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A Dual-User Teleoperated Surgery Training Scheme Based on Virtual Fixture

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***Abstract*—The widespread use of minimally invasive surgery (MIS) demands an appropriate framework to train novice surgeons (trainees) to perform MIS. One of the effective ways to establish a cooperative training system is to use virtual fixtures. In this paper, a guiding virtual fixture is proposed to correct the movements of the trainee according to trainer hand motion performing a real MIS surgery. The proposed training framework utilizes the position signals of trainer to modify incorrect movements of the trainee which leads to shaping the trainee's muscle memory. Thus, after enough training sessions the trainee gains sufficient experience to perform the surgical task without any further help from the trainer. The passivity approach is utilized to analyze the stability of system. Simulation results are also presented to demonstrate the effectiveness of the proposed method.**

***Index Terms*—Teleoperation, MIS, Eye surgery, Haptic training, Virtual fixture**

I. INTRODUCTION

Teleoperated systems have been used in several applications such as space missions, underwater explorations, handling hazardous materials, surgery, etc [1]. One of the recent applications in which teleoperated systems are used is training of Minimally invasive surgeries (MIS). A major challenge that limits the widespread use of MIS is training novice surgeons. In a MIS the operating workspace and the availability of visual and tactile feedback are limited; thus, special training is required to adapt the medical students to such limitations [2], [3]. In the last decade, dual user haptic systems have been utilized to compensate for aforementioned limitations and provide an effective training framework. Up to now, several control methodologies have been proposed for dual user haptic systems based on H_∞ control [4], six channel shared control architecture [5], PD+d control [6], [7], adaptive control [8]–[10], etc. In the above mentioned investigations a linear combination of the position signals of the trainer and the trainee is transmitted to the surgical robot as the desired position. Moreover, the authority of each surgeon over the task is determined by the dominance factor which is calculated based on the relative level of expertise of the surgeons. In fact, the dominance factor is mostly used in dual-master, single-slave teleopreation systems to have participation of both the trainer and the trainee in performing the surgical tasks.

A different training methodology which leads to less surgical complications is to give the full dominance to the trainer as long as the trainee is not experienced enough to perform the task on his own. In this approach, the trainer performs the surgical tasks and the trainee imitates the operations by receiving feedback from the trainer. In this training methodology one may employ the virtual fixture concept to achieve a fast an efficient hands-on training. The concept of virtual fixture was first introduced in [11] as a means to improve the precision in telemanipulation. To intuitively illustrate the concept of virtual fixture, it is stated that a perfectly straight line is drawn faster and more precise, provided that a ruler is used. In fact, the required mental process to perform the task is significantly reduces in contrast to the case that no ruler is used at all.

A virtual fixture is a command force calculated by software and applied to operator's hand. It can be used either in a cooperative task or a telemanipulation [12]. As discussed in [12] virtual fixtures are classified as Guiding Virtual Fixture (GVF) and Forbidden Region Virtual Fixture (FRVF). GVF helps the operator to move along a desired trajectory while FRVF prohibits the operator whenever the end effector is entering a forbidden region in the task space.

The concept of virtual fixture may also be utilized in the training since the computed command force is applied to the trainee's hands as a guidance cue to increase his skill level. After receiving such guidance cues for a while, the muscle memory is trained such that the trainee is able to perform the surgical tasks even in the absence of any guidance. In [3] a sphere-shaped virtual fixture with a time varying radius is utilized as a means to train novice surgeons. However in a small task space such as a MIS case stiffness of the virtual fixture may play a greater role than its radius. In this paper a new methodology to design a virtual fixture with time varying stiffness is proposed. The online calculation of the stiffness is accomplished based on a time interval for integration of the position tracking error. The stability of dual user haptic system in the presence of designed virtual fixture scheme is also analyzed using the passivity approach.

The rest of this paper is organized as follows: In Section II, a virtual fixture controller is introduced with varying stiffness for training purposes in a bilateral scheme. Section III describes dynamic formulation of the system and a passivity based stability analysis. Furthermore, the effectiveness of such controller is demonstrated in Section IV through simulation, and the concluding remarks are stated in Section V.

