2024 American Control Conference (ACC)
July 8-12, 2024. Toronto, Canada

Intention-Aware Reverse Passivity-Based Teleoperation Stabilizer for Physical Human-(tele)Robot Interaction

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Abstract— **In networked robotic systems, specifically haptics-enabled teleoperation, ensuring stability and trackig performance is of paramount importance. Recently, several stabilizers have leveraged the concept of "excess of passivity" (EoP) from non-linear control theory to decode and incorporate the dissipative energetic behavior of human biomechanics in the design of the stabilizers. This is done to counterbalance the effect of energy accumulation in the system due to the suboptimal non-passive communication behavior (which includes delays, jitter and packet losses). However, the dissipative behavior of human biomechanics naturally degrades the perceived force transparency when considering the "intended force" as the desired signal to be tracked. In other words, there is a "force gap" between the tracked forces and the intended forces. This is because parts of energy production are compensated for to move human biomechanics. This paper focuses on filling the gap by designing a networked robotic architecture that recovers parts of the dissipated active force of the operator so that the remote task is conducted according to the intended action of the operator rather than dissipated action. This requires a reformulation of the telerobotic architecture and the corresponding controllers. In this paper, we mathematically formulate a reverse telerobotic design and synthesize a new passivity-based stabilizer, named Intention-aware reverse Time Domain Passivity-Based teleoperation stabilizer (ITDPB) so that system stability is guaranteed while perceived transparency is recovered. In addition, we conduct extensive grid simulations, comparing the results of our proposed stabilizer to the state-of-the-art approach. The results indicate that the proposed approach has superior performance in terms of maximizing the ratio between the force intended by the user and the actual force transmitted to the environment while guaranteeing the system's stability. The proposed stabilizer is suitable for various telerobotic applications requiring accurate intentional force, such as telerehabilitation and telesurgery.**

I. Introduction

Two principal criteria are widely considered and optimized within the field of physical human-(tele)robot interaction: first, ensuring the safety of the interaction between humans and robots, and second, optimizing the energy transfer from human biomechanics to robotic mechanisms. In the area of haptics and teleoperation, these considerations deeply align with the principles of stability and transparency, which are crucial and consistently challenged features. For example, one primary challenge that jeopardizes the above-mentioned principles in human-telerobot interactions is the poor communication quality between haptic interfaces on two ends of the teleoperation (e.g., the leader and the follower robots). Problems including time delays, packet losses, and jitter are frequently seen as the cause of non-passive networked coupling [1]–[3]. Additionally, another challenge is the internal electromechanical inconsistencies of the teleoperation platform such as encoder faults, noise, and other measurement imperfections [4], which raise additional challenges to the safety and transparency and present significant obstacles to maintaining an effective and trustworthy system.

Therefore, various stabilizing algorithmic solutions have been formulated to mitigate the effects mentioned above specifically the non-passivity of the communication delays. Some popular solutions encompass wave variable control [5], time-domain passivity control (TDPC) [6]–[11], scattering control [12], small-gain control [13], and passive set-position modulation [14] to guarantee the system's stability. Besides guaranteeing safety, some passivity-based stabilizers go one step further to enhance transparency by taking the human biomechanics and its energy absorption capability during the human-robot interaction into account, related to the concept of the 'excess of passivity'. This concept is derived from the nonlinear control theory, and the stabilizer can significantly enhance energy fidelity by utilizing the energetic behavior of the human biomechanics as a "passivity margin" to reduce/compensate-for the damping that is supposed to be injected by the stabilizers to stabilize the system due to the poor communication conditions, resulting in less activation of the stabilizer and higher signal transfer fidelity due to higher tracking (note: the activitions of stabilizers affect signal tracking to guarantee stability). The references to examples of this development can be found in [15]–[19].

The aforementioned methods address the energy degradations in the system that are directly induced by conservative stabilizers while guaranteeing the system's stability. However, these approaches ignore another critical energy degradation source within the human-robot-interaction scenario: the involuntary energy loss associated with the human's internal reactive dynamic properties, such as the energy consumed by the biomechanics to merely move a limb during task conduction. A more damped and stiffed limb (such as in

