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著者(和文)	JAYASIRIA
Author(English)	Madam Arachchige Anusha Harshani Jayasiri
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Haptic Rendering of Dynamic Motion in an Image Sequence

Doctoral Thesis by

Anusha Harshani Jayasiri

Supervised by

Professor Makoto Sato

Tokyo Institute of Technology

Interdisciplinary Graduate School of Science and Engineering

Department of Information Processing

Tokyo Japan

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DECLARATION

I hereby declare that I am the author of this thesis “Haptic Rendering of Dynamic Motion in an Image Sequence”, which is a copy of the final version accepted by the panel of examiners.

Anusha Jayasiri

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ABSTRACT

Recently, humans' interest has grown significantly to use innovative technologies to create virtual worlds beyond the real worlds. Among them, haptic technologies play a vital role in virtual reality applications and are being used in a wide range of application areas such as in training, education, cultural applications, entertainment and 3D interaction. Apart from that, haptic technology can play a vital role in modern multimedia applications. Rather than the senses of seeing and hearing, it can be incorporate other senses such as feeling, smelling and tasting into multimedia applications by using haptic technologies.

However, the incorporation of haptic technology into an image sequence, which is known as a video, is still in its infancy and it has gained a worldwide recognition among researchers. There are three types of haptic effects, which are cooperating with haptic interaction with video media. Those are haptic structure, haptic texture and haptic motion. In this research we are focusing on the research area of haptic motion in an image sequence which refers to the rendering of forces related to the moving objects in the scene. Hence, in this research we explore different perspectives of getting the haptic perception of feeling the movement of objects in an image sequence, with the objective of enhancing the viewing experience of viewers to the near real world level. Therefore, we propose systems for two degrees of freedom (2DOF), three degrees of freedom (3DOF) and six degrees of freedom (6DOF) motion rendering to a 2D image sequence.

At first we research on how to associate haptic signals with an image sequence to feel the movement of objects in it, beyond passive seeing and hearing. Among the various haptic devices exist, we use the string-based haptic device SPIDAR-G in our research due to the simplicity, familiarity, 6DOF force rendering capability and the high quality of the feedback force generated. Here we focus on feeling the movement of objects along the x and y dimensions using the SPIDAR-G haptic interface. The proposed approach for 2DOF motion rendering has four major steps namely feature points selection, feature points tracking, motion estimation and haptic motion rendering. The main contribution in this research is haptic motion rendering. There we propose two candidate methods: linear gain controller and nonlinear gain controller methods with the intention of getting the 2DOF motion. The experimental evaluations involving real users convince that the feeling of object movements through the haptic interface significantly enhanced the viewing experience of an image sequence. Our evaluations further reveal that the nonlinear gain controller method

outperforms the linear gain controller method for translational motion rendering.

However, some limitations exist in the work such as the users are purely passive users, not suitable for object rich environments and background noise affected to the final solution. One of the best examples for such a feeling is feeling the wind in an image sequence. Hence, we extend our research to active user perspective of the haptic perception of feeling the movement of objects in an image sequence by incorporating 3D haptic interactivity on 2D image sequence using the SPIDAR-G. To interact three dimensionally with the image sequence, we define a user interaction along the z dimension with an object selected by the user by pointing it on the image sequence. This user interaction along the third dimension deals with the virtual distance between the user and the object, enabling the user to feel the movement of a desired object at varying virtual distances with the object.

Hence, the proposed approach enables users to point their desired objects and feel the movement of only those objects selected by pointing. Therefore, the proposed approach is capable of dealing with object rich image sequences as well. The ability to change the virtual distance also helps reducing the background noise as the users can select how much of a frame of an image sequence needs to be seen by changing the virtual distance. The experimental evaluation of the proposed system reveals that it has a significant impact on the users' viewing experience.

Moreover, we propose a method to 6DOF, which allow users' to feel the 3D translational and rotational motion of an object in the 2D image sequence using the SPIDAR-G haptic interface. The proposed approach has three major parts namely pose estimation, linear and angular velocity estimation and render of force and torque. In this research, we discuss how to feel the 6DOF motion, which is computed from the two modified methods using the linear gain controller and nonlinear gain controller methods. We have experimentally evaluated and shown that the users are able to feel the 6DOF motion from 2D image sequence from our proposed method. Our evaluations further reveal that the nonlinear gain controller method outperforms the linear gain controller method for 6DOF motion rendering.

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Chapter 1

Introduction

Recently, humans' interest to use innovative technologies to create virtual worlds beyond the real worlds has grown significantly. Among them, haptic technologies play a vital role in virtual reality applications. Haptic technologies enable users to interact with objects in a virtual world. The process, which enables users to touch, feel and manipulate virtual objects through haptic interface is called as haptic rendering [1] [2] [3]. Rather than traditional interfaces that provide visual and auditory information, haptic interfaces can generate mechanical signals, which stimulate human kinaesthetic and touch channels [4]. Various types of haptic interfaces exist and they are being used for different kinds of virtual reality applications. Few of them namely PHANTOM, Falcon, Delta and SPIDAR, are shown in Figure 1.

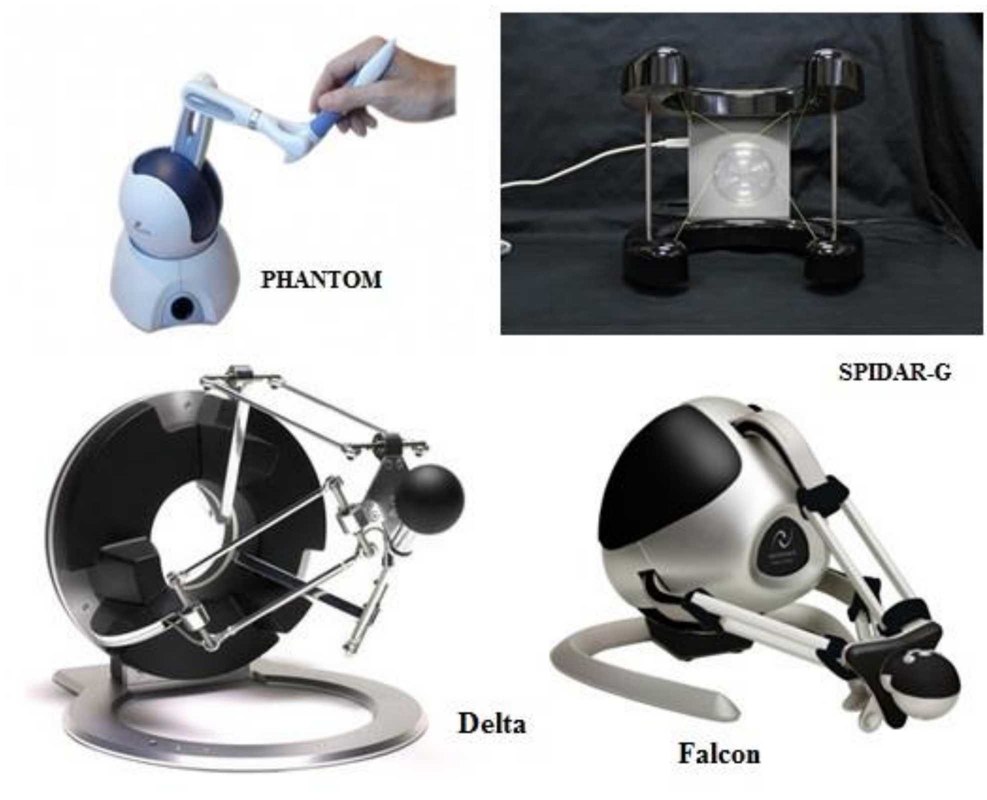


Figure 1 Different haptic interfaces

PHANTOM is a commercially available product, which allows users to touch and manipulate virtual objects [5]. PHANTOM is a 6DOF (i.e. Degrees of Freedom) force enable haptic device. Different types of PHANTOM devices exist and among them, PHANTOM Omni and PHANTOM Desktop devices are more popular as they offer affordable desktop solutions to users.

Falcon is a relatively inexpensive 3-DOF haptic device for 3D touch made by Novint for the gaming industry. The controller of Falcon uses a form similar to that of the delta-robot conjuration, thus makes an interesting apparatus for research into control and estimation problems for robots involving parallel linkages [6].

Grange et al have developed an innovative haptic device called the Delta haptic device that combines a parallel mechanic structure with dedicated electronic and software [7]. The device has 6 DOF and its performance in terms of workspace and applicable force and torque are high. The device can interact with a high-level virtual reality engine. This haptic solution has been integrated into different fields of applications such as simulation of virtual objects, teleoperation of mobile robots and nano manipulation.

