Measurements of Multimodal Approach to Haptic Interaction in Second Life Interpersonal Communication System

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***Abstract*—The sense of touch has much importance in technology-mediated human emotion communication and interaction. Many researchers around the world are aiming to leverage the sense of touch in the communication medium between multiuser 3-D virtual world and real environment. Driven by the motivation, we explored the possibilities of integrating haptic interactions with Linden Lab's multiuser online virtual world, Second Life. We enhanced the open source Second Life viewer client in order to facilitate the communications of emotional feedbacks such as human touch, encouraging pat, and comforting hug to the participating users through real-world haptic stimulation. These emotional feedbacks that are fundamental to physical and emotional development in turn can enhance the users interactive and immersive experiences with the virtual social communities in the Second Life. In this paper, we describe the development of a prototype that realizes the aforementioned virtual-real communication through a haptic-jacket system. Some of the potential applications of the proposed approach includes distant lover's communication, remote child caring, and stress recovery.**

***Index Terms*—Haptics, interpersonal communication, Second Life (SL), tactile feedback, virtual world.**

I. Introduction

THE use of sense of touch has much significance in interhuman communication. Social emotional touches in the form of handshake, encouraging pat, hug, tickle, etc., physical contacts are fundamental to mental and psychological development, and, hence, their applications in interpersonal communication systems have attracted attention of many researchers around the world [1]. In order to convey the emotional feedbacks, haptic is given high regards in live communication [2], [3] and in immersive virtual environments [4]. The haptic-based nonverbal modality can enhance social interactivity and emotional immersive experiences in a 3-D multiuser virtual world that presents a 3-D realistic environment, where people can enroll in an online virtual community [5]. One of the most popular and rapidly spreading examples of such systems is Linden Lab's Second Life (SL) [6]. In SL, similar to Active-Worlds [7] and Sims [8], once connected the users can view their avatars in a computer simulated 3-D environment and they can participate in realtime in task-based games, play animation, communicate with other avatars through instant messaging and voice. The social communication aspect of SL is hugely popular and counts millions of users. Moreover, its open source viewer [9] provides a unique opportunity to extend it further and equip it with other interaction modality such as haptic.

In this pursuit, we explored the possibilities of integrating haptic interactions in SL [10], [11]. We enhanced the open source SL viewer client and introduced a communication channel that provides physical and emotional intimacy to the remote users. In the prototype system, a user can take advantage of touch, tickle, and hug-type haptic commands in order to interact with the participating users by using visual, audio, or text-based interface modalities. A haptic stimulation of touch and other touch-based interactions is rendered to the remote user on the contacted skin through our previously developed haptic-jacket system [12] that is composed of an array of vibrotactile actuators. This paper illustrates a preliminary prototype exploring the aforesaid haptic interactions between virtual and real environment actors. An overview of the system components is shown in Fig. 1.

Our contribution in this paper is threefold. First, in order to bridge the gap between virtual and real, we present a SL viewer add-on, where we provide haptic interaction opportunity between the real users and their respective virtual avatars through a 3-D graphical user interface (GUI) using speech, mouse, text, and gesture-based interaction modalities. Second, we introduce touch, hug, and tickle haptic features for the SL users through chat and GUI interactions. Third, we incorporate 3-D annotation mechanism for the SL avatar so that user dependent interpersonal haptic and animation interactions become possible.

The remainder of this paper is organized as the following. At first, we present related work study in Section II. In Section III, we illustrate the various components of our proposed system that facilitates the SL-based interpersonal communication and provide a general overview of the system and its access mechanisms. Further in Section IV, we describe the implementation issues and development challenges of different modules. Also, in Section V, we present response time comparisons for different haptic and animation data, accuracy of different interaction modalities, and user study of the system. At the end, we provide

Manuscript received November 19, 2010; revised January 13, 2011; accepted January 14, 2011. Date of publication August 22, 2011; date of current version November 9, 2011. The Associate Editor coordinating the review process for this paper was Dr. Sethuraman Panchanathan.

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Digital Object Identifier 10.1109/TIM.2011.2161148

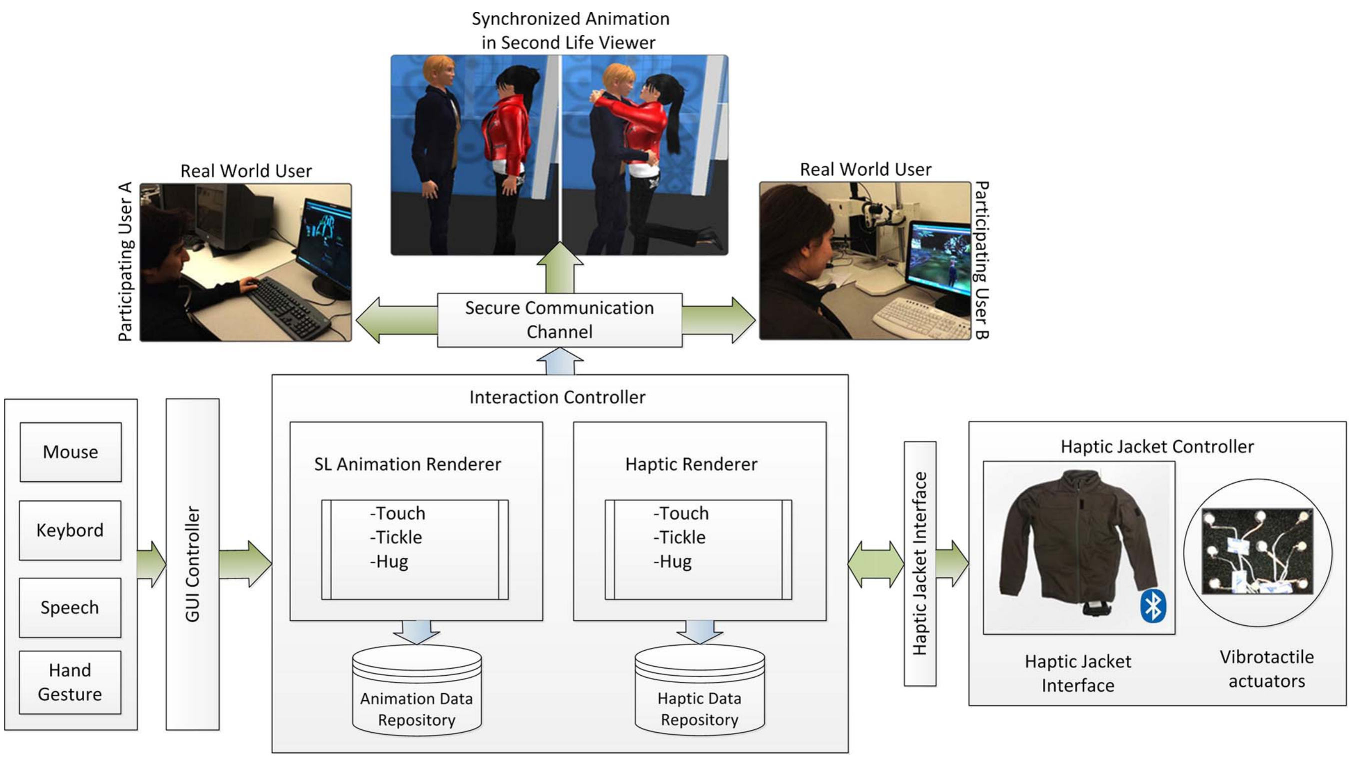

Fig. 1. Basic communication block diagram depicting various components of the Second Life interpersonal haptic communication system.

conclusion of the paper in Section VI, and state some possible future work directions.