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post-stroke patients with hypertonia during rehabilitation robotic sessions) would cause higher energy dissipation for generating the same output force. The portion of the energy consumed in the activation or movement of the limbs is inevitable, and thus, a prior energy degradation before transmitting the “intention” to the robot has always existed. In this case, there is always an energy gap between (a) the energy that muscles have generated according to motion intention, and (b) and the energy that is finally transmitted into the robotics system. The amount of the energy gap is relative to the individual’s intrinsic biomechanical property and the task dynamicity. More intuitively, this is reflected as a force gap between the intentional force that the user wants to apply to the robot and the actual force that can be measured on the robot applied by the user. This natural behavior will degrade the task’s performance, especially for tasks requiring precise force delivery, such as [20]–[22]. If we can access the individual’s intrinsic biomechanical property, we can potentially utilize this knowledge to recover and compensate for the energy loss and force gap thus we can achieve an ultra transparency (force tracking) which allows the intended force to be operational rather than the created force. This is a novel view to teleoperation which augments the sensorimotor experience of the operator and is targetted for the first time in this paper.

In this study, we present a new teleoperation framework and we synthesize a new stabilizer designed to enhance involuntary force transparency in a force-velocity domain using alternate-hybrid teleoperation architecture, which leverages the inherent energetic behavior of human biomechanics to counteract internal energy degradation. The goal is to recover the energy dissipated by the reactive component of the biomechanics and augment the transmitted energy. The formulation is conducted in the context of passivity control theory and the stabilizers is designed to guarantee L_2 stability of the closed loop system. The results show the new stabilizer embedded with the proposed force augmentation module enables a more exact and transparent transmission of the user’s intended force in teleoperation while guaranteeing the stability of the system. This is the first step towards telerobotic system that can respond to human intention rather than just sensory recording from the motions. In other words, the proposed framework enables a stable closed loop interaction between human intention and remote task conduction.

The rest of this paper is organized as follows. In Section II, we provide the Preliminaries regarding the definitions of passivity used in this paper. In Section III, we provide the derivation of the proposed system architecture and stability analyses. In Section IV, we provide the simulation results using the proposed stabilizer. The paper is concluded in Section V.

II. Preliminaries: System modeling and stability analysis

In Figure 1, we show the revised two-channel alternative hybrid bilateral teleoperation architecture [23], which serves as the foundation for the proposed system model. This design modifies the conventional Lawrence’s four-channel architecture (details can be found in [6]). As can be seen, the impedance model is located on the leader side which generates the leading force, and the admittance model is located on the follower side which generates the reactive velocity.

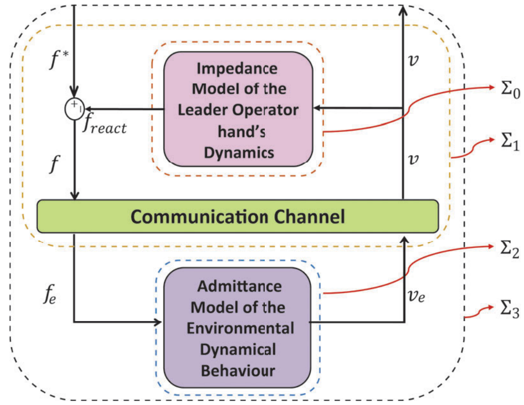

Fig. 1. System architecture

Besides displaying the information flow, Fig. 1 also shows the resulting interaction loop of the system. In this figure, subsystem Σ_0 is the impedance model of the leader terminal, and subsystem Σ_2 denotes the admittance model of the follower terminal. Subsystem Σ_1 encloses the communication channel and the leader, and subsystem Σ_3 denotes the overall teleoperation model.

A. Force decomposition

In the context of telerobotic systems involving human biomechanics in the loop, it should be noted that the operator’s intentional force f^* at the leader side, which is the force that represents the active exogenous component that the operator consciously decides to apply to the robot, can be decoupled into two components:

$$f^* = f + f_{react} \quad \text{and} \quad f_{react} = z(v, t). \tag{1}$$

Firstly, we denote the internal reactive force component as f_{react}, and the residual force component as f. The f_{react} is the resulting force generated by the nonlinear impedance model of the leader operator’s reactive dynamics $z(v_0, t)$ and the corresponding bio-mechanical resistance during the human-robot interaction. This force varies for each individual due to the fact that each person’s limbs have unique biomechanical properties. f is a residual component, which is the actual measurable force applied on the robot mechanism.

B. Passivity Based Stability Conditions

Taking advantage of the strong passivity theory, we can define the stability condition of the system utilizing the passivity definitions [24]–[27].