The SPIDAR-G haptic device, which we use for this research, belongs to the family of SPIDAR (Space Interface Device for Artificial Reality) haptic devices. SPIDAR is a project of the Sato laboratory of the Tokyo Institute of Technology. Among various kinds of SPIDAR devices, SPIDAR-G is a grip type, tension based 6 degrees of freedom; 3 degrees of freedom for translation, 3 degrees of freedom for rotation and grasp enabled force-feedback device [8] [9]. This device has a grip and this grip is attached to eight strings. Each string is connected to a motor and an encoder at one end and to the grip at the other end. The feedback force is determined by the tension of each string generated by the motor, which is transformed to the users hand through the grip. By connecting this device to a personal computer, it provides a high definition force feedback sensation to the user.

1.1 Motivation

Nowadays, haptic technologies are being used in a wide range of application areas such as in training [10] [11], education [12] [13] [14], cultural applications [15] [16] [17], entertainment and 3D interaction [18]. Apart from that, haptic technology can play a vital role in modern multimedia applications. With the recent developments of high technology multimedia systems such as three dimensional televisions, users' viewing experience has been enhanced significantly by pictures in natural color and true dimensions. However, these systems still rely on only two out of five basic senses of human nature in creating user experiences. Apart from the senses of seeing and hearing, there exists feeling, smelling and tasting. Those other senses such as feeling, smelling and tasting can be incorporate with multimedia applications by using haptic technologies [19] [20].

However, the incorporation of haptic technology into an image sequence, which is known as a video, is still in its infancy and it has gained a worldwide recognition among researchers. Therefore, we believe that user interactions with two-dimensional image sequences can be expanded to other perspectives than the traditional perspectives of seeing and hearing due to the development and pervasive use of haptization systems.

1.2 Research Background

Visual media are sources of data or information in the form of visual representations such as photographs, illustrations, maps, 3D models or videos [21]. Therefore, as shown in Figure 2, visual media haptization can be categorized as image haptization, 3D model haptization and video haptization.

In our research we are focusing on video haptization. As Dinder et al. discuss, there are three types of haptic effects, which are cooperating with haptic interaction with video media [22]. Those are haptic structure, haptic texture and haptic motion. Haptic structure refers to the touching or getting the feeling of the geometry of an object in the video scene. Haptic texture refers to the rendering of surface properties such as roughness of various objects in the video scene. Haptic motion refers to the rendering of forces related to the moving objects in the scene. Haptic structure and haptic texture effects are applicable to image as well as 3D model haptization. However, haptic motion effect is only applicable with video haptization. In this research we focus on the haptic motion part in the video haptization.

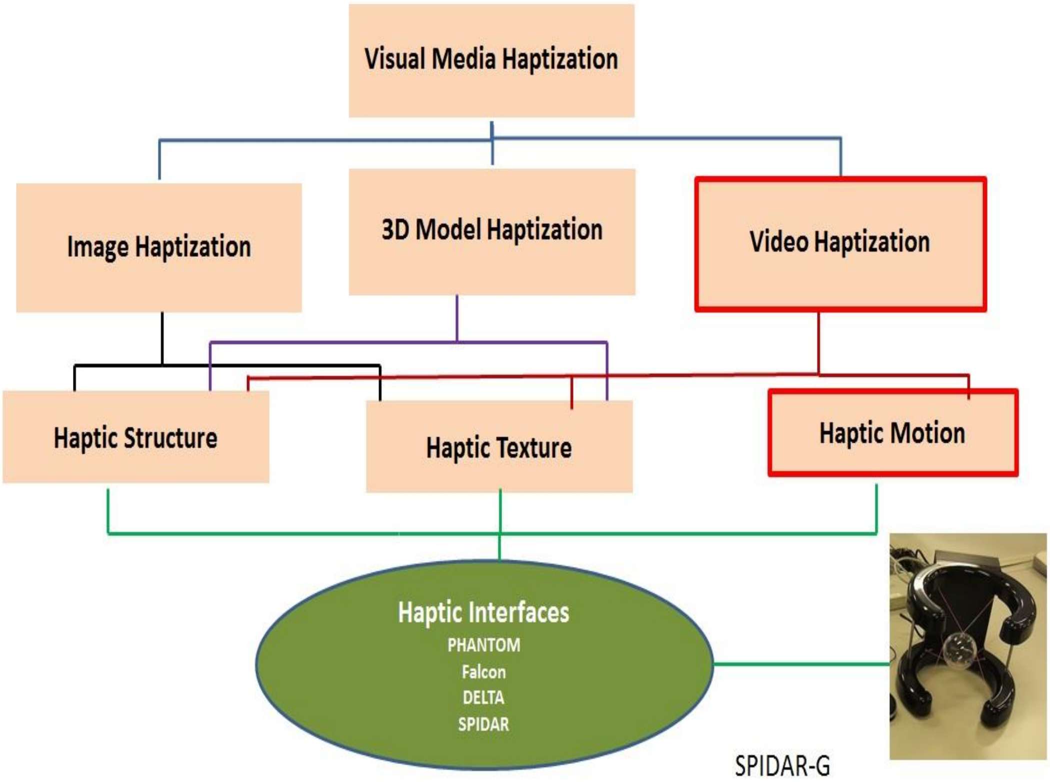


Figure 2 Research background

When it comes to enriching video viewing experience, there exist few whole body sensation devices. For example, the wearable tactile jacket introduced by Lemmens et al provides tactile stimuli to the viewer's body [23]. Apart from that, Surround Haptic is also a new tactile technology introduced by Israr et al , which allows users to feel digital contents directly on their body, from all possible directions using a small number of vibratory actuators [24] [25] [26] [27]. Moreover, the "HapSeat" is a novel and inexpensive approach for simulating motion sensations in audio visual experience [28] [29]. Multiple force feedbacks are applied to the seated user's body to generate a 6DOF sensation of motion as users are experiencing passive navigation. However, despite their success in providing full body sensation, these devices limit users' interactions with the image sequence. For example, Lemmens's wearable jacket lets users only to passively feel the video and does not let the users to have a control on the feeling they get.

Alternatively, there exist other haptic devices, which enable users to interact with objects in a virtual world by pointing the objects. These interactions involve users' hand and may involve various applications of object manipulation. PHANTOM, Falcon, Delta and SPIDAR-G are popular types of haptic interfaces, which are shown in Figure.1. Out of these four haptic devices, PHANTOM, Delta and SPIDAR-G are applicable for this particular work. However, due to the simplicity, familiarity, and the high quality of the feedback force generated, we use SPIDAR-G haptic interface in our research. Apart from that the 6DOF capability of the SPIDAR-G device allows us for the future expansion of our research such as feeling the 6DOF rotation and translation of objects in the image sequence. Moreover, even though the SPIDAR interface has been used in various types of virtual reality systems including image haptization and 3D model haptization, it has not been used for haptization in video media. Therefore, it was necessary to explore its applicability for haptization in video media.

1.3 Objective and Contribution

Our research mainly focuses on exploring different perspectives of getting the haptic perception of feeling the movement of objects in an image sequence, with the objective of enhancing the viewing experience of viewers to the near real world level. We use the SPIDAR-G haptic interface, which belongs to the family of SPIDAR haptic interfaces developed by the Sato laboratory of Tokyo Institute of Technology.

At first we research on how to associate haptic signals with an image sequence to feel the movement of objects in it. There we focus on feeling the movement of objects along the x and y dimensions using the SPIDAR-G haptic interface [30] [31].

One of the best examples for such a feeling is feeling the wind in an image sequence. The experimental evaluations involving real users convince that the feeling of object movements through the haptic interface significantly enhanced the viewing experience of an image sequence.

However, the users of that system are purely passive users, which is a major limitation of the system. In other words, the users could only passively feel the motion of objects in the image sequence along the x-y plane regardless of the number of objects in it. Thus, one possible extension of that system is to enable the users to be active, such as allowing them to interact with the system to feel the motion of objects in the image sequence.

In order to address this issue, we define a user interaction along the *z* dimension with an object selected by the user by pointing it on the image sequence. This user interaction along the third dimension deals with the virtual distance between the user and the object, enabling the user to feel the movement of a desired object at varying virtual distances with the object. This feature resembles an interesting real world phenomenon. For example, in a real environment when someone stands closer to an object, he or she sees the particular object larger without seeing much of the nearby objects. However, when the same person stands at a distance to the same object, he or she sees the object smaller than before together with a significant portion of the nearby objects. Accordingly, the intensity of the movement of the object felt to the user may vary.