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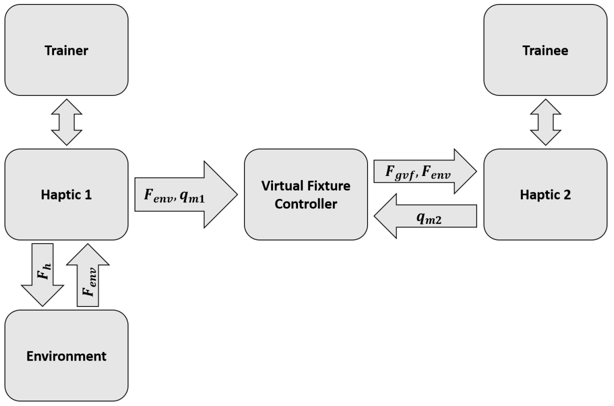

Fig. 1. The block diagram of our surgery training scheme.

II. TRAINING SCHEME

As it is mentioned before, the common topology for the training purposes is dual-master, single-slave. The drawback of such topology is that the surgeon cannot focus solely on the surgery and does not have a real tactile feedback of the environment. It is possible to omit the robot from the structure thus the trainer can perform the surgical task freely and yet provide the trainee with some hands-on training. The idea is to capture trainer's hand motion and transmit them along with environmental force to the trainee; hence, there is a reference to correct trainee's movements and it is possible to provide him/her with telepresence. To arrange such configuration, two identical haptic devices may be used, one should be attached to the surgery tool and the other one will be at trainee's control. The first haptic device should ideally not interfere with the trainee's hand motion and the second haptic can effectively act like a correcting hand, holding the end of the surgery tool and helping the trainee to do the correct moves. In this paper it is proposed to apply a GVF to trainee hand, according to the trainer's hand motion at all time. Figure 1 depicts the block diagram of the presented surgery training scheme.

Let us now, describe the objective of training in a mathematical framework. For any given time $t > 0$ the position error between the trainer and the trainee is expected to be bounded as follows:

$$||q_{m2} - q_{m1}||_2 \leq r_{TZ} \tag{1}$$

in which q_{mi} refers to the position of master $i = 1$ represents the trainer's parameters, and $i = 2$ represents that for the trainee, r_{TZ} is a scaler indicating the radius of a sphere-shaped trust zone. Intuitively, equation (1) restricts the trainee to follow the trainer's movements with an allowed margin of error determined by r_{TZ}. In order to satisfy equation (1) the trainee is forced to move back inside of the trust zone if he/she tries to do otherwise. This is possible if a sphere-shaped GVF is represented by:

$$F_{gvf} = -K_{gvf}||q_{m2} - q_{m1}||_2 \delta(E_p) \tag{2}$$

in which F_{gvf} is the force applied to the trainee's hand to correct his movements, and K_{gvf} represents the stiffness of the GVF. Besides, $\delta(E_p)$ is defined as follows to provide a linearly smoothed relay function:

$$\delta(E_p) = \begin{cases} 0 & \text{if } E_p < \epsilon + r_{TZ} \\ 1 & \text{if } E_p \geq 2\epsilon + r_{TZ} \\ \dfrac{1}{\epsilon}(E_p - r_{TZ} - \epsilon) & elsewhere \end{cases} \tag{3}$$

where,

$$E_p = ||q_{m2} - q_{m1}||_2 \tag{4}$$

is the distance function between position vectors of trainer and trainee. Furthermore, ϵ is an arbitrary small positive design parameter. The GVF is defined according to the trainee's skill level. It is more stiff if the trainee is not doing well, and more compliant if the trainee has tracked the trainer accurately for a suitably long time. This concept is formulated as follows:

$$K_{gvf} = max(K_1, K_{gvf,min}) \tag{5}$$

in which K_1 is:

$$K_1 = \frac{\int_{t-T}^{t} ||q_{m2}(\tau) - q_{m1}(\tau)||_2 d\tau}{max(\int_{t-T}^{t} ||q_{m2}(\tau) - q_{m1}(\tau)||_2 d\tau)} K_{gvf,max} \tag{6}$$

and in (5) $K_{gvf,min}$ is chosen such that it fits the actuators limits and to satisfy the stability condition given later in (19), and $K_{gvf,max}$ is chosen such that to satisfy the actuator saturation limits. The maximum accumulated error over time window $max(\int_{t-T}^{t} ||q_{m2}(\tau) - q_{m1}(\tau)||_2 d\tau)$ may also be set to the worst case scenario in the available workspace; thus, it is representing a normalizing coefficient.