II. Related Work

Thayer [13] states that touch as opposed to other forms of human-to-human communication will be more trusted by the person touched as a genuine reflection of emotion. Particularly in remote communication, touch is a unique channel in affect conveyance as the relation of touch to affect is immediate [3]. Haptic-jacket [12] -based rendering of touch has been incorporated previously into a conventional teleconferencing system to provide haptic interactions to the remote users. This approach uses marker-tracking technique to specify touchable parts of the user's body. The markers are further tracked using a dedicated camera. The system employs an expensive 3-D camera in order to automatically create 3-D touchable surface of the user.

In instant messaging, Rovers and van Essen [14] have provided a detailed study on the usage of hapticons that essentially are vibrotactile icons representing smileys. They incorporated six vibrotactile patterns that represent six associated smileys. These smileys could be triggered using mouse or keyboard-based interactions. In a 3-D virtual environment, we attempted to employ similar methodology. In our attempt, the smileys are replaced by a different type of avatar animations such as hug, tickle, and touch that resembles the emotions that the user is trying to communicate to the other.

O'Brien *et al.* [15] investigated on an approach relating to intimate communication for couples. In this approach, a person could virtually hold hands by using their proposed probe to share tactile experiences with his or her partner's hand. They placed a small microchip inside the ball. When the ball is squeezed by a user the system sends vibrotactile data to the other ball that his or her partner is holding. For couples in long-distance relationships, these communication technologies may be a primary means of exchanging emotions [16]. In distance communication, SL presents a multi-user communication framework that presents opportunities for interactions that connect people through a shared sense of place. Haptic-based input modes have been investigated in SL in order to assist the blind people to be able to interact with the SL world [4]. The authors have implemented two new input modes that exploit the force feedback capabilities of haptic devices and allow the visually impaired users to navigate and explore the virtual environment. Recently, in SL, Tsetserukou *et al.* [5] has attempted to analyze the text conversations in SL chatting system. This system provides emotional haptic feedbacks to the users by using a specially designed wearable hardware. While the different hardware designs for HaptiTickler, HaptiHug, HaptiButterfly, and HaptiHeart are commendable, this approach does not seem to consider visual or pointer-based graphical interactions in the 3-D environment other than the text-based conversation system. For example, it seems impossible to interact with specific parts of the virtual 3-D avatar that can be used to generate haptic touch stimulation in that respective body part of the real user. Moreover, gesture [17] and audio-based interaction modalities can enhance the navigation and interaction experiences of the user in a 3-D virtual gaming environment [18]. Hence, in our proposed haptic communication framework, we incorporated a flexible GUI-based multimodal interaction mechanism in order to provide more natural, easy, and accessible interactions in SL.

III. Proposed Framework

In this section, we present the different components of the system and their functional descriptions. The components of the system are depicted in Fig. 1 as a block diagram. In this diagram as a first step into the building of the interpersonal communication system, we present SL Viewer and its development options. We illustrate those details further in Section III-A. Afterwards, in Section III-B, we describe the haptic jacket and its communication interfaces to the system. Further in Section III-C, we present the rendering techniques, access control mechanism, and avatar annotation and animation technique. Finally, in Section III-D, we present the four interaction modalities in detail.

A. Second Life Viewer

SL provides both commercial and open source versions of its client that are termed as viewer. The open source version of the viewer is called Snowglobe [9] that provides the mechanism to handle different haptic responses and avatar animation sequences. We developed an add-on to communicate with the viewer and developed listeners to the SL communication channel. This coupling architecture provided the option to incorporate haptic interactions without affecting the functionality of the SL communication system. In SL viewer, all message are valid within a particular area, which is dependent on the avatar's virtual 3-D location. This area normally is defined as 10 to 30 square meters centered on the user's virtual location. In our add-on, we develop a module that listens to the events that are generated from message transmissions in a SL component named nearby interaction event handler. The event handler performs actions by using text-based messaging protocol. A message contains event trigger data, animation data, or simple communication data. The message transmission module captures all the messages that are generated in the SL. By manipulating the 3-D avatar, the user triggers events in the 3-D environment, e.g., a collision event with other avatars or objects. The message transmission module captures those events and transfers the event messages to the nearby interaction event handler for further processing. The event handler module determines the particular event handling routine for a specific event and then packs the event-handling message with the handling routine. Afterwards, the handler sends the packet to the interaction event decoder. Message transmission module also receives animation data from the animation parcel manager and generates animation sequence for the avatars in the 3-D virtual world.

B. Haptic-Jacket Interface

Vibrotactile actuators communicate sound waves and create funneling illusion when it comes into the physical contacts with skin. The haptic jacket consists of an array of vibrotactile actuators that are placed in particular portions of the jacket, and their patterned vibration can stimulate touch in the user's skin [19]. A series of small actuator motors are placed in a 2-D plane in the jacket in a certain manner. An AVR microcontroller controls the vibration of these actuators. We have configured the microcontroller so that it processes input commands that are sent from the haptic interaction controller. In order to achieve the input command transmission, the haptic interaction controller uses the bluetooth communication channel. Fig. 2 depicts the components of the jacket into more detail.

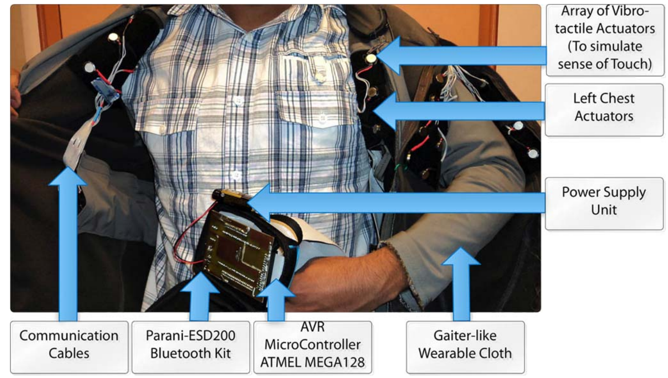

Fig. 2. Haptic-jacket controller and its hardware components. Array of vibrotactile motors are placed in the gaiter like wearable cloth in order to wirelessly stimulate haptic interaction.