This user interaction defined along the third dimension helps to address another issue of our previous work. The performance of the work is satisfactory only for the image sequences containing one object. However, image sequences of the real world contain multiple objects and our previous system is not capable of handling such object rich image sequences because the user feels the collective movement of all objects instead of the movement of the desired object. The proposed approach enables users to point their desired objects and feel the movement of only those objects selected by pointing. Therefore, the proposed approach for with haptic active user is capable of dealing with object rich image sequences as well. The ability to change the virtual distance also helps reducing the background noise as the users can select how much of a frame of an image sequence needs to be seen by changing the virtual distance. For example, in an image sequence of a car race, a user may decide whether to feel the movement of one particular car, a group of cars or even a group of cars and the background.

Despite that, the motions of the objects are not only translational but also rotational. We believe that it would be interesting and highly necessary to research on how to incorporate three dimensional translational and rotational features as 3D technologies are becoming increasingly popular. Since SPIDAR-G is a 6 DOF device, this could be implemented through SPIDAR-G. Hence, we propose a method to feel the 3D translational and rotational motion of an object in the 2D image sequence using the SPIDAR-G haptic interface.

1.4 Applications of the Research

Among many potential application areas of this research, below we describe two significant application areas.

Entertainment:

Rather than traditional multimedia systems, Haptic-Audio-Visual (HAV) Multimedia systems allow users to feel a physical event or an object in the movies rather than just seeing and hearing it [32]. It brings more interactive and immersive experience to users because of the haptic modality. For example this allows users to feel a physical event, such as an earthquake or wind, happening in a movie.

Digital Museum / Multimedia-enabled Museum:

Adopting multimedia technologies at a museum such as audio, video and animations, helps enhancing the experience of the visitors in different ways. In traditional museums, visitors learn about the artifacts by looking at them and reading the descriptions underneath them. However, incorporation of multimedia based services enables them to attain a more holistic knowledge, understanding and appreciation about the artifact being observed [33] [34] [35]. For example, a historical artifact displayed at a museum could be accompanied by a digital display that shows a series of pictures that explain its background and natural setup or a video that shows some functionality. These digital contents could further be published in the website of the museum to provide a pre-visit experience to visitors. Furthermore, these multimedia contents are useful to enhance the experience of the visitors with some disability hearing impairment or blindness.

However, these digital multimedia contents form only a one-way information link with a visitor. In other words, visitors become only passive receivers of information even though the received information represents different dimensions. For example, usually the museum visitors are not allowed to touch the surface of a historical or astrological artifact or a sculpture. However, an active interaction as such with museum artifacts would be very important not only for visually impaired visitors but also for students, researchers and even ordinary visitors to attain a better understanding and appreciation. To enable such kind of active involvement, researchers propose the incorporation of haptic technologies, which makes object haptization for museums a promising research area [15] [36] [37]. Object haptization, for example, could be used to touch and explore the surface of an untouchable historical artifact kept inside a glass chamber. In such a case, visitors interact with a digital image of the artifact, instead of the real object, through a haptic device [36] [37] [38].

Most research attempting to apply haptic technology to museum setups have focused on haptic interaction with still images of museum artifacts. However, modern museums increasingly use video galleries of artifacts, in addition to image galleries, to better explain their natural setups, functionalities and use contexts [39]. Therefore, we recognize our research is highly applicable of applications of haptic technologies in museum setups which have video media. For example, in a railway museum, haptic interaction with a video of running different trains may help the visitor to understand the speediness of them by giving the feeling of presence in the real use environment.

1.5 Thesis Outline

The remainder of the thesis is organized as follows.

Chapter 2 reviews existing literature on the related work on haptic interaction with visual media such as in image haptization, 3D model haptization and video haptization using SPIDAR-G and other different haptic interfaces.

Chapter 3 presents proposed systems for haptic rendering of dynamic motion which include the 2DOF motion rendering, 3DOF motion rendering and 6DOF motion rendering systems. The proposed 2DOF system allows users to feel the 2D motion force of moving objects in the image sequence. Main contribution of this research is the haptic motion rendering. Here, we propose two methods: linear gain controller method and a nonlinear gain controller method with the intention of getting the 2DOF motion. To overcome the problems exist in the 2DOF method and allow users to be active such as enables the user to select objects by pointing it on the image sequence and get the feeling of the selected object's movement, then we propose a 3DOF system.

Moreover, the research extends for 6DOF motion rendering with the intention of allowing users to feel the 6DOF translational and rotational movement of objects in the image sequence. For that we modify the proposed linear gain controller method and a nonlinear gain controller method with the intention of feeling the 6DOF motion.

Chapter 4 discusses the results of an experimental evaluation involving the feedbacks of real users regarding their viewing experience of an image sequences with and without haptics. Furthermore, we evaluate the performance of the system with haptics in active and passive user environments (i.e. 2DOF motion rendering system and 3DOF motion rendering system). Conclusion of the research reveals that the feeling of object movements through haptic interface significantly enhances the viewing experience of user and the users experienced an increased appreciation of the image sequence by adding 3D interaction by allowing user to active with the use of proposed object haptization method on a 2D image sequence.

Moreover we evaluate the proposed system for 6DOF and test whether it enables the user to feel the motion of translation and rotation three dimensionally. It evaluates the performance with respect to the two proposed approaches: linear gain controller and nonlinear gain controller. Results conclude that the users not only get the feeling of the translational motion, they get the feeling of the rotational motion too in the image sequence and hence the proposed approach is suitable for 6DOF motion rendering. Furthermore it reveals that more than 70% of users responded that using the nonlinear gain controller method is better than using a linear gain controller method for translational as well as rotational motion rendering.

Chapter 5 concludes the work and presents the future work.

Chapter 2

Related Work on Visual Media Haptization

This chapter summarizes the existing research on haptic interaction with visual media using different haptic interfaces. As shown in Figure 3, haptization of visual media can be image haptization, 3D model haptization and video haptization.

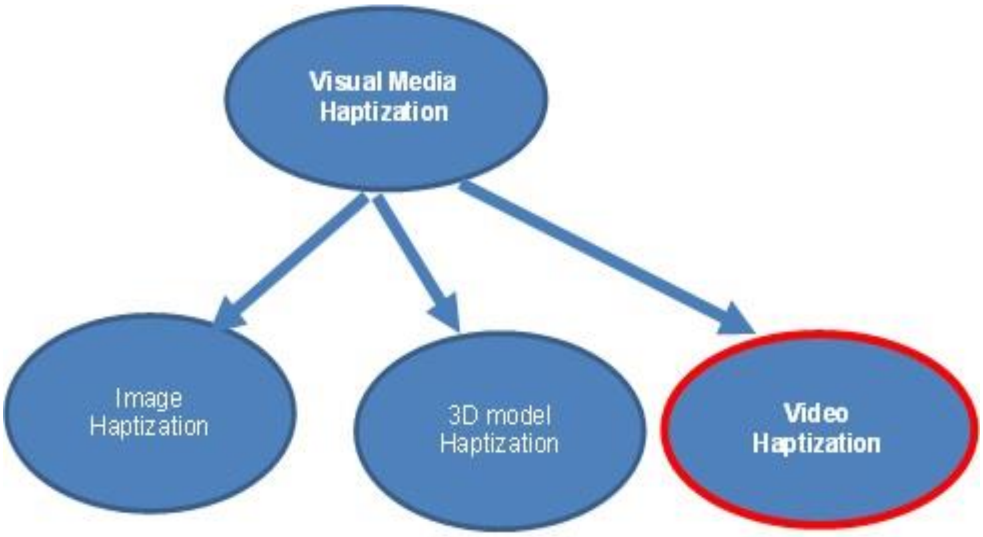


Figure 3 Sub areas of the visual media haptization

2.1 Research on image haptization

This section summarizes few of the research on haptic interaction with images using SPIDAR-G and other haptic interfaces such as PHANTOM Desktop, PHANTOM Omini, Delta etc.

2.1.1 Using different haptic interfaces

Nikolakis et al. have proposed a system, which allows blind and visually impaired people to perceive grey scale images using PHANTOM Desktop haptic device [40]. They have described two methodologies for representing grey scale images in a haptic environment. The first method is based on the creation of a height map that depends on the grey level of the image. The second method used to represent the grey levels by modifying the friction coefficient of a plane depending on the position of the stylus on it. The system was evaluated with blind and blindfold users. The results showed that the users could distinguish dark and light areas in the images and to understand simple shapes.