Definition 1 (Passive System): a system $S(t)$, with input $I(t)$, output $O(t)$, and initial energy $E_S(0)$, is passive if and only if:

$$E_S(t) + E_S(0) \geq 0, \, \forall t > 0, \tag{2}$$

where $E_S(t)$ is the system's energy and is defined as:

$$E_S(t) = \int_0^t I(t)^T O(t) dt. \quad (3)$$

Definition 2 (Output Strictly Passive System): a system with input $I(t)$, output $O(t)$, and initial energy $E_S(0)$ is considered as output strictly passive (OSP) system if:

$$\int_0^t I(t)^T O(t) dt + E_S(0) \geq \xi \int_0^t O(t)^T O(t) dt \quad (4)$$

when there is a non-negative Excess of Passivity (EoP) coefficient of $\xi \geq 0$. It can be shown that an OSP system is L_2 stable with a finite L_2 gain of $1/\xi$. Also a strictly passive system is asymptotically stable [27]. Additionally, it should be noted that, according to the definition in (4), the system is output non-passive (ONP) with a shortage of passivity (SoP) coefficient of ξ if $\xi \leq 0$.

Based on the definitions above, we will design the stabilizers of the proposed architecture. One can say that the interconnected system in Fig.1, is stable if the entire interconnection subsystem Σ_3 is passive, which is equivalent to satisfying equation (3):

$$\int_0^t f^*(t)^T v(t) dt > 0 \quad (5)$$

where the f^* is the operator's intentional force, and v is the velocity feedback from the follower side through the communication channel. Combining equation (1) and (5) and decoupling f^*, the passivity criterion of the system becomes:

$$\int_0^t f_{react}(t) v(t) dt + \int_0^t f(t) v(t) dt > 0 \quad (6)$$

It should be noted that the human operator's biomechanics are usually considered in the literature as a (strictly) passive system [28], such that $\int_0^t f_{react}(t) v(t) dt > 0$. Therefore, we can have a conservative passivity criterion as follows:

$$\int_0^t f(t) v(t) dt > 0 \quad (7)$$

C. Impedance-Based EoP Estimation

The nonlinear biomechanical EoP is related to the intrinsic energetic performance of the operator's biomechanics to absorb kinesthetic energy during the human-robot interaction. In our previous study, we proposed a mathematical foundation and an offline systematic identification procedure to identify the EoP of the human upper limb [15], [17]. The outcome of the identification procedure is a Passivity Map, which displays corresponding EoP under several aspects such as muscle contraction levels, geometric directions of perturbation, and perturbation frequencies; more detail of the experimental setup can found in the following reference [29]–[32].

The mathematical foundation of the EoP is based on the OSP condition derived from nonlinear control theory, as we mentioned in (4). By applying the OSP condition, we can assess the human biomechanics' passivity margin. In this case, a desired perturbation velocity of '$v_{m,\omega,i}$' is applied to the human arm, causing it to assume the reactive force '$f_{m,\omega,i}$' during the interaction; 'm, ω, i' relate to the muscle activation level, perturbation frequency, and direction of perturbation respectively. Thus the EoP of human biomechanics can be written as:

$$\xi_{m,\omega,i} = \frac{\int_{T_s}^{T_e} v_{m,\omega,i}(t)^T f_{m,\omega,i}(t) dt}{\int_{T_s}^{T_e} f_{m,\omega,i}(t)^T f_{m,\omega,i}(t) dt}, \quad (8)$$

where the resulting passivity margin of the limb during the interaction is shown in equation (8) as $\xi_{m,\omega,i}$. T_s and T_e indicated the beginning and ending times of each perturbation direction. A higher value of the ξ indicates that human biomechanics has a greater capacity to absorb energy during physical human-robot interaction (pHRI) in the force-velocity domain.

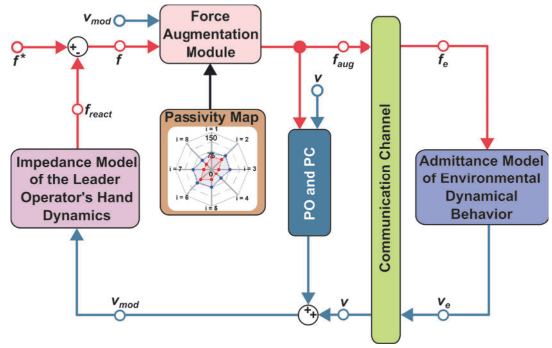

Fig. 2. Proposed Stabilizer architecture

III. Stabilizer Derivation

Based on a discrete formulation of definitions given in the previous section, here, the proposed force augmentation and a new stabilizer are introduced. Fig.2 illustrates the schematic design of the proposed intention-aware alternative hybrid Time Domain Passivity-Based teleoperation stabilizer architecture. This proposed architecture contains three essential components: the Passivity Observer (PO), the Passivity Controller (PC), and the Passivity Map. The PO monitors the system's energy level consistently, and the PC accordingly injects damping into the system to guarantee the passivity criterion, mainly through force modifications in this context. In addition, the Passivity Map illustrates the extra passivity margins accessible under various conditions, providing a guide for potentially improving the system's overall performance.