C. Interaction Controller

In representing the interaction controller, the engine of the system, we will introduce the avatar annotation procedure in Section III-C1. The annotation provides personalized animation and haptic feedback customization options. The way we provide security and authenticity in the avatar-based interactions is described in Section III-C2. We also present the avatar animations and define the associated haptic signal patterns in Section III-C3 and C4, respectively.

1) Avatar Annotation: In our system, we annotated visible body parts of the avatar in SL and specified the corresponding physical haptic actuators to render the haptic feedback. For each haptic signal, we also annotated the avatar animation. Fig. 3 depicts the geometric-based avatar annotation scheme. We attached LSL scripts [6] in each of the annotated parts of the avatar that contain the haptic commands as well as the identification number of the animation sequences. For example, we annotated the 3-D male avatar's left arm and specified particular vibrotactile actuator stimulation for it. Further, we specified the interacting animations for both the participating male and female virtual avatars. Afterwards, when the user representing the female avatar issues a GUI interaction command to the male avatar arm, then the annotated haptic stimulation is rendered at the real male user's arm through the haptic jacket.

For intimate interactions such as a hug, we employed group-based annotation scheme. As evident, hugging with parents is different to that with a friend. Hence, we needed separate animation and haptic rendering for each type of hugs, touch, etc., interactions. We created groups and incorporated group-based annotation scheme of the 3-D avatar. For each group, we created different avatar animation and haptic rendering options. By using the script-based dialog interface, any interacting contacts were then assigned to a group (default is formal). We provided four different groups namely family, friend, lovers, and formal.

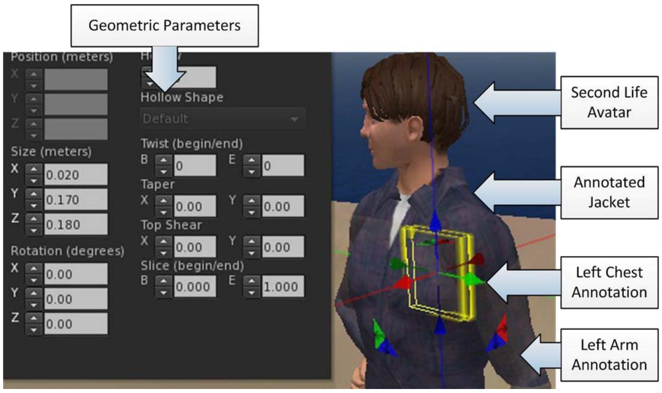

Fig. 3. Flexible avatar annotation scheme allows the user to annotate any part of the virtual avatar body with haptic and animation properties. When interacted by the other party, the user receives those haptic rendering on his/her haptic jacket and views the animation rendering on the screen.

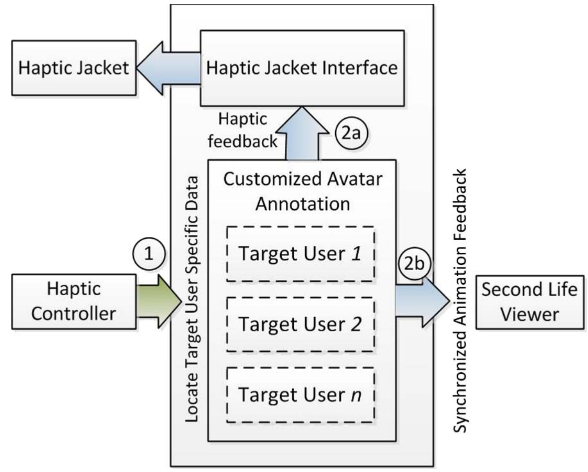

Fig. 4. User-dependent haptic interaction access design. The haptic and animation data are annotated based on the target user groups such as family, friend, lovers, and formal.

This group-based haptic interaction in SL further assisted the user to personalize his/her experience.

2) Access Control Scheme: In our prototype application, we incorporated user profile specific access control mechanism in order to provide the participating users the means of authenticating and personalizing their interactions. For example, if user A issues a hug command to user B, then, the animation and haptic rendering take place only if user B acknowledges the permission. A permission window is shown at user B's SL viewer for this purpose, where the interaction could be accepted or rejected. We used SL message notification and GUI to display the permission window in which the user is already adapted. In SL, each user is associated with a string-based identification number. Message originated from a user's computer bears that identification number as a preamble to that message. Hence, in order to provide access control, we compared the identification number with the list of contacts of the user and decided accordingly. In order to deliver user-specific haptic feedbacks to the user, we used the group annotation. In any haptic interaction, the originator user information is mapped to obtain the group of the user. This phenomenon is depicted in Fig. 4. In this approach, the haptic renderer (HR) uses the group-specific avatar animation and haptic rendering data in order to deliver customized interactions to the users.

3) Avatar Animation: Animation helps the user to express the emotion in an intuitive manner (if compared to instant messaging). The animation rendering depicting, a hug, for example communicates the user's emotion directly when rendered with the hug haptic feedback. SL animation is a BVH (Biovision Hierarchy) file, which contains text data that describes each figure part's rotation and position along a time line. We controlled the avatar position or movement by triggering a message to animation parcel manager, which then executes the BVH animation file for that animation. We created these animation files for hug, touch, and tickle animations by using MilkShape 3-D version 1.8.5 [20]. Both the participating male and female virtual avatars play out the defined animation sequences in the SL viewer using their respective animation files. Empirically, we created four different hug animations for the four groups of users in order to verify our concept that group-dependent animations were taking place in the SL viewer. In order to control the hug animations, we used the SL scripting language of SL. In order to start the animation, user A issues a hug, touch, or tickle command, the participating second user B consents to it. Afterwards, in hug animation, the two virtual avatars of user A and user B (who must be at the same virtual location in SL) come closer by walking and hold each other closely. Similarly, for the touch animation, user A waves a hand emulating a touch activity and user B smiles or frowns (if done repeatedly) indicating that a touch has taken place. If user A touches stomach or neck of the avatar of user B, then, tickle animation for user B takes place. In tickle animation, the avatar of user B moves awkwardly and laughs.

4) Haptic Renderer: The haptic jacket provides the funnelling illusion-based touch haptic feedback. We leveraged the touch feature to create hug- and tickle-based haptic feedbacks. We made careful observation about the real life hug and noticed that when two people hug each other, both feel a gradual touch feeling in some specific body parts. In a formal hug, a user receives touch feedbacks at the chest area and at the back shoulder area. Similarly, during our observations, we noticed that in a tickle, most users react to the random touch at the stomach area, at the underarm area, and sometimes at the neck area. Using these empirical parameters, we constructed touch, hug, and tickle haptic feedbacks as the following:

- According to the virtual annotation, the haptic touch sensation is delivered by incorporating the funnelling illusion into the haptic jacket to stimulate real touch at the real user. When one person touches another person, then, both the participating users receive touch feelings.
- In order to create hug-type haptic feedbacks for the participating users, we systematically increased the jacket's $leftChest$, $rightChest$, $neck$, $leftBackShoulder$, and $rightBackShoulder$ motors intensity levels to produce the funnelling illusion. The systematic control of the actuator intensity levels creates the touch effect in those areas and offers a hug-type haptic stimulation. The lover-type hug is different to that of the formal hug. In addition to the areas defined above, we decided to add haptic touch stimulation in the stomach area to emulate the joy emotion [5],

[21]. Hence, by following the laws of funnelling illusion, we activated the arrays of vibration motors attached to the abdomen area of a person.