Barbieri et al. have proposed a solution to blind users that allows tactile haptic feedback and aural exploration of the graphs of a mathematical function [41]. They used a device called AudioTactTM, which is a transducer that allows a multimodal exploration of images such that it generates the sonorous and tactile stimulus simultaneously together with a graph editor BlindGraph. BlindGraph is a software application that allows the graph exploration receives as input file.

Moreover, Roth et al. have proposed a method of audio-haptic tool that enables blind computer users to explore a picture by the hearing and feeling modalities [42]. The tool is divided in to two entities: a description tool and an exploration tool. The description tool allows sighted person to describe a scene. Therefore, the scene is firstly segmented manually or automatically into a set of objects (car, tree, house, etc.). For every object, the sighted person can define a behaviour which correspond either to an auditory (i.e., using speech or non-speech sound) or to a kinaesthetic rendering. The blind person uses the exploration tool in order to obtain the audio-haptic rendering of the segmented image previously defined by the sighted person. Depending on the nature of the feedback defined (audio, kinaesthetic), the blind user interacts either with a graphic tablet and/or a force feedback device.

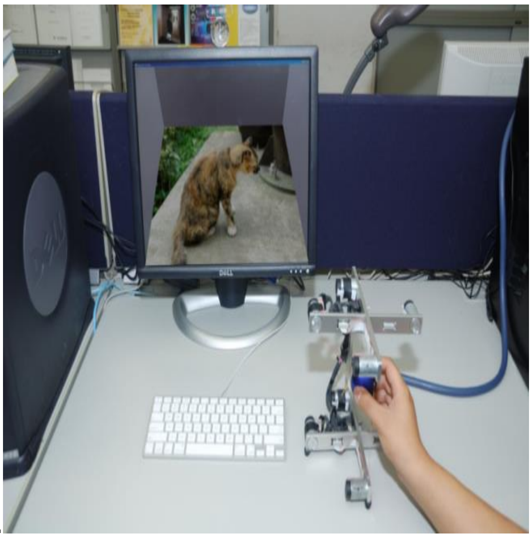
Wu et al. have proposed a novel haptic texture display method based on the height map of the texture that is acquired based on the Gauss filter in frequency domain [43]. The 3-DOF texture force and the friction force are modelled based on the height map using the 6DOF DELTA haptic device.

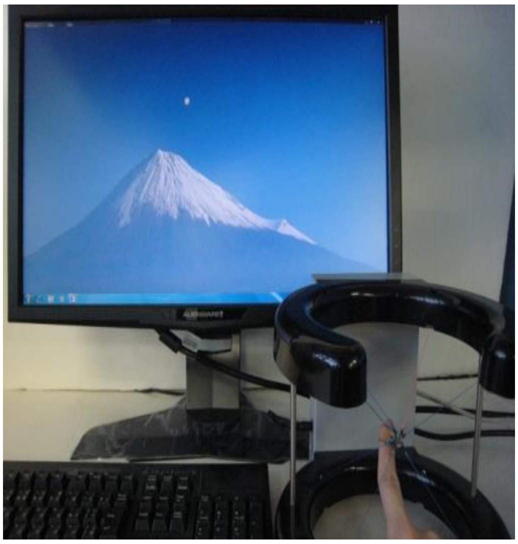
Kagawa et al. have proposed an advanced image edition tool with force feedback sensation [44]. Users can utilize additional haptic information for image editing. An editing image is expressed as a plane in a three dimensional virtual space. This virtual plane provides the force and tactile information from the image to users using the 6DOF PHANTOM Omini haptic interface. Users use that information to extract object in the image.

2.1.2 Using SPIDAR haptic interface

Liu et al. have proposed a 2D image haptization system, which provides the users with sense of touch on an image with local deformations using the SPIDAR-G haptic interface [45]. This 2D image haptization system has used the color haptic parameter mapping and the penalty method to render the haptic feedback. Local deformation has been applied by using an image distortion to the local area of the pointer.

Takahama et al. have proposed a 2D image haptization system based on color and edge information using SPIDAR-G haptic information, which provides the users with sense of touch on image edges [46]. Pictures of both of the above systems that have used SPIDAR-G are shown in Figure 4.





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(a) Demonstration of Liu et al (b) Demonstration of Takahama et al

Figure 4 Image haptization systems using SPIDAR

2.2 Research on 3D model haptization

This section summarizes few of the research on haptic interaction with 3D models using SPIDAR-G and other haptic interfaces such as PHANTOM Desktop, PHANTOM Omini etc.

2.2.1 Using different haptic interfaces

Walker et al have proposed an interactive 3D browser for large topographic maps using a visual display augmented by a haptic feedback using 6DOF PHANTOM Desktop haptic interface [47]. They use proxy-graph algorithm which allows efficient haptic display of very large triangular meshes consisting of hundreds of millions of polygons.

Moreover, most research attempting to apply haptic technology to museum setups have focused on haptic interaction with 3D representations of artwork or museum artifact. Usually the museum visitors are not allowed to touch the surface of a historical or astrological artifact or a sculpture. The incorporation of haptic technologies allows museum visitors to explorer three-dimensional works of art by “touching” them. Butler et al have developed a system for virtual museum which allow users the ability to interact with a 3D virtual replica using the PHANTOM Omini haptic interface [37].They have developed a 3D model and a user interface which represents the virtually interactive version of the object placed next to the real object. They have used Phantom Omini haptic device to feel the smooth and rough surface properties of a virtual sculpture and showed that the time spent while viewing sculptures with haptic was high.

Margaret et al have proposed a haptic collaboration system which allows museum visitors, museum staff members and students to jointly explore three-dimensional works of art by touching them, using PHANTOM and CyberGrasp devices [38].

2.2.2 Using SPIDAR haptic interface

Liu et al. have further extended their research on 2D images to 3D image haptization with local deformations by using depth representation of image [48]. In the depth image haptization system, a triangle polygon mesh is extracted and built from the depth image for the haptic rendering. Revised proxy graph algorithm is used to calculate the contact force between the contents and the user's finger. Local deformation is applied by moving the corresponding vertices towards the vector of proxy and endpoint. Image of the demonstration of the system is shown in Figure 5.

Figure 5 Liu et al 3D model haptization system using SPIDAR

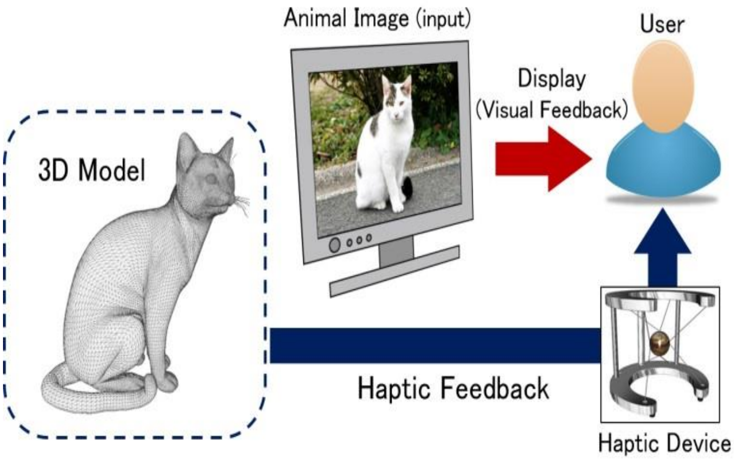

Figure 6 Okubo et al 3D model haptization system using SPIDAR

Okubo et al. have proposed a haptization system as shown in Figure 6, for animal images by using a 3D model of animals [49]. The system allows users to get the feeling of the geometry of the animals using the SPIDAR haptic interface. They improve the three-dimensional impression and the sense of presence by placing a 3D model of an animal on an image and performing the haptic feedback. The proposed system has an existing 3D model and poses information, and then users can choose and place them.

2.3 Research on video haptization

Incorporation of haptic technology into video media is not adequately researched in the haptic rendering field. This section summarizes few of them that are available using the haptic interfaces PHANTOM, Falcon etc.

2.3.1 Using different haptic interfaces

When it comes to research on haptic motion, Dinder et al. have introduced the concept of haptic motion for the first time and they have discussed a method to compute haptic structure and motion signals for 2D video-plus-depth representation [22]. That method enables the viewers to navigate the scene and get the experience of the geometry of objects in the scene as well as the forces related to moving objects in the scene using PHANTOM Omini haptic interface. They have used depth map information to get 3D video representation. They have also modelled the total force as the sum of static and dynamic forces. While the static force is related to the geometry, material and the surface properties of an object's, dynamic force related to the relative motion between the object and the haptic interaction point. In their research, dynamic force for haptic motion is related to the relative motion between the object and the haptic interaction point and in that case if the user moves the haptic interface point towards an accelerating object, force experience is increased and otherwise it is decreased.

