{diff} = F_R - F_L \tag{9}$$

The entirety of F_{diff} is likely not solely opposing between the hands. The only component of F_{diff} involved in IFR is the component along the unit vector between the positions of each hand (P_{hand}).

$$\mathbf{v}_{\text{between}} = \mathbf{P}_{\text{hand},R} - \mathbf{P}_{\text{hand},L} \tag{10}$$

$$\mathbf{u}_{\text{between}} = \frac{\mathbf{v}_{\text{between}}}{|\mathbf{v}_{\text{between}}|} \tag{11}$$

The component of the force difference along this unit vector provides a scalar measure of the magnitude of the antagonistic force. The antagonistic force between hands, F_{ant}, serves as a scalar measure of the degree of opposition between the hands. To drive VF feedback, we linearly scale F_{ant} by a chosen gain K.

$$F_{ant} = \left|\text{proj}_{\mathbf{u}_{between}}(F_{diff})\right| \tag{12}$$

$$I_{excite} = K F_{\text{ant}} \tag{13}$$

This antagonistic force is mapped linearly to vibrocactor excitation current with minimum and maximum saturation. The minimum current is maintained to allow for greater feedback resolution during low-force operations, where excitation

Fig. 5: Vibrotactile feedback gloves worn by the teleoperator with vibrotactors in the center of the palm secured by a strap to ensure sensation transmission to the operator.

current is commonly low enough that static friction in the vibrotactor can lead to a dead-band, introducing non-linear and intermittent feedback.

D. Vibrotactile Feedback Delivery

VF is provided through gloves worn by the operator shown in Fig. 5. These gloves were designed to facilitate intuitive understanding and interpretation while minimizing operator cognitive load and maintaining dexterity.

The center of the palm was chosen as VF delivery points as they are particularly sensitive [47] and have underutilized sensory channels, which is ideal for receiving tactile cues without sensory input or cognitive processing bottle-necking.

1) Vibrotactors: Selecting appropriate vibrotactors is critical for effective VF systems. Optimal frequencies for stimulating Pacinian corpuscles in human skin range from 200-400 Hz [48]–[50], typically targeting 250 Hz [27], [28], [32]. However, skin resonance models suggest optimal excitation occurs at skin's resonance frequency [31]. Literature explores amplitude and frequency modulation in VF [51], [52]. To maintain experimental focus on a minimal metric, we selected hardware to modulate both amplitude and frequency simultaneously - PrecisionMicrodrives 307-103 motors' frequency range closely aligned with frequencies optimal for humans sensing (0-300 Hz) and exhibit linear relationships between both amplitude/frequency and excitation current [53]. This supports both avenues of data encoding, simplifies control, and ensures consistent feedback performance. Vibrotactors were excited through current control at 1kHz using an ESCON Module 50/5.

III. Experiments

Experiments are designed to investigate if the proposed IFR method is viable as a light-weight teleoperation feedback system during dynamic motions. Experiments in [54] show that VF can be used in goal matching during quasi-static operations. However, these experiments are simple and slow enough that cognitive load and sensory channels are not full. Adding a secondary task increases the challenge.

In this set of experiments, the effect of the proposed IFR feedback is ascertained by measuring the magnitude and fluctuations of internal forces during teleoperated operations. There is always some form of visual feedback between the operator, system, and payload to inform manipulation.

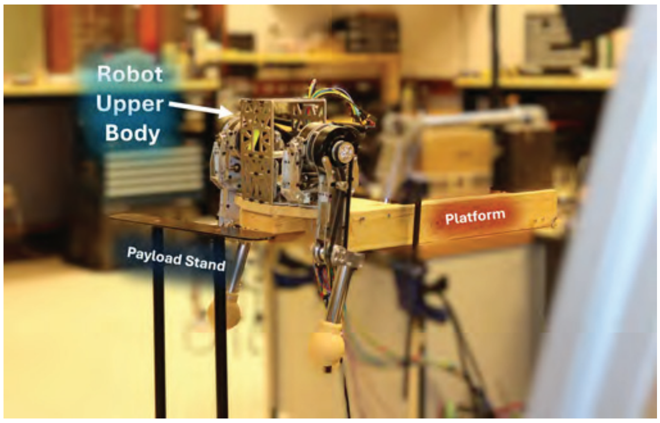

Fig. 6: Base setup for teleoperated bimanual manipulation experiments. Shown is the upper body mounted onto a rigid wooden platform. With all electronics mounted below, SATYRR can manipulate and grab objects from the black stand in front of its chest.

1) Experimental Procedure and Design: Figures 6 and 1 respectively show the base experimental setup, where the upper half of SATYRR was rigidly secured leaving its arms free, and an operator teleoperating the system.

During the experiments, the operator was instructed to pick up a rectangular payload to the robot's shoulder level and return it to waist-level cyclically, while minimizing the magnitude and change of internal forces as much as possible without dropping the payload. A metronomic pulse was produced through a speaker connected to the operator, used to synchronize payload motions between experiments.