- As described earlier, following our empirical study, the tickle haptic feedback is evoked by incorporating random and unpredictable touch at the stomach area, at the underarm area, and at the neck area provided that a GUI interaction at those virtual body places was performed.

D. GUI Controller

The interaction controller works as a core service and takes action according to the user inputs from the GUI controller. The GUI controller enables the usage of keyboard, mouse, speech, and gesture-based inputs from the user. For example, a user representing a female avatar can point her mouse on a male avatar and produce a click event using the mouse. The GUI controller detects if the annotated body parts of the male avatar have received any GUI commands and sends the avatar body ID and type of action performed to the interaction controller. In our prototype, the hug command is issued by using the speech, keyboard, and gesture-based interaction inputs. The GUI commands that were used in the various interaction inputs are discussed in the following:

- Keyboard: While processing the keyboard (text) -based inputs from the requester (sender), the controller analyzes the text messages sent to the jacket owner (receiver). The text message-based commands have certain preamble before the commands. Therefore, the interaction controller easily distinguishes the haptic commands that are issued based on the text inputs. The text command forms are HUG $username$, TOUCH $\langle username\ bodyparts\rangle$, and TICKLE $\langle username\ bodyparts\rangle$, where $bodyparts = \{leftChest,\ rightChest,\ stomach, leftShoulder, rightShoulder, leftBackShoulder, leftRightShoulder, leftArm,\ rightArm, neck\}$.
- Mouse: It is extremely flexible to provide touch and tickle commands using a mouse. For each mouse click, at the annotated body parts, a touch command is issued. When the mouse click happens on the stomach and the neck area of the virtual avatar, a tickle command is captured. In order to provide hug command, the user clicks a GUI button on the screen and the nearest user is issued a hug command automatically.
- Speech: Similar to our previous speech-based interaction methodology [18] in virtual environment, we processed the speech-based haptic commands from the user. The touch and tickle input commands are similar to that of keyboard interaction, where the user speaks out the type of interaction (touch, tickle) followed by body part names. In order to issue hug input command, the user simply speaks out hug, and the nearest user is issued a hug command. User name recognition was not attempted in our approach.
- Gesture: In our previous work, we have proposed a novel motion path-based gesture interaction system [17]. This system allows the user to define a drawing symbol that can be associated with particular command. We tailored the motion path-based gesture interaction approach by introducing three main drawing symbols e.g., h, T, k representing hug, touch, and tickle commands, respectively. For each body parts, we associated the following gesture commands, $bodyparts = \{leftChest(L, C), rightChest\ (\Gamma, C),\ stomach\ (S), leftShoulder(L, S),\ rightShoulder(\Gamma, S), leftBackShoulder\ (L, b),\ leftRightShoulder\ (\Gamma, b), leftArm\ (L, m),\ rightArm\ (\Gamma, m), neck(n)\}$. The gesture drawing symbols were chosen based on their selection accuracy. For example, the gesture recognition rate for Γ is higher than R and since the selection.

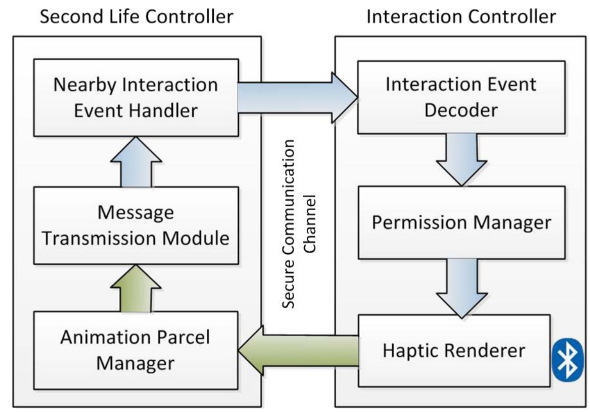

Fig. 5. Second Life and haptic communication system block diagram.

IV. Implementation

In our prototype application, the interaction listener was developed as a service, which listens to a communication serial port (COM). A bluetooth device was connected with the PC's USB port, which was virtually configured with the COM port so that the bluetooth device can send signals to the haptic jacket. For the haptic signal transmission, bluetooth was configured at the PC COM port of the respective computers that interfaces with the hardware controller of the jacket. In the following, we present a detailed illustration of the various modules of our system.

A. Development of Different Modules

Here, we present the details of the implementation issues of different modules of our proposed system. We incorporated Microsoft Visual Studio 2005 IDE to develop our system and the primary language used was Visual C++. We adopted Microsoft Foundation Class library and asynchronous socket programming scheme to create a socket-based secure communication channel. In order to implement voice-based interaction, we used Microsoft Speech SDK (SAPI version 5.1) [22]. We now briefly illustrate the development of different modules, which are SL controller, interaction event decoder, permission manager (PM), and haptic renderer (HR). These modules and their inter message communications are depicted in Fig. 5.

1) Second Life Controller Module: In order to develop the SL add-on, we locally build the SL open source viewer Snowglobe [9] version 1.3.2 by using the latest version of CMake (version 2.8.1) [23]. SL message transmission module is

```
state_entry()
{
    //Request animation permission to Second Life
    llRequestPermissions(llGetOwner(), PERMISSION_TRIGGER_ANIMATION);
    llSetTimerEvent(1.0);

    //Specify communication channel
    llListen(&iChannel,"",llGetOwner(),"");
}
touch_start(integer WHICH)
{
    //Obtain the calculated body part from the GUI interaction
    llGetAnnotationSelection(iChannel,&vBody_trg,
                             (string)llDetectedKey(iChannel));

    //User specific haptic feedback and animation
    aAnimations = SL_GetUserAnim(SL_GetUser(this),vBody_trg);
    hFeed = SL_GetUserFeed(SL_GetUser(this),iChannel,vBody_trg);

    //Render animation and haptic feedback
    llStartAnimation(llList2String(aAnimations,WHICH));
    SLStartFeed(llList2String(hFeed,WHICH));

    //Animation calibration and user interaction throttling
    if(WHICH++ >= TOTAL)
    {
        WHICH = INITIAL VALUE;
    }
```

Fig. 6. Code snippet depicting portion of the Linden Script that allows customized control of the user interaction.

```
<?xml version="1.0" encoding="utf-8"?>
<InteractionRules>
  <hug userType="Friends" hapticFeedback="Yes" name="hug1">
    <animationModules>
      <UUID>6b61c8e8-4747-0d75-12d7-e49ff207a4ca</UUID>
      <animationBVH>hug.bvh</animationBVH>
      <animationPriority>MEDIUM</animationPriority>
      <animationLooped>YES</animationLooped>
      <animationSpeed>30</animationSpeed>
      <animationDuration>LOW</animationDuration>
      <animationScaleTo>0.75</animationScaleTo>
    </animationModules>
    <tactileModules>
      <module name="leftChest">
        <highestIntensity>15</highestIntensity>
        <lowestIntensity>0</lowestIntensity>
        <vibrationType>GRADUAL_INCREASE</vibrationType>
        <interactionTime>500</interactionTime>
        <numberOfRepetation>3</numberOfRepetation>
      </module>
      <module name="rightChest">...</module>
    </tactileModules>
  </hug>
  <hug userType="Family" hapticFeedback="Yes" name="hug2">...</hug>
  <touch>...</touch>
  <tickle>...</tickle>
```

Fig. 7. Overview of the target user group-specific interaction rules stored (and could be shared) in an XML file.