Cha et al. have proposed a touchable 3D video system which provides haptic interaction with objects in a video scene through the Falcon force feedback device [50][51][52]. They used Depth Image-Based Haptic Representation (DIBHR) to add haptic surface properties and the system enables to physically explore the video content and feel various haptic properties such that texture, height map and stiffness of the scene.

Kim et al. have proposed a 3DTV system which enables not only enjoying a high-quality 3D video in real time, but also user can experiencing various user-friendly interactions such as free viewpoint changing, composition of computer graphics and haptic display [53]. They have created a new representation of dynamic 3D scene, called 3D depth video and the viewer can touch the shape of it by wearing a haptic device using a haptic rendering algorithm.

Moreover, O'Modhrain et al. have discussed how haptic interaction can enhance and enrich the viewer's experience in broadcast content [54]. They have proposed a touch TV project with the use of 2 DOF gaming joystick called Gravis Xterminator force and remote control handset to generate haptic cues for cartoons and live sports broadcastings, which adds greater sense of immersion. They have proposed "presentation interaction", which allows the relocation of a character's rendered position in a scene of a created cartoon without having to alter the structure of the narrative in any way [55].

2.3.2 Using SPIDAR haptic interface

Because of the distinguishing features of scalability, string based and transparency made from SPIDAR system, its interface is used in various types of virtual reality systems [56]. However, to the best of our knowledge there is no evidence of using SPIDAR-G for haptization in video media. Due to the simplicity, familiarity, and the high quality of the feedback force generated, we use SPIDAR-G haptic interface in this research

Chapter 3

Systems for Haptic Rendering of Dynamic Motion

In this chapter we consider how to associate haptic signals with an image sequence to feel the motion of objects in it. There, we propose solutions such that they discuss different perspectives of getting the haptic perception of feeling the movement of objects in an image sequence with the objective of enhancing the viewing experience of viewers to the near real world level. We present our proposed systems for two degrees of freedom (2DOF), three degrees of freedom (3DOF) and six degrees of freedom (6DOF) motion rendering to a 2D image sequence.

3.1 Haptic Rendering of 2DOF Motion

Here we discuss how we incorporate haptic interface with 2D image sequence which enables the users to feel the motion of objects in it, beyond passive seeing and hearing.

As shown in Figure 7, the proposed approach in this research has four major steps namely feature points selection, feature points tracking, motion estimation and haptic motion rendering. The first step of this sequence of steps is feature point selection. In that step, it identifies good features of each image frame of the image sequence. The next step, feature point tracking involves the tracking of those feature points reliably from frame to frame. In the motion estimation, it calculates the motion of an object in the image frame by getting the average motion of feature points in the image frame. In this research our main contribution is in the final step i.e. haptic motion rendering. There we propose two candidate methods for haptic motion rendering: linear gain controller method and a nonlinear gain controller method with the intention of getting the 2DOF motion. The following sections broadly describe the above parts.

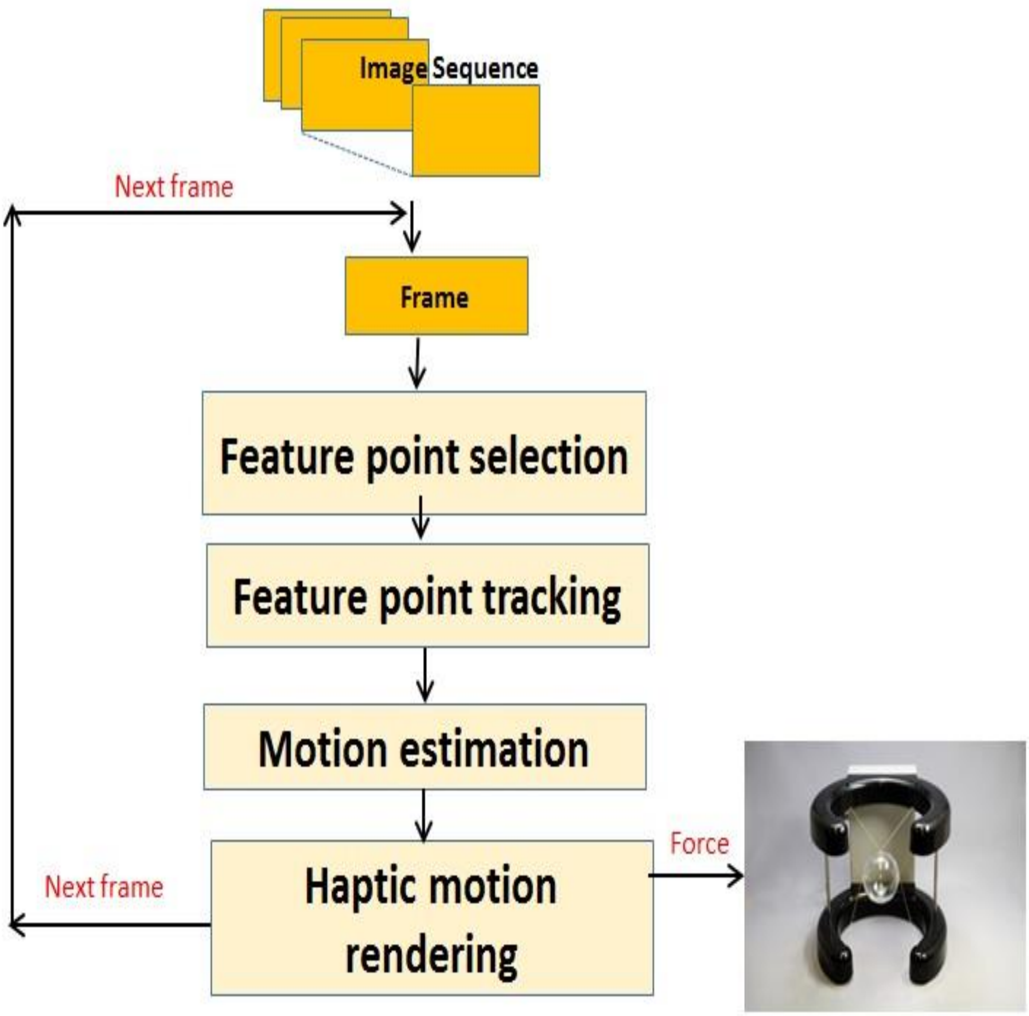

Figure 7 Proposed approach for 2DOF haptic motion rendering

3.1.1 Feature point selection

Feature point selection is an important task of any computer vision and image processing applications. Since feature point selection is the starting point of many computer vision algorithms, the performance of the subsequent algorithm as well as the overall performance of the process basically depends on it.

Feature point selection finds which points are good to track. For example corners or good textures may be good feature points of an image. There are various methods exist for feature selection such as Harris, Shi & Thomasi, Canny, Sobel etc. Among those methods Shi & Thomasi algorithm gives better results than the others [57]. Besides, this algorithm is more efficient in feature point detection and hence, the processing time of the overall process becomes less. Therefore we use Shi & Thomasi algorithm for feature point selection in the image sequence. This algorithm is based on the assumption that the brightness of a pixel does not change from frame to frame.

3.1.2 Feature point tracking

Feature point tracking involves identifying above features reliably from frame to frame. These feature points are then used to measure the motion of the objects between two frames in an image sequence. In this research, we use the optical flow technique for feature point tracking [58].

Optical Flow is the distribution of apparent velocities of movement of brightness patterns in an image. Optical flow arises from relative motion of objects and the viewer [59]. The way an object moves when it is seen or followed in a video or sequence of images is known as optical flow [60]. There are two types of optical flow methods namely dense optical flow and sparse optical flow. In dense optical flow methods, it associates velocity with every pixel in an image. 'Horn- Schunck method' and 'Block matching method' are examples for this type of optical flow [58]. In practice, calculating dense optical flow is not easy because of the high computational cost. Alternatively, sparse optical flow techniques calculate velocities only on the points which have certain desirable properties.

We use Pyramid Lucas-Kanade algorithm, which is a pyramidal implementation of the Lucas-Kanade feature tracker [61]. At first in this technique, it solves optical flow at the top layer of the pyramid and then use the resulting motion estimates as the starting point for the next layer down. It continues going down the pyramid in this manner until it reaches the lowest level. Therefore by using this method, it can track faster and longer motions [58]. This has less computation and therefore it could be easily adapted for real time applications. [57]

Figure 8 shows the obtained results for feature point selection and feature point tracking with the use of Shi & Thomasi algorithm and the Pyramid Lucas-Kanade algorithm for the image sequence of a bouncing ball. Figure 9 shows the flow information of that image sequence. In that figure, the direction of each arrow represents the direction of optical flow and the length of each arrow represents the magnitude of the optical flow.