III. SYSTEM DYNAMICS AND STABILITY ANALYSIS

In this section we elaborate on closed loop system dynamics including the controller proposed in (2), then analyze the stability through a passivity based approach. The dynamic formulation of the haptic console for trainee may be represented by:

$$M(q_1)\ddot{q_1} + C(q_1, \dot{q_1})\dot{q_1} + G(q_1) = F_{h_1} - F_{env} - F_{w_1} \tag{7}$$

where $M(q_1)$ is the inertia matrix, $C(q_1, \dot{q_1})$ represents the Coriolis and centrifugal terms, G contains the terms describing gravity's effect of the haptic console, F_{h_1} is the force exerted by trainee's hand, F_{env} is the contact force with environment, and F_{w_1} represents all forces which cause energy loss in the system. Note that, F_{env} is assumed to be measurable and known. For the trainee console, we may write the dynamics formulation as:

$$\begin{aligned} M(q_2)\ddot{q_2} + C(q_2, \dot{q_2})\dot{q_2} + G(q_2) = F_{h_2} - F_{env} \\ - F_{w_2} + F_{gvf}\delta(E_p) \end{aligned} \tag{8}$$

where q_1 refers to position vector of the trainer while q_2 refers to position vector of the trainee. It is assumed that two identical haptic consoles are used for trainee and trainer, and therefore, their dynamic matrices are considered the same. The contact force to the environment is assumed to be known by use of appropriate force sensors. The friction losses in the trainee haptic device is represented by F_{w_2}, and is considered to be

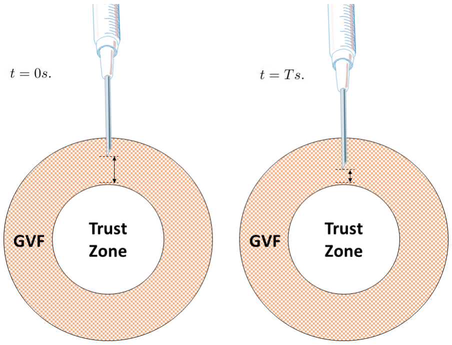

Fig. 2. The first scenario in the analysis.

trajectory dependent. F_{gvf} is used in this device as represented by (2). Some useful properties of the dynamic formulations 7 and 8 are given as follows [13]:

Property 1. *The inertia matrix $M(q_i)$ is symmetric and positive definite for all $q_i \in \mathbb{R}$.*

Property 2. *The matrix $\dot{M}(q_i) - 2C(q_i, \dot{q}_i)$ is skew symmetric and satisfies:*

$$v^T(\dot{M}(q_i) - 2C(q_i, \dot{q}_i))v = 0, \forall v \in \mathbb{R}. \tag{9}$$

The stability analysis is discussed for a general 3-DOF haptic device. The system data is assumed to be sampled every T seconds. In this section the initial distance function ,$E_p(0)$, is represented by E_{p_0} and the final distance function ,$E_p(T)$, is represented by E_{p_T} for the sake of simplicity. Inspired by [14], four cases are considered which span all of the possible scenarios encountered with GVF in a surgical operations.

1) Trainee starts inside the GVF and ends up less deep but still inside the GVF ($E_{p_0} > r_{TZ} + \epsilon, r_{TZ} + \epsilon \leq E_{p_T} < E_{p_0}$). It means that the trainee is not tracking the trainer well at $t = 0s$ but he does better at $t = Ts$. Figure 2 depicts this scenario.
2) Trainee starts inside the GVF and ends up deeper inside of the GVF ($E_{p_0} \geq r_{TZ} + \epsilon, E_{p_T} > E_{p_0}$). It means that tracking error increases from $t = 0s$ to $t = Ts$. This scenario is shown in figure 3.
3) Trainee starts inside the trust zone but outside the GVF and ends up inside of the GVF ($E_{p_0} < r_{TZ} + \epsilon, E_{p_T} \geq r_{TZ} + \epsilon$). It means that trainee starts to deviate from the correct trajectory within the considered period of time T.
4) Trainee starts and ends inside the trust zone ($E_{p_0} < r_{TZ} + \epsilon, E_{p_T} < r_{TZ} + \epsilon$). This is the desired situation for the trainee.