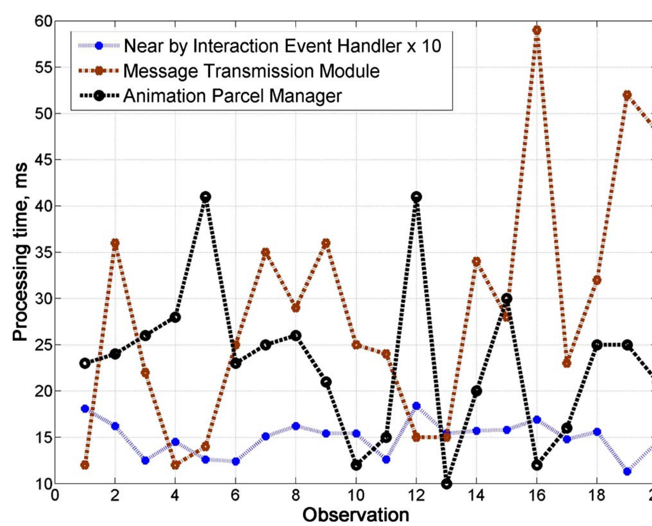

Fig. 8. Processing time of different interfacing modules of the Second Life controller. The figure depicts the modules that interface with our system.

responsible for dispatching all the messages to handle virtual environment. All the messages are in XML (Extensible Markup Language) format with detail avatar and virtual environment related data. All the event type messages are filtered by nearby interaction event handler.

2) Interaction Event Decoder Module: Interaction event decoder is a component in the interaction listener. It receives all the output messages from the nearby interaction event handler in an encrypted XML [24] format. The primary responsibilities of the module are to decrypt those received messages and transmit them further to the communication channel toward the PM.

3) Permission Manager Module: The PM looks up the user-dependent access control scheme and produces appropriate permission dialogues in SL viewer. The PM issues these dialogues by using SL script and receives appropriate permission parameters. Fig. 6 shows the code snippet that is used to control user-dependent animation and the vibrotactile motors in the haptic jacket. As shown, before commencing avatar or haptic rendering functions, we call $llRequestPermissions(key\ AvatarID, integer\ perm)$ function. The function takes two parameters; the first parameter is the user's Avatar ID who requested an event. The second parameter $PERMISSION\_TRIGGER\_ANIMATION$ is a permission type for that event.

4) Haptic Renderer Module: The HR operates the haptic jacket and notifies the animation parcel manager for synchronized animation feedback. In order to control the jacket motors, it parses an XML file containing haptic patterns and sends a message to the microcontroller unit of the jacket accordingly. Portion of the XML file is shown in Fig. 7. In our implementation, the actuator motors have a total of 16 intensity levels from 0 to 15. Where, 0 means no vibration and 15 indicates the maximum vibration level. To repeat the vibration patterns, we set the value for the $numberOfRepetation$ attribute.

B. Processing Time of Different Modules

In order to ensure that the implemented interacting modules of our system perform on par with the interfacing modules of the SL controller, we measured their performances with a set of haptic and animation data. The data size for the haptic and animation rendering in each step of the experiments was kept the same for all the components. In order to measure the performance metrics, we embedded performance thread hooks in the components and recorded the responses of those. For each pair of haptic and animation rendering, the experiment setup was repeated for four times and later averaged. In Fig. 8, the performance of the SL interfacing modules is depicted. Similarly, for the same data, the processing time of the implemented interacting modules is shown in Fig. 9.

In order to compare the processing times, we evaluated the component in the SL controller that required the highest processing time. As shown in Fig. 8, in the experiment setup number 12, the nearby interaction event handler required more than 175 ms to compute the interaction and report that to the interaction event decoder. However, the two core components, e.g., the interaction event decoder and the PM, processed the

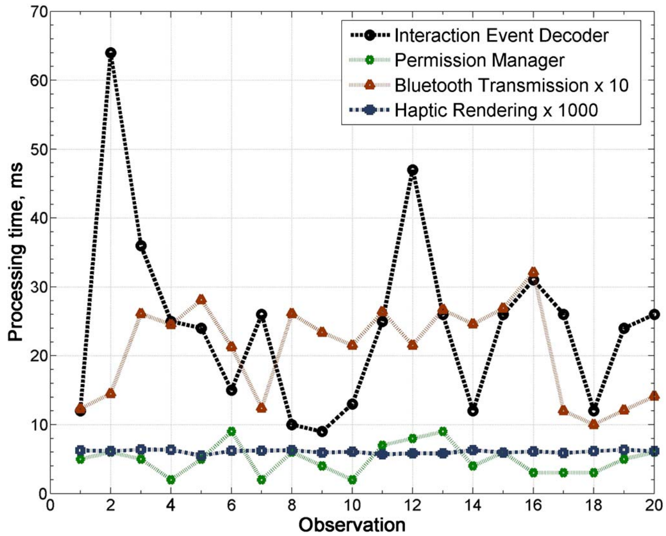

Fig. 9. Processing time of the components of the implemented interaction controller with respect to different haptic and animation interactions.

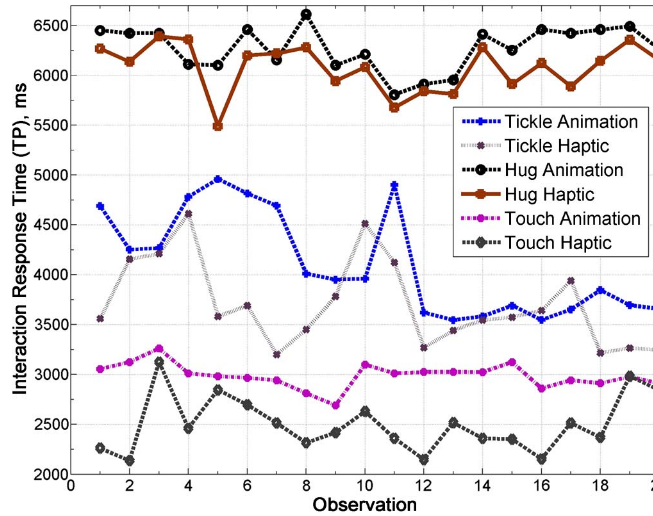

Fig. 10. Haptic and animation rendering time over 18 samples. The interaction response time changes due to the network parameters of Second Life controller system.

message data in less than 65 ms and 10 ms, respectively in all the experiments. This showed that the core components of our system were able to handle the message data as par to that of the SL controller. The two other components namely the bluetooth transmission module and the haptic rendering module render their operations locally and dependent on their hardwire processing time of the bluetooth and the haptic controller subsystem, respectively.