In this paper, we utilize the EoP information from the Passivity Map to drive the force-augmentation module, which augments the force in a way that effectively reduces the force error caused by the energy gap in motor intention and actual motor function. This bridges the intentional and applied force to the robot. Therefore, instead of directly delivering the measured force f, we consider the augmented force f_{aug}, which takes into account the EoP information. This augmented force is proposed in discrete time as follows when n is the time stamp:

$$f_{aug}[n] = f[n] + \xi[n] v_{mod}[n-1] \tag{9}$$

By doing this, the force transmitted to the follower side is the force after the augmentation, which depends on the force before augmentation $f[n]$, the previous time stamp velocity $v_{mod}[n-1]$, and also the EoP value under that time stamp condition $\xi[n]$.

In this regard, the energy that the PO monitors at n time stamp is denoted as E_{obs}[n], which is equal to:

$$E_{obs}[n] = \sum f_{aug}[n] v[n] \Delta T \tag{10}$$

where ΔT is the sample time in the discrete time system. In this design, the reflected velocity is modified by the passivity controller which injects damping through the gain, α, based on the following equation:

$$v_{mod}[n] = v[n] + \alpha[n] f_{aug}[n] \tag{11}$$

The value of α is determined as follows to guarantee the passivity condition:

$$\alpha[n] = \begin{cases} \text{if } E_{obs}[n] > 0, \alpha[n] = 0 \\ \text{if } E_{obs}[n] < 0, \alpha[n] = \frac{-E_{obs}[n]}{f_{aug}[n] f_{aug}[n] \Delta T} \end{cases} \tag{12}$$

As can be seen, when the observed energy is positive which indicates a passive interaction, no damping is introduced by the system. However, when the observed energy is negative which indicates a non-passive interaction (thus potential instability) an adaptive damping of $\alpha[n]$ is introduced to dissipate the amount of observed non-passive energy in one shot. This would result in a variable structure controller that guarantees the passivity condition thus stability of the system. It should be noted that the utilized force in this derivation is the augmented force (instead of the measured force) that is designed as per (9). Thus the proposed formulation would augment the force to fill out the energy gap and would introduce just-enough dissipation to impose passivity, as in (12) thus guarantee stability.

IV. Result

In order to verify the performance of the proposed stabilizer, a series of grid simulations, including 225 variations of the parameters, are conducted. The stabilizer module is considered to be (a) The proposed ITDPB stabilizer with the force augmentation module and (b) the conventional alternative hybrid TDPC stabilizer, which follows the force/velocity information transmit structure. Table 1 demonstrates the details of the simulation setup. We denote the model of the human's upper limb biomechanics as an impedance model on the leader side as Z_h. And f^* is the exogenous force, which is the intentional force the operator applies on the leader side. The Excess of Passivity, ξ, is set as 80 Nm/s, which is around 80% of the actual magnitude of the human biomechanic damping coefficient and close to the values obtained through offline EoP identification.

The environment model's damping coefficient is defined as b_e, which varied from 0 ms to 40 Nm/s with fifteen equal step sizes, resulting in fifteen different delay values. Similarly, the one-way communication delay value τ is varied from 0 ms to 200 ms with fifteen equal step sizes, resulting in fifteen different delay values. Through these settings, a total of 225 simulation trials are conducted for each stabilizer. During each trial, the intentional force, measured force, velocity, and corresponding energy within the system are recorded.