The scenarios are discussed one by one and sufficient condition which grants passivity in each case is obtained.

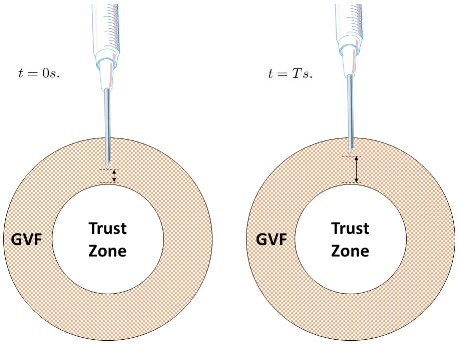

Fig. 3. The second scenario in the analysis.

A. Stability analysis of the first scenario

For the first scenario the work done on trainee's hand is

$$\begin{aligned} W_1 &= W_W + W_{gvf} + \int_{q_0}^{q_T} G(q)\dot{q}dq \\ &+ \frac{1}{2}(\dot{q}_T - \dot{q}_0)^T M(q)(\dot{q}_T - \dot{q}_0) - W_{env} \end{aligned} \tag{10}$$

in which W_W is the work done by Coulomb and Viscous friction. W_{gvf} is the work done on operator's hand by the GVF and it is calculated as

$$W_{gvf} = -F_{gvf}(q_0)(q_T - q_0) \tag{11}$$

in which $F_{gvf}(q_0) = K_{gvf}(q_0)q_0^T$. Furthermore, W_{env} is the work done by the environment calculated as (12).

$$W_{env} = -F_{env}(q_{m_{1_0}})(q_T - q_0) \tag{12}$$

in which $q_{m_{1_0}}$ is the position signal of the trainer sampled at the $t = 0$.

The proof concept is to prove that this system is more dissipative than a lossless (and passive) system. The standard system is an identical haptic device with no energy loss which has a passive and lossless spring attached to its end effector coming in contact with the same environment. The spring constant is $K = K_{gvf,min}$ and it is assumed to have no mass properties. We chose the stiffness of reference spring in a way to match the minimum possible stiffness for GVF, since the smaller the stiffness is, the more energy is stored in the system in the form of kinetic energy rather than potential energy, which in turn causes the system to have the potential to become non-passive. The work done on operator's hand by the standard system, which is shown with W_2, is a combination of the losses in kinetic energy, potential energy stored in the spring, work done by the environment and work done by the gravity.

$$\begin{aligned} W_2 &= \frac{1}{2}(\dot{q}_T - \dot{x}_0)^T M(q)(\dot{q}_T - \dot{q}_0) \\ &+ \frac{1}{2}K(q_T^T q_T - q_0^T q_0) + \int_{q_0}^{q_T} G(q)\dot{q}dq - W_{env} \end{aligned} \tag{13}$$

Now consider $J = W_2 - W_1$, which represents the difference in the amount of energy exerted from real haptic fixture controller and the lossless haptic device with spring. If we prove that the J has a non-negative lower bound we can conclude that potential energy stored in the system with the GVF controller is not greater than the potential energy stored in the ideal spring which is simply $\frac{1}{2}q^T Kq$. It is stated and proved in [14] that the trajectory which minimizes the energy loss due to Coulomb and Viscous friction is a monotonic trajectory which has no stops at finite time. Considering such trajectory, and model the Coulomb friction with a simple linear retarding force with no switching involved as

$$\begin{aligned} J = \frac{1}{2}K(q_T^T q_T - q_0^T q_0) + W_{gvf} - f_c(q_T - q_0) \\ + \int_0^T \dot{q}^T(t) b \dot{q}(t) dt \end{aligned} \tag{14}$$

The problem of finding lower bound for J is the same problem of finding lower bound for W_{gvf} and $\int_0^T \dot{q}^T(t) b \dot{q}(t) dt$. It can be proved that the lower bound on W_{gvf} is determined as follows:

$$K_{gvf,min} q_0^T (q_T - q_0) \le K_{gvf}(q_0) q_0^T (q_T - q_0) \tag{15}$$

As for $\int_0^T \dot{q}^T(t) b \dot{q}(t) dt$ by applying Cauchy-Schwarz inequality one may find a lower bound as the square of trajectory length

$$\frac{b}{T}(\int_0^T \dot{q}(t)dt)^T(\int_0^T \dot{q}(t)dt) \le \int_0^T \dot{q}^T(t) b \dot{q}(t) dt. \tag{16}$$