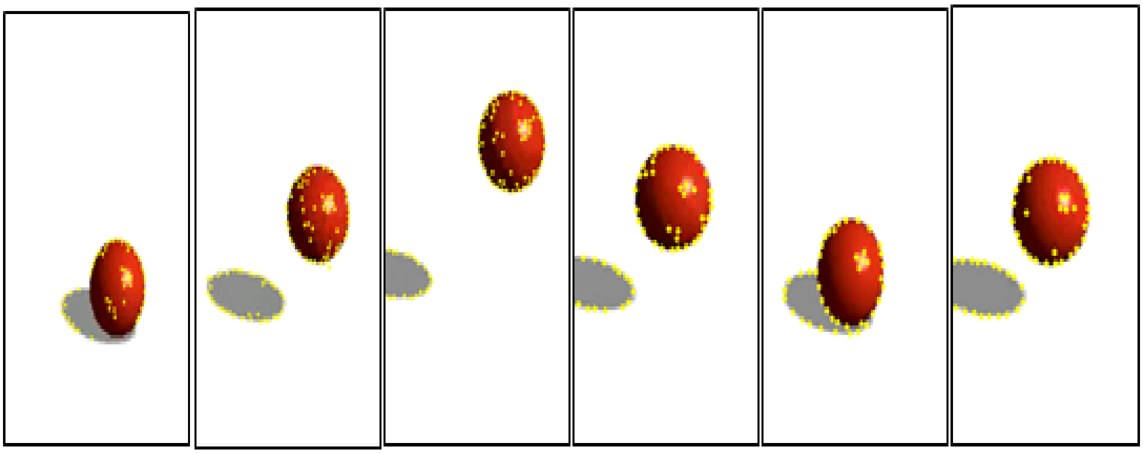

Figure 8 Feature point selection and tracking

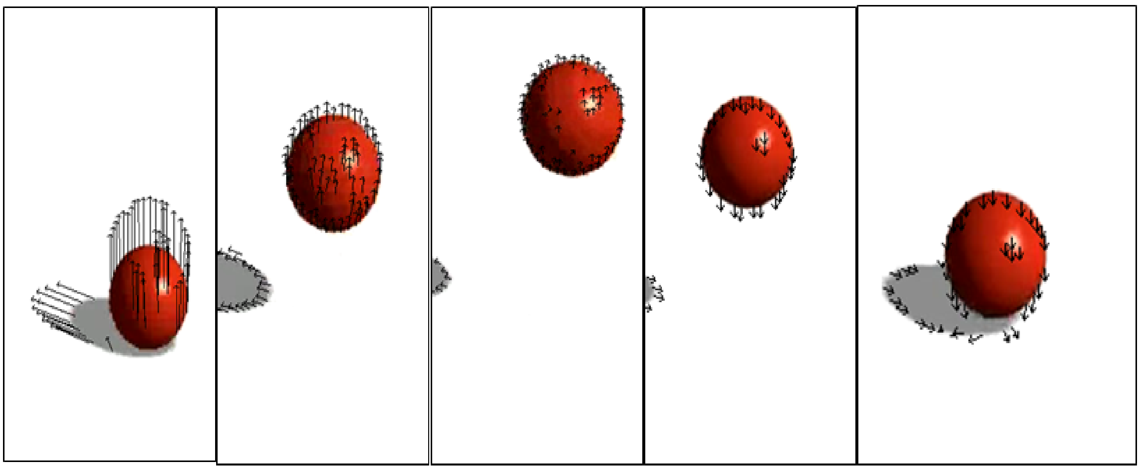

Figure 9 Results of optical flow

3.1.3 Motion estimation

This section explains how we calculate the motion of an object in the image frame.

We use velocity of a feature point to estimate the motion. The position of a feature point in two subsequent frames at time *t* and $(t + \Delta t)$ can be represented as $p_i(t)$ and $p_i(t + \Delta t)$.

The velocity of a feature point is calculated using the equation (1).

$$V_i(t) = \frac{P_i(t+\Delta t) - P_i(t)}{\Delta t} \qquad (1)$$

If there are *N* feature points in a frame, then the velocity of each frame is given by the average velocity of feature points in the image frame, as shown in equation (2).

$$\overrightarrow{V_f(t)} = \frac{1}{N}\sum_{i=1}^{N} v_i(t) \qquad (2)$$

3.1.4 Haptic motion rendering

Haptic motion rendering means rendering of forces related to the moving objects in the scene. In this section we explain how we calculate forces based on the above velocity changes in the image sequence.

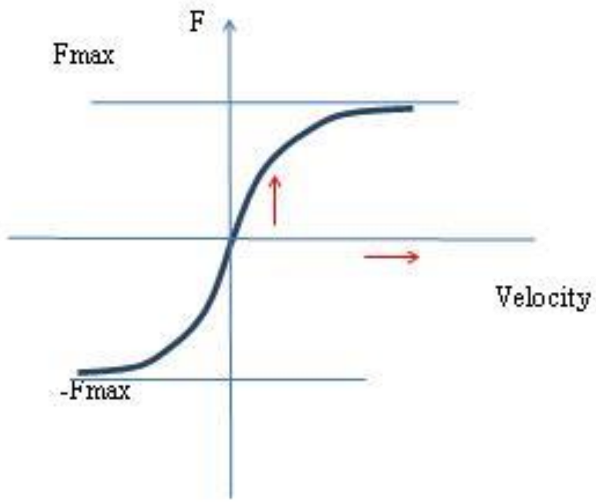

Figure 10 Purpose of the force rendering methods

We use SPIDAR-G haptic device which is a six degrees of freedom force feedback device by controlling the tension of each string in the system. However, the high velocities produced by high force and low velocities produced by low force lead to an unrealistic sensation. To overcome this problem of haptic jitter and to get a realistic sensation to the user we need to reduce force for high velocities and increase the force for low velocities. Figure 10 illustrate this idea in a graphical form.

For this purpose, we evaluate two methods, a method using a linear gain controller and a method using a nonlinear gain controller with the objective of identifying the better method.

Linear Gain Controller Method: Automatic gain controller is a feature found on many electric circuits that automatically controls the gain of a signal. We used this concept to control the force of the haptic device.

Using the linear gain controller method, the feedback force is calculated from equation (3). This enables user to get the feeling of the movement of the object.

$$\overrightarrow{\mathrm{F(t)}} = \mathrm{k} * \overrightarrow{V_f(\mathrm{t})} \qquad (3)$$

Here ***k*** is a gain controller.

Calculation of ***k*** is done as in equation (4) to control the feedback force within a sensible region for all velocity levels. In other words, the purpose of the gain controller ***k*** is to increase the feedback force for weak changes in velocity and decrease the feedback force for strong changes in velocity.

$$\mathrm{k} = \frac{\mathrm{F_{max}}}{\mathrm{V_{max}(T)}} \qquad (4)$$

Here F_{max} is the maximum force output level of the SPIDAR-G device for better sensation for this application. $\mathrm{V_{max}(T)}$ is the maximum velocity of the video frame at a time *T*, which can be expressed as in equation (5).

$$V_{max}(T) = \{ V_{max}(t) \quad 0 \leq t \leq T \qquad (5)$$

Nonlinear Gain Controller Method: Similar to the previous method, the purpose of using a nonlinear gain controller method is to maintain the feedback force in the sensible region by decreasing the feedback force for high velocities and increasing the feedback force for low velocities.