V. Results

We present the different parameters that affect the transmission time of the haptic and animation data in our system in Section V-A. In Section V-C, we illustrate a detailed analysis of the impact of different interaction modalities. Results pertaining to the multi-user access performance and usage of the system are discussed further in Section V-B. Further, in Section V-D we describe the usability study setup and its analysis.

A. Response Time

We calculate the haptic taransmission time from the sender machine to the receiver jacket by using (1). Where user's average interaction time to interact with the SL viewer is I unit, average data transmission rate via the server is Π, n is the message size, and the time for sending data from the receiver machine to the jacket actuators is β_1 unit.

$$R = I + \frac{n}{\Pi} + \beta_1 \tag{1}$$

After generating a haptic interaction, the system approximately requires $R = (3775 + 270 + 344)$ms to complete the transmission. Here, in our experiments, the average of the interaction time is 3775 ms, network overhead is 270 ms, and β_1 is 344 ms. The haptic acknowledgement from the receiver machine to the sender jacket is represented by (3). Here, n/Ω is the average time for transmitting n byte feedback message from the receiver machine to the sender machine. We assumed that the transmitted message and its acknowledgment were of the same length.

$$\begin{aligned} S &= I + \frac{n}{\Pi} + \beta_2 + \frac{n}{\Omega} \\ &= R + \frac{n}{\Omega} + (\beta_2 - \beta_1) \\ &= R + \frac{n}{\Omega}, \quad (\beta_2 - \beta_1) \simeq 0. \end{aligned} \tag{2}$$

On average, the time S is higher than R by n/Ω unit, which is the network transmission delay. In order to ensure that the difference between S and R does not affect the interaction experience of the participating users, the haptic rendering and animation rendering are synchronized locally in respective users' machines. Fig. 10 depicts the processing times required to render different haptic and animation data. From the result, we see that hug interaction needs more time than other interactions, as for the hug-type rendering, the system is required to process more data than the others.

However, the SL message transmission architecture also plays a role to introduce delay in the synchronized haptic and animation rendering thereby increasing the interaction processing time. We present two main factors that we observed during our experiments. We found out that the nearby interaction listener component introduces delay in its message processing when the server receives too many requests from the surrounding of the avatar. To measure the difference in the processing times, we designed experiment sessions on five empirically selected time intervals during a day. We continued to sample the interaction time responses in three successive weeks by running the same set of experiments. We show the recorded data in the following Fig. 11. As seen in the figure, the interaction time responses reached its pick during the weekends.

In SL, the users can navigate to different map locations in the virtual world. A convenient method of specifying locations and teleporting to that location is achieved by using the slurls [25],

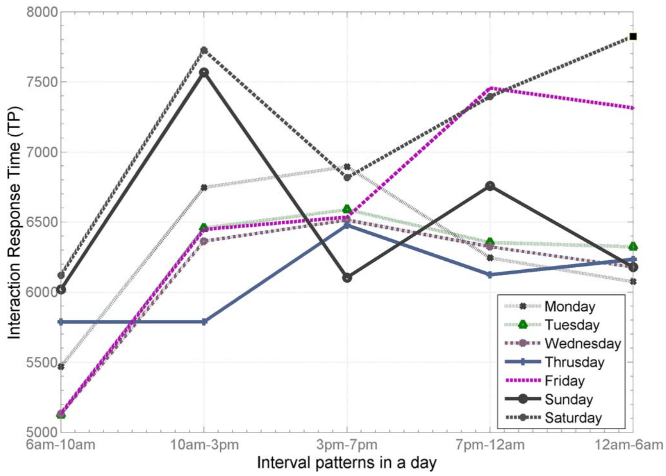

Fig. 11. Average of the interaction response times that were sampled on particular time intervals. The data were gathered during three weeks experiment sessions and averaged. From our analysis, we observed that based on the server load, the user might experience delay in their interactions.

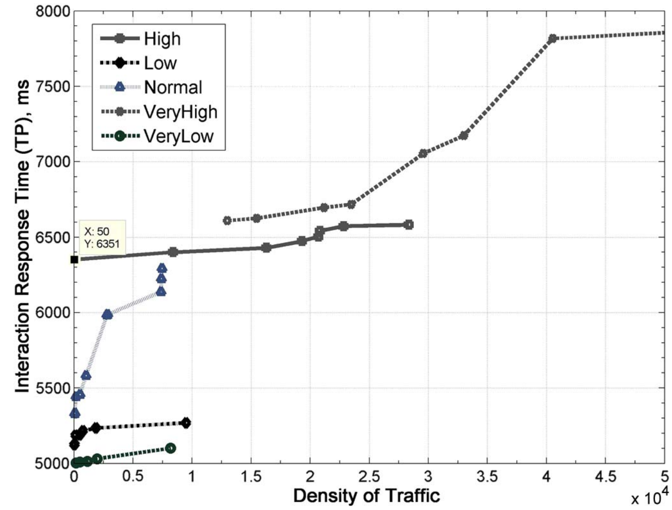

Fig. 12. Interaction response time in varying density of traffic in the Second Life map location for the nearby interaction handler.

TABLE I
INTERACTION RESPONSE TIME BASED ON PRIM SIZE ON VARIOUS SECOND LIFE MAP LOCATIONS

Location (Slurl) [25]	Area (m2)	Prims on parcel (Object Density)	Interaction Re-sponse Time (TP), ms
OakGrove/128/128/11	528	600	5120
SaintLucia/128/128/22	1792	269	5469
Amberville/128/128/2	5472	1391	6089
Boreal/128/128/122	7168	1495	6201
KissenaPark/128/128/2	8192	1426	6213
Wichi/128/128/2	9408	2018	6213
MooseBeach/50/57/20	19008	1382	6428
NewYorkNYC/128/128/2	21936	4341	6901
ZenDestani/128/128/18	28672	2556	6310
SolaceBeach/128/128/2	38832	4911	6052
LondonUK/128/128/22	47760	5460	7168

which are hyperlinks that allow users to login directly to that site or teleport to it if they are already inside SL. We noticed that different slurls have different 3-D object density (Prims), and they are spanned in varying size. When then number of Prims increases, the interaction complexity with the present virtual avatars in that area increase. These metrics, therefore, influence the interaction response time in our experiments as shown in Table I.