Hence, the lower bound of J may be found as

$$\begin{aligned} J \ge \frac{b}{T}(q_0 - q_T)^T(q_0 - q_T) + f_c(q_0 - q_T) + \\ \frac{1}{2}K(q_T^T q_T - q_0^T q_0) + \frac{1}{2}K_{gvf,min} q_0^T (q_T - q_0) = \\ \alpha(q_0 - q_T)^T(q_0 - q_T) + f_c(q_0 - q_T) \end{aligned} \tag{17}$$

in which, α is introduced as

$$\alpha = \frac{b}{T} - \frac{K_{gvf,min}}{2} \tag{18}$$

Analysing the quadratic nature of (17) one may conclude that lower bound of J is positive if

$$\alpha \ge 0. \tag{19}$$

According to (19) passivity of the GVF is sufficiently guaranteed in the first scenario if the minimum possible stiffness of the GVF is not greater than $\frac{2b}{T}$.

B. Stability analysis of the second scenario

In this scenario we want to guarantee that any potential energy stored in the GVF is accompanied by at least as much prior work input by the operator. Thus we define

$$W_3 = -W_2. \tag{20}$$

similar to what defined before one may define J as:

$$\begin{aligned} J = W_h - W_3 = \frac{1}{2}K(q_0^T q_0 - q_T^T q_T) + W_{gvf} + \\ f_c(q_T - q_0) + \int_0^T \dot{q}^T(t) b \dot{q}(t) dt. \end{aligned} \tag{21}$$

Hence, it can be claimed that

$$J \ge \alpha(q_0 - q_T)^T(q_0 - q_T) - f_c(q_0 - q_T) \tag{22}$$

For the lower bound to be positive other than (19), f_c needs to be positive which is always true. As a result, (19) sufficiently guarantees the passivity in the second scenario as well.

C. Stability analysis of the third scenario

In this scenario, we enter the GVF between two samples. In this scenario, the work done by the operator consists of two parts. In the first part some work needs to be done just to get the end effector in contact with GVF. In this part no energy is stored while some energy is dissipated to overcome the friction forces. The second part is the same as the second scenario. Hence, the sufficient condition for the second scenario is also sufficient for the third scenario.

D. Stability analysis of the fourth scenario

This is a trivial case in which the device does not come in contact with the GVF at two consequent sampling phases. If the trajectory comes in contact with the GVF after one sampling phase and leaves before the next sampling phase the analysis would be a combination of the first and the third scenario which already has been discussed.

E. Summery of Analysis

As it is discussed, finding a positive lower bound for quantity J as introduced in (14) ensures the passivity of a general 3-DOF haptic device with a virtual fixture described as (4) centred at its end effector between two samples, this time period is regarded as $t = 0s$ and $t = Ts$, regardless of the scenario. The lower bound obtained is a mathematical term with quadratic nature which is always positive if (19) holds. It can be shown that there is a more conservative but linear positive lower bound for J at any given point. Tangent line at each point is a straightforward suggestion to be considered. Therefore, at any given time between samples there is a linear positive lower bound for J. Now we can conclude that a linear combination of all this lower bounds can be considered as a measure to discuss the passivity in a general time frame and not restricted to one sample. This can be summarized as follows:

Theorem. *A general 3-DOF haptic device with a sphere-shaped virtual fixture fixed at its end effector is passive if* $\alpha \ge .0$

Proof. If $\alpha \ge 0$ holds the quadratic lower bound of J is not negative. A series of tangent lines to this positive quadratic lower bound are combined to form a positive lower bound not only between two samples but also in general. This positive lower bound proves the system to be more dissipative than a lossless and passive system which in turn can prove the system to be passive. □