Before experiments were conducted, the operator was familiarized with teleoperation until they were comfortable with all motions/controls and passed basic functionality tests. As this preliminary study explores feasibility and approach, experimental emphasis is not on in-depth human-machine interaction conclusions that would be provided by a study with a large number of diverse trial participants. Here, one operator conducted 20 trials.

IV. Results and Discussion

A. Increased Consistency in IFR During Dynamic Motions

Results indicate that adding VF with the proposed metric to bimanual teleoperation increases the consistency of internal force regulation and decreased the magnitude of antagonistic internal forces.

Figure 7.A shows averaged motion trajectories with standard deviations for trials with and without VF. Both trial types follow almost identical trajectories, especially during transitions - with slightly more variability at apexes where peak acceleration occurs. A consistent upward drift in payload height is seen across trials, likely an artifact rather than a feedback-related effect. Although the mean signals remain quite similar, individual runs highlight a noticeable difference: without vibrotactile feedback, the operator tended to overshoot the payload's vertical position more often, whereas with feedback, there was a tendency to undershoot.

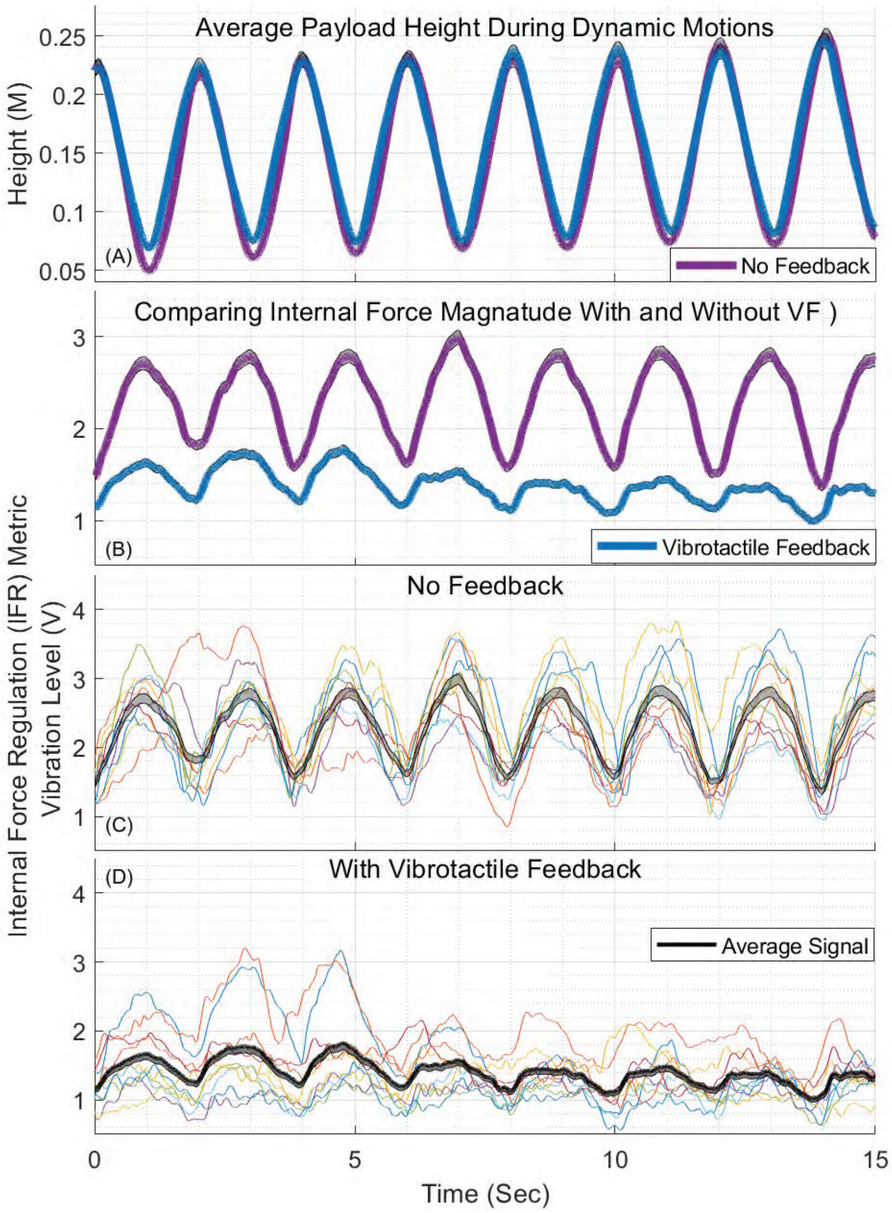

Fig. 7: **A)** Mean motion trajectories with and without VF with their standard deviations. Signals show similar overall profiles, with higher variability at apexes where peak acceleration occurs. A gradual upward drift in the mean position is observed in all trials, suggesting a consistent artifact rather than a significant difference between the two feedback conditions. Individual runs show distinct behaviors: the non-VF condition often overshoots the payload's vertical position, whereas the VF condition leans towards undershooting. This may result from operators adjusting their grip/efforts based on feedback. **B)** Average internal forces and their standard deviations in trials conducted with and without vibrotactile feedback. The non-VF condition exhibits significantly higher forces overall, while VF trials remain both lower and more consistent. The maximum average force in VF trials is approximately equal to the minimum force in non-VF trials, demonstrating great effect. **C-D)** All trial internal force signals alongside their respective averages, separated by With and Without VF.