In the nonlinear gain controller method we use a nonlinear function to map the velocity into force and the resulting feedback force to sense the motion of objects as shown in equation (6).

$$F(t) = f(v_f(t)) \qquad (6)$$

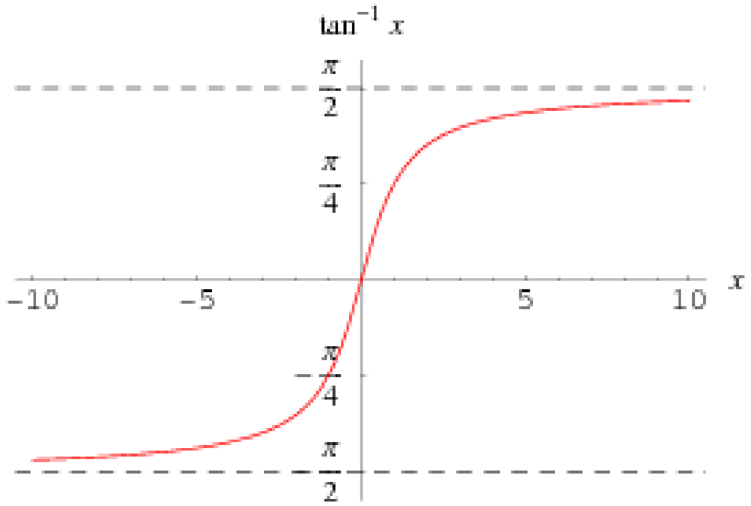

Figure 11 Inverse tangent function

Our requirement in selecting a nonlinear function is the ability of bringing down the feedback force into the sensible region of SPIDAR-G. As shown in Figure 10, due to the S-shape behaviour, the sigmoid function proved to be a good candidate. However, as the velocity needs to be zero when changing the moving direction, we get an additional requirement such that the selected sigmoid function needs to go through the origin. Therefore, we select the inverse tangent function as shown in equation (7).

$$F(t) = \frac{2\,F_{max}}{\pi}\tan^{-1}(\alpha * V_f(t)) \qquad (7)$$

To choose the parameter α, we tested α for the values of 0.001, 0.01 and 0.1. As shown in Figure 12, the value of the α determines the linearity of the inverse function.

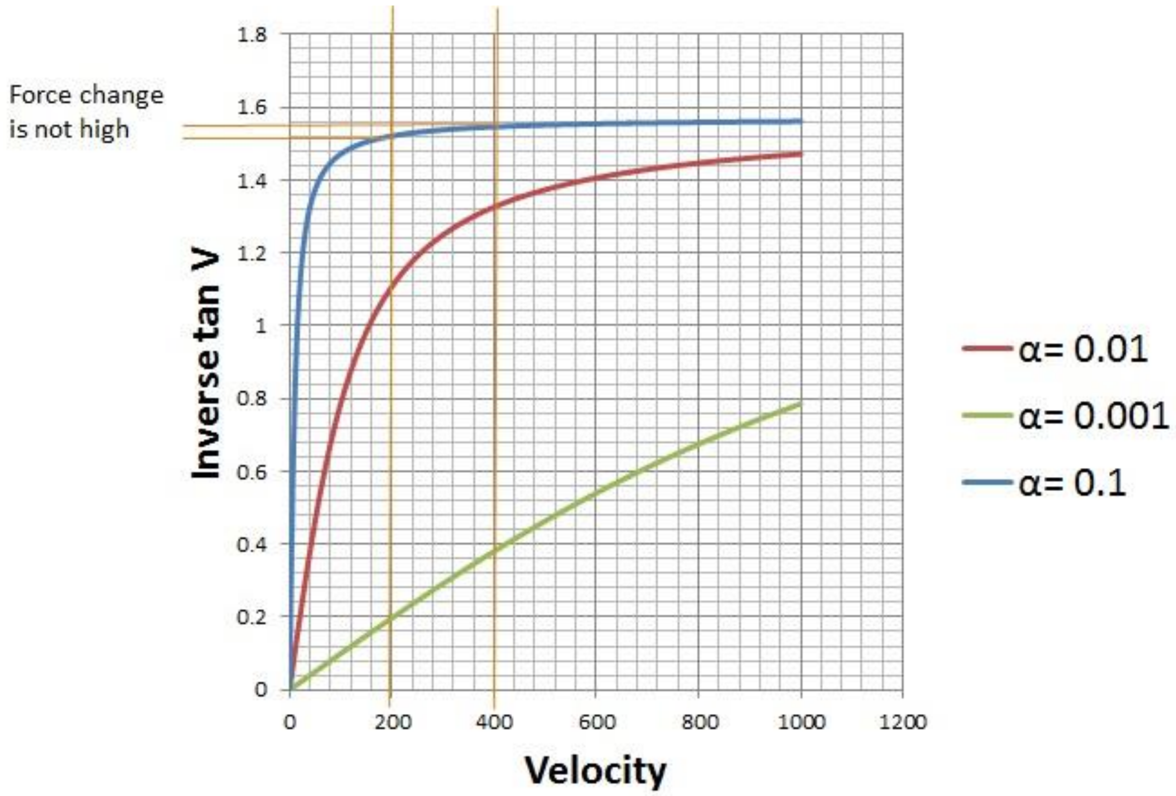

Figure 12 Linearity change of the inverse tangent function

For two different values of the velocity V_1 (200 pixels/second) and V_2 (400 pixels/second), force change is not significant when α = 0.1. Moreover, feeling of the force is less when α = 0.001. Hence to get a better feeling of the force change for large range of velocity values, we select α as 0.01.

3.2 Haptic Rendering of 3DOF Motion

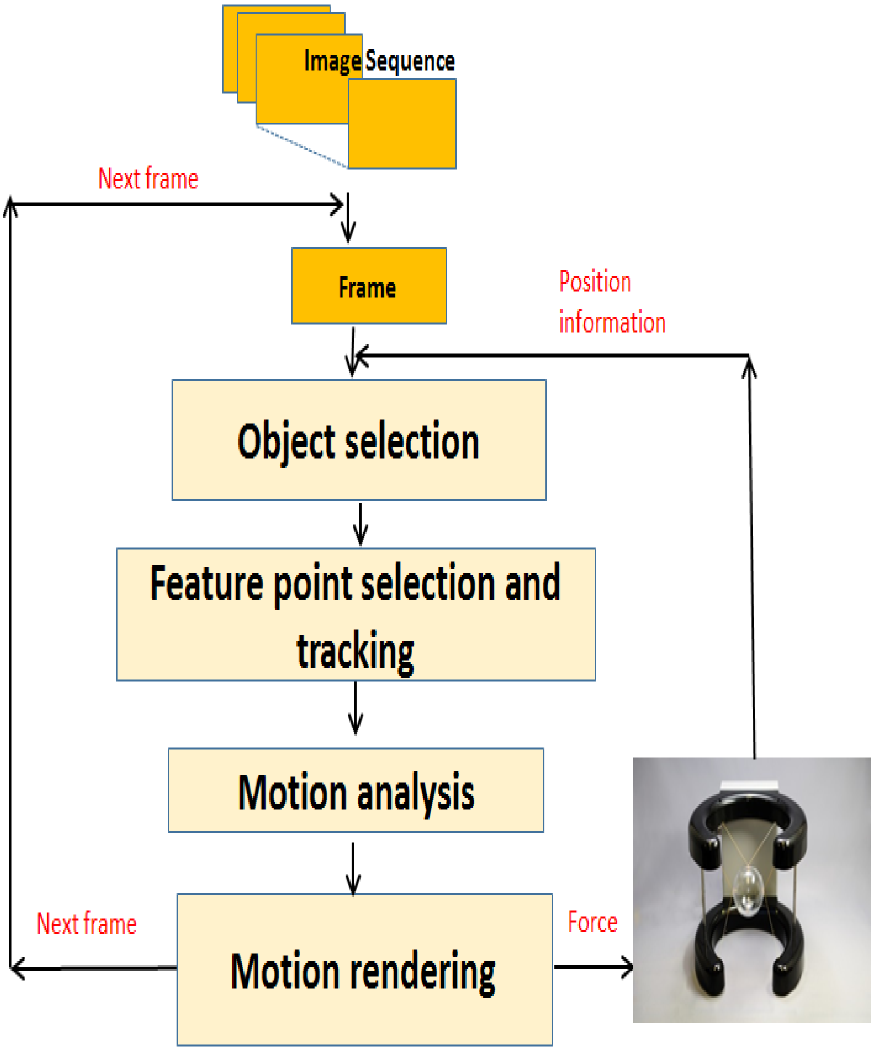

Figure 13 Proposed approach for 3DOF haptic motion rendering

In this section we present an active user interaction with the 2D image sequence by incorporating 3D interactivity. We define a user interaction along the third dimension, which enables the user to select objects by pointing it on the image sequence. This user interaction along the third dimension deals with the virtual distance between the user and the object, enabling the user to feel the movement of a desired object at varying virtual distances from the object.

As shown in Figure 13, the proposed approach in this research has four major steps namely object selection, feature points selection and tracking, motion analysis and finally motion rendering. The first step of this sequence of steps is object selection. In that step, user can select specific object among many in the image sequence using the haptic interface. The next step, feature points selection and tracking involves identifying good feature points and tracking of those feature points from frame to frame. In the motion analysis, it calculates the motion of an object by getting the average velocity of each feature point around the region of the haptic interface point. In the final step describes how the motion information mapped into the haptic device for better rendering of force. The following sections broadly describe the above parts.