TABLE I
SIMULATION PARAMETER

Operator Model:	$Z_h = 2s^2 + 100s + 5\frac{1}{s}$
Exogenous Force:	$f^* = 20(sin(1\pi t) + sin(0.5\pi t)$ N
Excess of Passivity:	ξ = 80 Ns/m
Communication Delay:	$t_d = (\tau + 0.25\tau sin(20t))$ s
Environmnet Model:	$\frac{s}{10s^2 + b_e s + 5}$

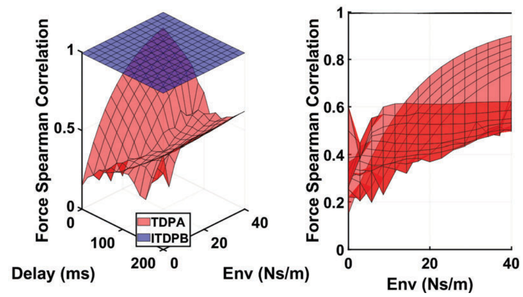

Fig. 3. Spearman correlation between Intentional force and measured force of TDPC and ITDPB stabilizers

A. Intentional Force transparency

Spearman Correlation Coefficient: The Spearman correlation coefficient [33] between the intentional force and the applied force is illustrated in Fig.3. The Spearman correlation coefficient reflects the nonlinear, monotonic relation between two variables. The calculation of the Spearman correlation is followed [34]. If a value is close to 1, it means that the intentional force and the applied force have a stronger monotonic relationship maintained by the stabilizer. Likewise, if a value is close to 0, it means that the force tracking between the intentional force and the applied force is poor.

In Fig.3, the surface plot demonstrates the Force Spearman correlation coefficient for each simulation trial where the delay and environment damping coefficients are varied as mentioned in setting values above. The blue surface plot is the result of the proposed stabilizer ITDPB, and the red surface is the result of the conventional TDPA stabilizer without the force augmentation module. As can be seen, the values in the blue surface plot are always higher than the values in the red surface plot, regardless of the various parameters. This phenomenon indicates that, with the force augmentation module, the proposed stabilizer has a better force tracking performance between the intentional and applied force in terms of magnitude and direction, resulting in a more continuous and intuitive feeling at the environment side of the teleoperation architecture.

Root Mean Square Error (RMSE) and Force Reflection Ratio: RMSE is a frequently used and standard metric to quantify how different, on average, the fitness between

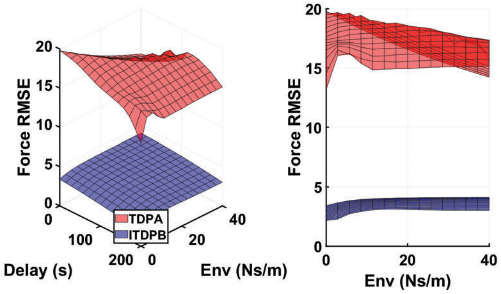

Fig. 4. Force RMSE between Intentional force and measured force of TDPC and ITDPB stabilizers

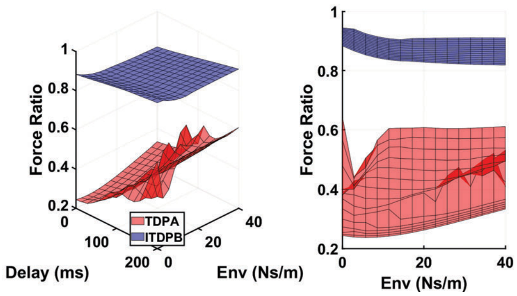

Fig. 5. Force Reflection Ratio between Intentional force and measured force of TDPC and ITDPB stabilizers

two variables are in a given experiment. In our specific scenario, low RMSE values indicate that the intentional and the applied force has less error and, therefore, preserves greater fidelity. The method to calculate the RMSE can be found in [35]. Similarly to how the RMSE is used to assess the fidelity between the intentional and the applied force, the Force Reflection Ratio is another metric to delineate the accuracy and fidelity further. The force reflection ratio is calculated as the applied force's absolute mean divided by the intentional force's absolute mean, over the whole simulation period. If the force reflection ratio is close to 1, it means that the applied force's magnitude has a high preservation of the intentional force, maintaining a superior quality of transparency in the force loop.

As can be seen in Fig. 4, the RMSE value of the conventional TDPA exhibits a significantly higher value than the RMSE value of the proposed ITDPB stabilizer. This phenomenon is observed across all environmental parameters and communication delays. Similarly, Fig. 5 illustrates that the ITDPB stabilizer outperforms the traditional stabilizer in all evaluated conditions by maintaining a Force Reflection ratio closer to the ideal value of 1. These results highlight the effectiveness of incorporating the force augmentation module within the stabilizer. The module effectively improves the intentional force tracking performance by actively counteracting the inevitable force reduction caused by the activation and movement of the human biomechanics. It should also be mentioned that the amount of compensation introduced by this force augmentation module depends on the EoP value drawn from the unique Passivity Map for each individual.