One explanation for this pattern may be an increased caution stemming from feeling the payload "slip" through the vibrotactile cues, prompting the operator to adjust their grip or motion. Alternatively, a learning curve could account for these results, suggesting that additional practice or more nuanced feedback parameters may help operators converge on an optimal motion profile.

Now that motion trajectories are proven to be appropriately aligned and functionally equivalent, it is possible to examine the internal forces that drive SATYRR's vibrotactile feedback directly. Figure 7.B shows the average metric value for each trial type, which is directly proportional to the internal load applied to the payload, shown alongside their standard deviations. The most striking observation is that the internal forces are substantially higher (65.3% higher) in the experiments conducted without VF. Furthermore, there is far less variation in magnitude when VF is present, with the standard approach exhibiting 208.6% larger osculation amplitude; this indicates that operators are better able to maintain consistent levels of internal force. The maximum average force for the VF trials is comparable to the minimum force in the non-VF trials, results further supporting the value of real-time vibrotactile cues. The addition of VF appears to allow rapid correction of unintended applied forces.

Figures 7.C and 7.D display each individual trial run in addition to the averaged signals to analyze aggregate trends along-side individual trials. Non-VF trials tend to exhibit higher variance and do not show a progressive reduction in internal force amplitude; the operator seems to settle into a habitual pattern early on, lacking feedback that could encourage a more stable force profile. In contrast, trials with VF generally begin with few relatively large loads—likely as the operator adapts to the haptic cues—and then settle toward lower amplitude and steadier applied force. This trend suggests that vibrotactile feedback guides operators to continually adjust their grip and motion to minimize internal force as the task progresses. Further, this result suggests that it is a learned behavior; since the the operator quickly adapt to correct this error, it stands to reason that the error can trained out of operators without large time or effort. While one could argue that training could be as effective without VF, the data indicate a longer adaptation period with a smaller success metric in all trials.

One notable outlier with VF, shown in red, displays below-average displacement and above average force, evidence of a slip event: the operator responded by adopting more conservative motions and deliberately maintaining higher forces to ensure stability for the remainder of the trial. This further supports that real-time force feedback can drastically influence operator behavior, prompting immediate corrective actions and ultimately improving overall task performance.

B. Drop Occurrences

In each trial type, payload drops did occur; however unexpectedly, there were qualitatively more drops in trials with vs without VF. In this preliminary exploration, we hypothesize that this initially counterintuitive result may reflect operators pushing closer to the minimum feasible limits, due to the heightened confidence to refine their grip and applied force enabled by VF. By comparison, those without VF tended to rely on a consistently higher force — essentially erring on the side of caution. While the data supports this hypothesis - and indicates that additional training could help operators fully leverage VF's benefits without risking payload drops - further experiments should be conducted to more fully explore potential heuristics and how to pack additional meaningful data into them without increasing the size of data. Potential avenues include adding slip detection terms and shaping the VF curve to provide null or intense signals when nearing a drop. Experiments should also include a higher volume of trials and subjects.

V. Conclusion

In this research, we theorize and introduce a novel metric based on antagonistic forces applied during bimanual manipulation, proposing that it can be conveyed through vibrations alone — without additional feedback — and that this is sufficient for greatly improving internal force regulations during teleoperated bimanual manipulation.

The SATYRR robotic platform was used to experimentally explore the metric and feedback delivery systems. Experimental results highlight several benefits of incorporating the proposed metric through VF into teleoperated manipulation: VF greatly reduced average internal forces, dampened force spikes, exhibited decreased variability across motion cycles, and may import more confidence in operations. In contrast, non-VF trials showed on average 65.3% higher mean and 108.6% larger amplitude more erratic - but more conservative - internal force magnitudes, indicating worse regulations of internal forces. Results confirm that antagonistic VF significantly improves control over internal forces, supporting its role as a valuable addition to teleoperation interfaces.

Overall, results confirm VF as a powerful tool for improving force control in dynamic tasks. Conducted experiments were sufficient to prove that simple VF can provide sufficient feedback to greatly improve IFR during bimanual teleoperation - a primary goal. However, future research could revisit these experiments with larger sample sizes, more diverse operators, and extended study durations/scope. This extension into further studies could enter and explore the Human Machine Interface (HMI) field. Future studies exploring additional SaSA benefits, such as estimating the mass of a payload or initiating robotic contact, are another intriguing extensions of this research.

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