The area of the slurl effectively creates different density of the avatars with particular prims in their surrounding virtual locations. In order to measure the effect of different density levels, we teleported the avatars in locations with very low to very high density and determined their impact on the interaction response time. Our findings are depicted in the following Fig. 12.

We equipped the interaction controller to sense these network parameters. By sensing the density of the avatars, prims, nearby interaction message parsing frequency, and day time metrics, the interaction controller empirically calculates a threshold that can distinguish disruptive effects of network lag in the interpersonal communication. However, as our system extensively used the communication platform of the SL controller, we tackled the lag at the network communication level by deciding to inform the participating users about the delay. The interaction controller incorporates the calculated lag threshold and provides color-coded decorators at the SL viewer's heads up display (HUD). In this regard, we adopted the decorator scheme proposed in [26]. We developed a bar in the HUD that displays Green when the prims and avatars interaction messages do not create congestion. Similarly, a Red bas is displayed reflecting the delay in the communication. Later, in our usability study, we noticed that when the user was informed about possible interaction delays by using the decorators, s/he accepted the lag with ease and reacted more intuitively.

B. Multiuser Haptic Interaction Response Time

The haptic and animation rendering-based communication is not specific to a pair of users. Rather, multiple users from different groups can interact with each other at the same time. This essentially extends the interpersonal interaction and provides option to leverage the framework in a group specific interaction scenario. The developed interaction listener supports interaction requests from multiple users. For example, when a user A receives interaction request from user B and C, it creates aqueue of request for user A on a first come first serve (FCFS) basis. In such cases, the interaction response time can be calculated by using the Little's formula, which is a classical conservation equation in queuing theory.

$$E(T) = \frac{E(n)}{\lambda} \tag{3}$$

Here, $E(T)$ is the average delay for a user request, i.e., average throughput time, $E(n)$ is the average number of requests to the interaction listener. λ is the arrival rate of the requests. However,

$$E(n) = \frac{\rho}{1-\rho} \quad \text{and} \quad \rho = \frac{\lambda}{\mu}. \tag{4}$$

TABLE II
COMPARISON OF DIFFERENT INTERACTION MODALITY

Modality	Average Time	Accuracy	Suitability
Keyboard	5110 ms	85%	hug, touch, tickle
Mouse	2075 ms	99.6%	touch, tickle, hug
Speech	3790 ms	55%	hug, tickle, touch
Gesture	4125 ms	78.1%	hug, touch, tickle

Where, ρ is the fraction of time the interaction listener requires to process the requests. Hence, combining (3) and (4), we get

$$E(T) = \frac{\rho}{\lambda(1-\rho)} = \frac{\frac{\lambda}{\mu}}{\lambda\left(1-\frac{\lambda}{\mu}\right)} = \frac{1}{\mu-\lambda}. \quad (5)$$

Here, μ is request processing rate from the queue, and (5) is the queuing delay. In this equation, λ is the arrival rate of a interaction request by a user, and μ is the average service rate. From Figs. 8 and 9, we measured that the average service time is approximately 6.5 s. Hence, average service rate $\mu = 1/6.5 = 0.1538$ per second. For example, in case after every 60 s, an interaction request is triggered to the interaction listener, then, $\lambda = 1/60 = 0.0167$ request per second. Therefore, from the Little's formula [(5)], the total waiting time including the service time $=1/0.1538 - 0.0167 = 7.29$ seconds (approximately).

C. Analysis of Different Interaction Modalities

A comparison of different interaction modalities used and their suitability for each haptic interactions are given in Table II. The two other parameters are average time needed to produce the command and average accuracy, which are also listed. However, not all haptic input commands were convenient to use for each interaction modalities. For the keyboard (text) interaction modality, we found that writing body parts names takes time, and, often, spelling mistakes impaired the accuracy of the command. Touch and tickle input commands were very easy to issue using the mouse-based modality. However, while issuing hug input command using the mouse, it became difficult to assign the command to a particular user; hence, nearest user was selected automatically from the user group lists. Similar problem occurred while using speech and gesture-based interaction modalities as it became cumbersome to recognize the user names using either of those two approaches. From the table, we see that the percentage of accuracy is highest for mouse-based interaction modality, which is 99.6%. This and its flexibility for usage in pointing and interacting with annotated body parts made it the ideal medium for haptic input command delivery in our system.

D. Usability Study

We have incorporated the usability evaluation guidelines [27] and designed our tests accordingly with the sensory analysis [28] of the system involving both the user and the targeted sensory communication modules. Before performing the usability test, we designed a test plan where we defined our evaluation objectives, developed questions for the participants, identified the measurement criterion, and decided upon the target users of the system. The test took place at a university laboratory with sixteen (16) participants comprising of different age groups. Five (5) of the participants are in age group 13–18, eight (8) of them are in age group 18–36, and the rest three (3) are in age group 36+. Furthermore, in multi-user interpersonal communication setting, the users were divided into two groups, namely Group A and Group B (Table III).

TABLE III
USABILITY TEST QUESTIONS TO THE USER

#	Question
Q1	Perceived system response was acceptable
Q2	The haptic feedbacks are realistic and/or acceptable
Q3	Consider using the system in Second Life
Q4	Perceived delay between haptic response and avatar rendering was tolerable
Q5	Easy to get familiar with

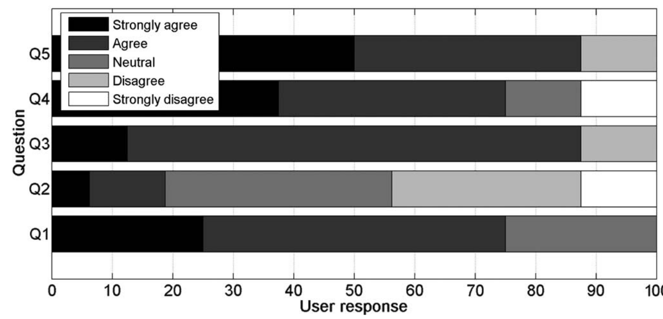

Fig. 13. Usability study of the Second Life haptic interaction system.

TABLE IV
USER SATISFACTION ON THE OVERALL EVALUATION IN LIKERT SCALE

	Mean	Std. Dev.	Mean Percentage
Acceptability	4	0.7303	80%
Haptic feedback	2.6875	1.0782	53.75%
Likeliness	3.8750	0.8062	77.5%
Delay	3.875	1.3102	77.5%
Ease of use	4.25	1	85%

For the traditional experiments, two users were chosen. In order to ensure that each communicating participant can converse with different age groups, their selection was made randomly. Moreover, to ensure the distributed communication behavior, the physical location of the users was separated. In a user's test machine, the enhanced SL viewer was installed to provide animation and GUI-based interactions.

At a time, the selected volunteers were told to put on the haptic jackets and requested to use the prototype system by participating in certain haptic interaction-based tasks. Their activity was monitored throughout the experiment and recorded for analysis. Afterwards, based on their interaction experiences, the users filled out a questionnaire where they were requested to provide ratings of their likeliness, familiarity, ease of usage, etc., of the system.