IV. Simulation Results

The proposed training scheme is utilized for two identical 2DOF serial links with revolute joints as haptic devices. System dynamics are given in [15] for further consideration. In the simulations we assume the lengths l_1 and l_2 to be $0.1m$, the masses m_1 and m_2 to be $0.1kg$ and the initial conditions $\ddot{q}$, $\dot{q}$ and q are all set to zero. The model of environment is considered to be of Kelvin−Voigt [16] with $B = 0.0387$ and $K = 0.813$. The friction forces are modelled with $f_c = 0.001$ and $b = 0.001$. The forces exerted by trainer and trainee are shown in figure 4 in a typical simulation scenario. Trainee follows the trainer perfectly from $t = 0s$ to $t = 10s$. In this time period, the last scenario in the analysis is simulated. Then, the trainee exerts slightly less force than trainer from $t = 10s$ to $t = 30s$. In this time period the third scenario is realized in which the trainee starts to perform the movements with error. Afterwards, from $t = 30s$ to $t = 50s$ the trainee tries to correct himself/herself; however, at this period of time the excessive force applied by the trainee is greater than the trainer, leading to even more tracking error. Therefore, the second scenario is implemented in this time period. Then, from $t = 50s$ to $t = 70s$ the trainee exerts less force than before but still more than the trainer , and this simulates the first scenario. Finally, from $t = 70s$ to $t = 100s$ the trainee starts to exert forces equal to the trainer. This time period realizes the first scenario in which trainee reduces or fully compensates his/her error.

TABLE I
PERFORMANCE INDEXES FOR A GVF WITH TIME VARYING STIFFNESS (CASE (A)) AND FIXED STIFFNESS (CASE (B)) FOR q_1

Performance index	ISE	IAE	ITSE	ITAE
CASE (A)	4.075	457.896	167.963	19826.361
CASE (B)	31.059	971.215	1217.047	39502.208

TABLE II
PERFORMANCE INDEXES FOR A GVF WITH TIME VARYING STIFFNESS (CASE (A)) AND FIXED STIFFNESS (CASE (B)) FOR q_2

Performance index	ISE	IAE	ITSE	ITAE
CASE (A)	3.5519	443.526	142.844	18268.763
CASE (B)	19.203	828.727	759.649	33415.443

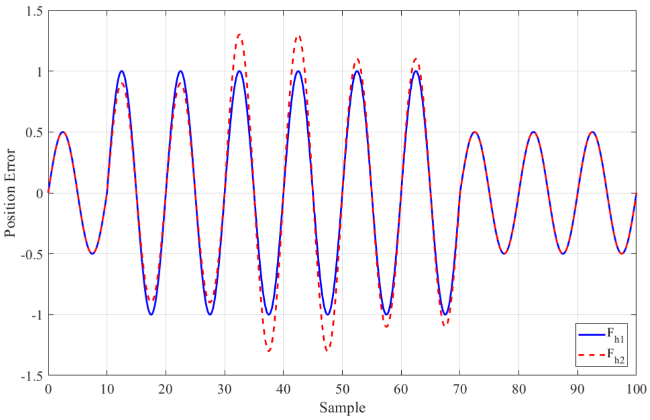

Fig. 4. The training trajectory followed by trainer and trainee.

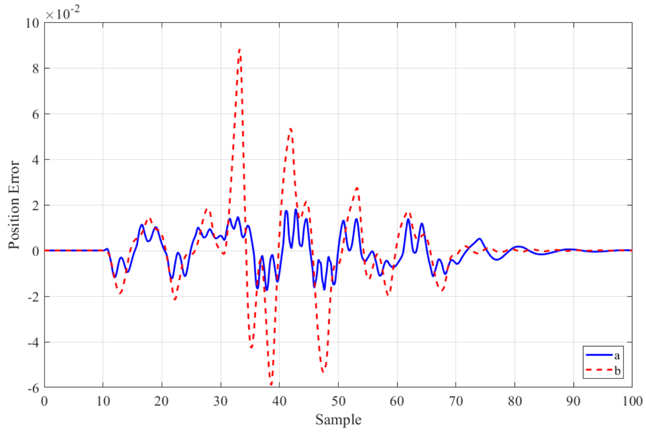

Fig. 5. The training process is done once with the proposed GVF controller (a) and once with a GVF controller with fixed stiffness equal to mean value of time varying case (b). The results for q_1 are presented.