Simulation Case Analysis: To better assess the intentional force-tracking performance under the two abovementioned stabilizers, we examine a portion of the trials from the large

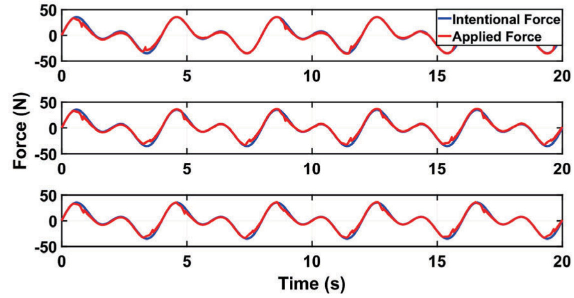

Fig. 6. Case analysis from the grid simulation of the proposed stabilizer. From top to bottom: 1) b_e = 0Nm/s, 2) b_e = 20Nm/s, and 3) b_e = 40Nm/s.

grid simulation, concentrating on representative situations that accurately represent the system's performance in various parameter settings. We selected trials with a delay parameter of 200ms to demonstrate the performance of the stabilizer while encountering a high communication delay. Within the 200ms simulations, three different environment damping parameters are selected: b_e = 0Nm/s, b_e = 20Nm/s, and b_e = 40Nm/s, which are the lower boundary, the median value, and the upper boundary of the environment-damping coefficient simulation range, which enables a comprehensive understanding of the stabilizer's adaptability and resilience in a variety of conditions.

In Fig. 6, we plot the intentional force (blue) and applied force (red) using the proposed ITDPB stabilizer. As can be seen, the intentional force and applied force exhibit a high degree of overlap. This phenomenon can be found in all representative trials, which result from utilizing the potential energetic behavior from the human upper limb to compensate for the intentional energy loss, resulting in greater force transparency through time.

In contrast, Fig.7, which are force profiles using the conventional stabilizer, depicts a different result. The blue and red lines display a minimal degree of overlap, showing a significant difference between the magnitudes of the intentional force and applied force. Even though the situation improves slightly as the environmental damping value increases (the system becomes a more passive system), the force gap remains notable. This phenomenon is caused by the inevitable energy dissipation during the activation of biomechanical dynamics in human-robot interactions, resulting in reduced force applied to the robot and, thus, diminished force transparency. As can be seen by reducing the gap using the excess of passivity of the biomechanics we are able to have a much closer force tracking when all trajectories are bounded.

V. Conclusion

In this paper, a new passivity-based stabilizer is proposed for haptics-enabled network teleoperation systems, named Intention-aware Reverse Time Domain Passivity-Based (ITDPB) stabilizer. The ITDPB stabilizer utilizes knowledge of the human biomechanics' energetic properties and embeds it into the stabilizer design during the human-robot interaction. This paper targets the inevitable energy consumption problem that arises from the activation or movement of biomechanical dynamics in human-robot interactions, which results

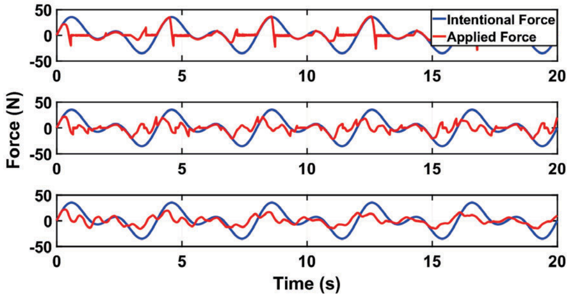

Fig. 7. Case analysis from the grid simulation of the state-of-the-art stabilizer. From top to bottom: 1) b_e = 0Nm/s, 2) b_e = 20Nm/s, and 3) b_e = 40Nm/s.

in a force gap between the human intention force conceived in the brain and the actual force received by the robot and degrades the system's performance. Here, for the first time, we utilize the energetic behavior of human biomechanics to develop a stabilizer with a force augmentation module to eliminate the energy degradation and thus minimize the aforementioned force gap. The performance of the proposed stabilizer has been verified. The results demonstrate that after implementing the proposed stabilizer, the received force by the robot is significantly amplified by the force augmentation module, thus resulting in greater intentional force transparency and fidelity while guaranteeing the stability criterion of the system. Due to the proposed stabilizer's remarkable performance in multiple settings presented in this paper, in the future this stabilizer can be employed in various telerobotic applications that require accurate intentional force received, such as in telerehabilitation and telesurgery.

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