The user responses are shown in Likert Scale [29] in Fig. 13. The ratings of the questionnaire were in the range of 1–5 (the higher the rating, the greater is the satisfaction). The average of the responses of the users was calculated in percentage form and measured after the usability tests. Fig. 13 shows the user's responses for each given assertions. It is worth mentioning that

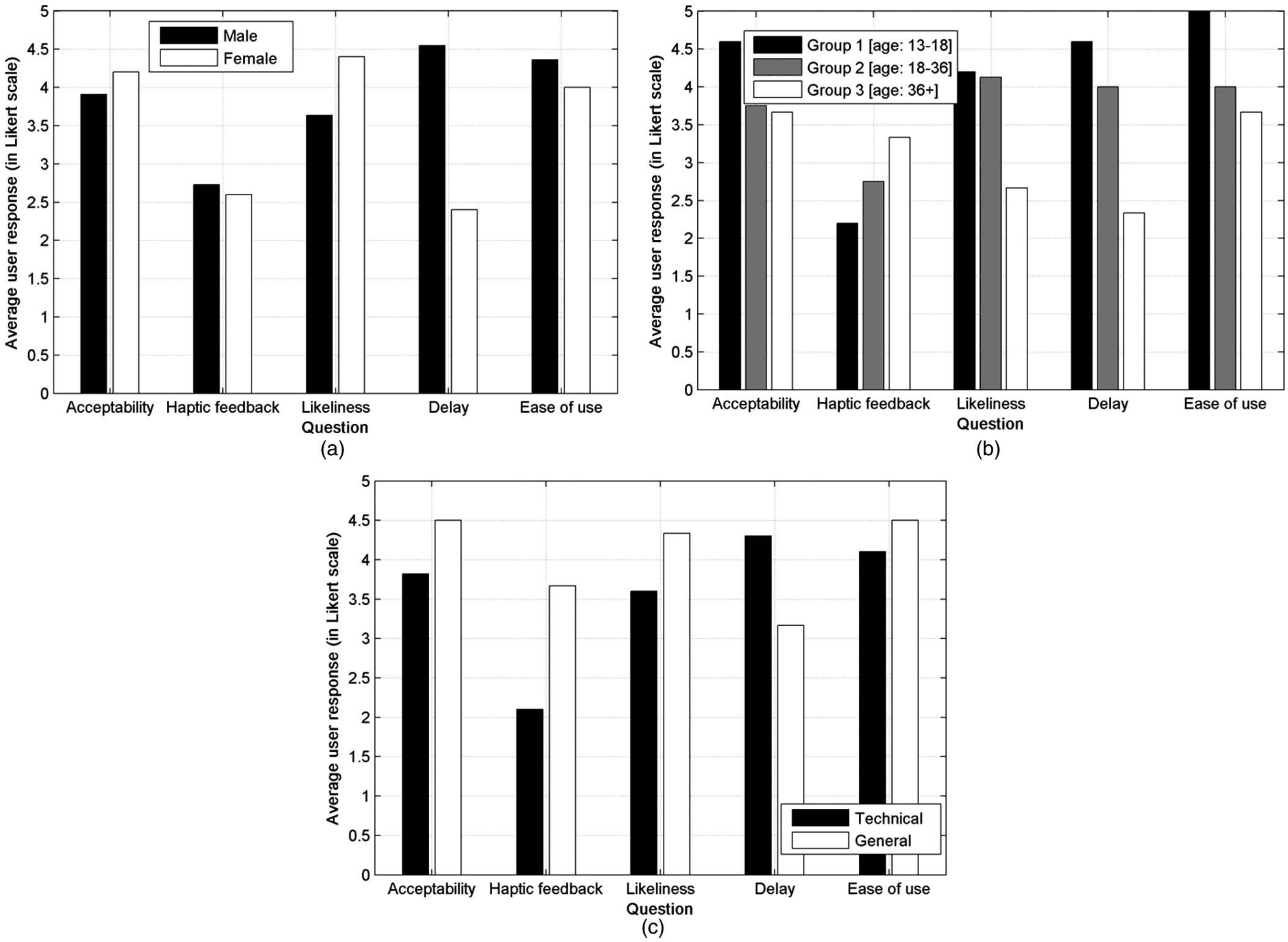

Fig. 14. Comparison between the responses of users from different (a) gender, (b) age groups, and (c) technical background.

more than 80% of the users would like to communicate using the enhanced system through haptic and animation interaction if they were available in SL. Overall, the users were also satisfied with the synchronized animation and haptic rendering responses, and 75% of users consented to that.

We conducted usability tests to evaluate the user's quality of experience with our proposed system and to measure the suitability of the approach. Table IV summarizes the overall performance score of the users. The higher mean values of system response, haptic feedbacks, and easy to familiar represent a very satisfactory user response, while the moderate mean values of system in SL and perceived delay show relatively good user satisfaction.

In our study, we also attempted to evaluate the acceptability of the system by the users from different genders, age groups, and technical backgrounds. The result of these studies is depicted in Fig. 14. We infer from Fig. 14 that (a) the female users gave more positive feedback in acceptability and likeness than the male users. However, the male users confirmed that it was easier for them to use the system after a couple of dry runs. Moreover, all the users favored that a refined haptic rendering is needed to make the interaction experience natural and realistic. In case of different age groups, we divided the users into three age groups, namely *group*-1: ages 13–18, *group*-2: ages 18–36, and *group*-3: ages 36+, and recorder their responses in Fig. 14(b). In retrospect, compared to the older group of users, the users from the younger group seemed to be more attracted in using the system and wanted to participate in remote touch, hug, and tickle interactions. Also, from Fig. 14(c), we received favorable responses and recommendations from users with nontechnical background than that of the technical people, although nontechnical users were less happy with the interaction response time of the system.

VI. Conclusion

In this paper, we presented a SL haptic interaction prototype system that attempts to bridge the gap between virtual and real world events by incorporating interpersonal haptic communication system in SL. The developed system works as an add-on and loosely coupled to the SL viewer. The haptic and animation data are annotated in the virtual 3-D avatar body parts. The 3-D avatar and the annotated body parts representing a real user receive inputs when they are interacted through gesture, mouse, speech, or text-based input modalities and produce emotional feedbacks such as touch, tickle, and hug to the real user through the haptic jacket. We presented the implementation details of a preliminary prototype exploring the aforesaid haptic interactions in a real-virtual collaborative environment.

In multi-user haptic interaction scenario, we employed FCFS approach to process the waiting interaction requests from the queue. However, in our future work, we wish to provide user group-based priority customization option, where the user will be able to prioritize the haptic interaction requests from two or more users of different user groups. In addition, the user may also assign highest priority to certain individual in the user's chat list following a similar strategy. Lastly, from our usability study, we received suggestions from the users to improve the tactile feedbacks for the hug-type interactions. We are working to add new hardware features into the haptic jacket to accommodate the recommendations of the users.

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