Figures 5 and 6 show position tracking error for the aforementioned simulation scenarios. In case (a), the proposed controller given in (2) is applied. For the sake of comparison, another controller is applied indexed as case (b), in which on the contrary to the proposed controller scheme with time varying GVF, a simple GVF with the mean value of the applied stiffness in case (a) is considered. In table I different performance indices of the resulting responses are compared. It is shown that in general time varying GVF controller performers significantly better than that of fixed stiffness GVF controller. However, in some scenarios the fixed stiffness GVF controller ,with the stiffness equal to mean value of the time varying GVF, may grant better results, If the time windows in time varying GVF is not tuned properly. This can be seen in figures 7 and 8, in which, intentionally the time window of integrations in time varying GVF are not tuned properly. Due to the fact that the variation of forces are different in different scenarios, finding the appropriate time window to incorporate these variations fast enough into reaction force is very influential in the transient response of the closed loop system. in such cases the averaged stiffness value performs better if the actuator bandwidth is limited.

V. Conclusion and Future Work

In this paper, a GVF controller with time varying stiffness is proposed. The proposed controller, if properly tuned, results in significantly better results than the conventional fixed stiffness GVF controllers; hence, a better training process is ensured through the proposed controller. Simulation results verifies that the proposed approach outperforms the conventional fixed stiffness GVF controller. Our future research is focused on to determine the appropriate values for the trust zone and

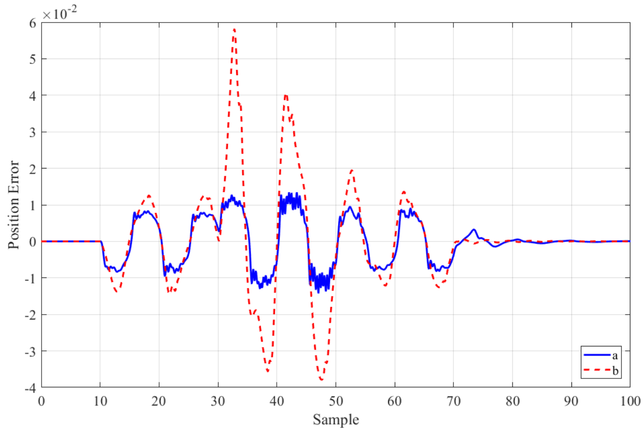

Fig. 6. The control effort is represented for the proposed GVF with time varying stiffness (a) and fixed stiffness (b). The results for q_2 are presented.

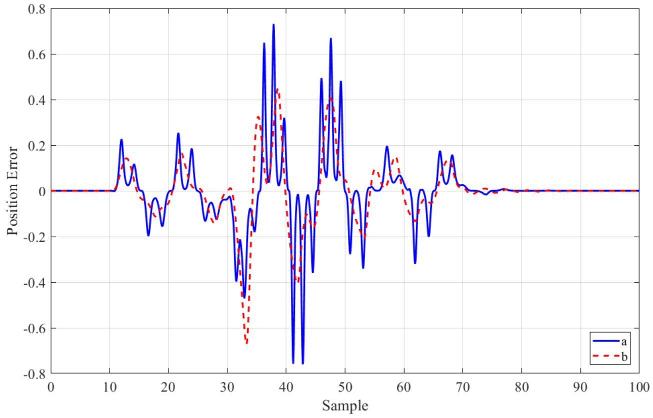

Fig. 7. The training process is done once with the proposed GVF controller (a) and once with a GVF controller with fixed stiffness equal to mean value of time varying case (b). The results for q_2 are presented.

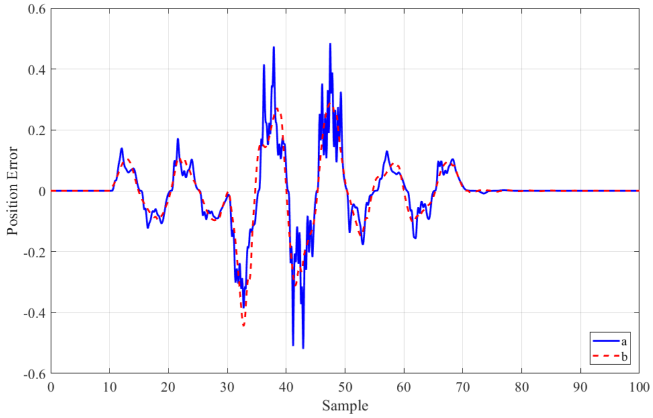

Fig. 8. The control effort is represented for the proposed GVF with time varying stiffness (a) and fixed stiffness (b). The results for q_1 are presented.

integration time, in an experimentally verified application on eye surgery training device.

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