3.2.1 Object selection with the haptic pointer

In this research, we use the SPIDAR-G haptic device to interact with the objects in the image sequence. By holding the grip of the SPIDAR-G device, user can point and touch the objects on the image sequence according to his or her desires. From this point-based haptic interaction, user can see the end point of the haptic device, also known as the haptic interface point where they want to select in the image.

Mapping of haptic device coordinates to image coordinates:

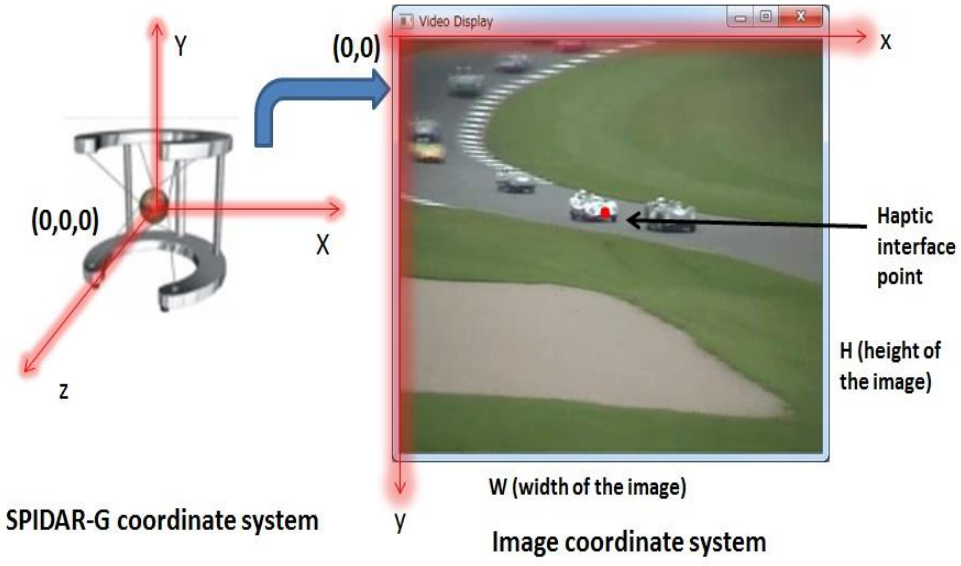

Figure 14 Image coordinate system and haptic device coordinate system

In order to touch the image through the haptic device, it is necessary to identify the properties of the input image frame and the hardware limitations of the SPIDAR-G device.

As shown in Figure 14, input image is a color image with ***W*** pixels of width and ***H*** pixels of height. Workspace of the SPIDAR-G device has a width of ***X*** mm, height of ***Y*** mm and depth of ***Z*** mm. Since the coordinate systems of the image and the SPIDAR-G device are not corresponding, it is mandatory to map the SPIDAR-G coordinates to image coordinates, in order to identify the corresponding position of the pointed object point on the image.

Equation (8a) and (8b) shows the mapping of SPIDAR-G haptic device coordinates into image coordinates.

$$w = \frac{W}{2} + \left(\frac{W}{X} * x\right) \quad (8a)$$

$$h = \frac{H}{2} + \left(\frac{H}{Y} * (-y)\right) \quad (8b)$$

Here ***w*** and ***h*** are the coordinates of the point of interest on the image and ***x*** and ***y*** are the coordinate values of the SPIDAR-G device along the ***x*** and ***y*** axes on its 3D coordinate space.

Focusing of objects in the image sequence:

As shown in Figure 15, in order to select a specific object among many and to limit the area around the object (or in other words the region of interest (ROI)), we use a square region around the haptic interface point. This limits every action performed to the image sequence and hence, user can feel the haptic feedback only from the selected object rather than the entire image. It avoided the background noise affecting to the final outcome.

Figure 15 Object selection around the haptic interface point

Adding 3D interactivity to change the region of interest:

Moreover, to interact three dimensionally with the 2D image sequence, we use the ***z*** coordinate value of the SPIDAR-G system to change the size of the square corresponding to the region of interest around the haptic interface point. Size of the ROI act as a determinant of the user`s virtual distance to the object. For example, in a real situation when the user stands closer to a scene he or she sees a small area but if he stands away at a significant distance, he or she sees a larger area of the scene. Similarly, by using the ***z*** coordinates, we enable the user to maintain a virtual distance. This concept is shown in Figure 16 and this leads to an interactive haptization with an image sequence such that user can select the area of a single object or many objects, of which they want to feel the motion. As shown in Figure 14, when the haptic point of SPIDAR-G is moved to the ***–Z*** direction, the square corresponding to the ROI becomes smaller where as it becomes bigger when the haptic point is moved to the ***+Z*** direction.

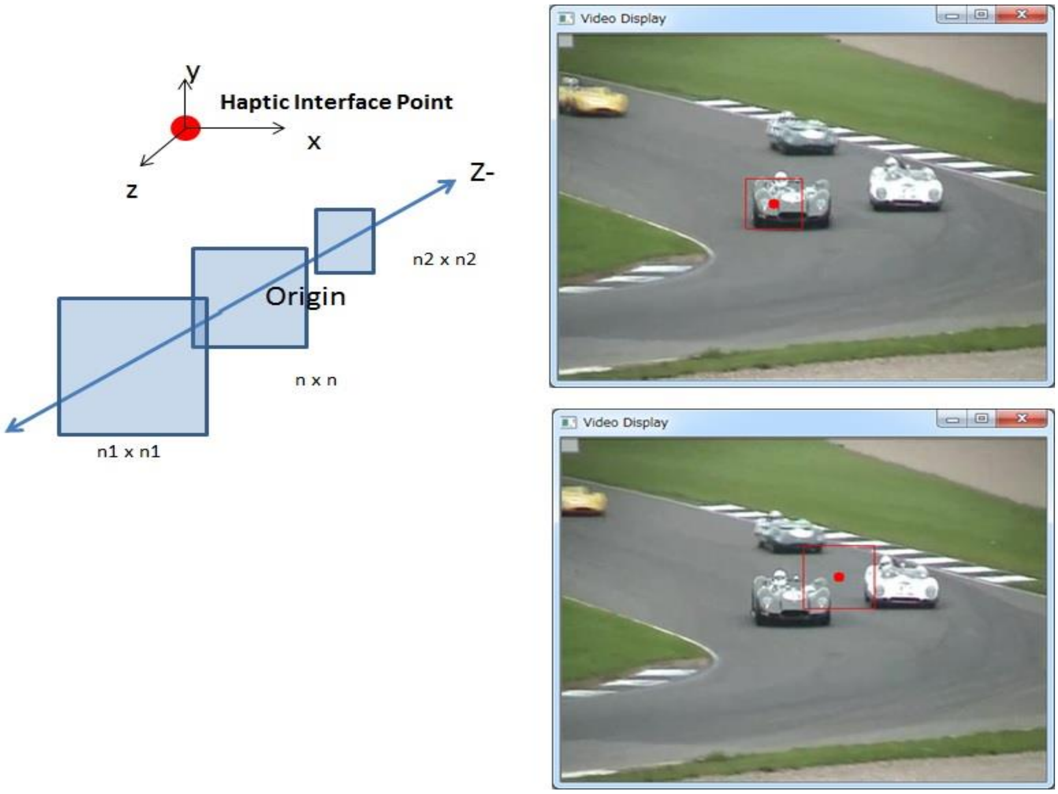

Figure 16 Change the region of interest around the haptic interface point using the *z* coordinate values of SPIDAR-G device

3.2.2 Selecting and tracking feature points

We limit the area of the feature point selection to the area represented by the ROI. Among the various methods exist for feature point selection; we use the Shi and Thomasi algorithm for feature point selection. Because this algorithm is more efficient in detecting feature points, the processing time of the overall process becomes less [57]. Figure 17 shows the result of the selected feature points in the ROI of some frames in the image sequence of racing cars, which has total 1422 frames. This image sequence was obtained from [62].

Feature point tracking identifies above features reliably from frame to frame and those features are tracked by feature matching. In order to feel the movement of objects, it is necessary to measure the motion of the objects between two frames in an image sequence without any prior knowledge about the contents of those frames. Therefore, we use the optical flow technique to evaluate object motion between two image frames. More precisely, we use the sparse optical flow technique called Pyramid Lucas Kanade algorithm for feature point tracking and identify the way an object moves when it is seen or followed in a sequence of images [59][60][61][62].

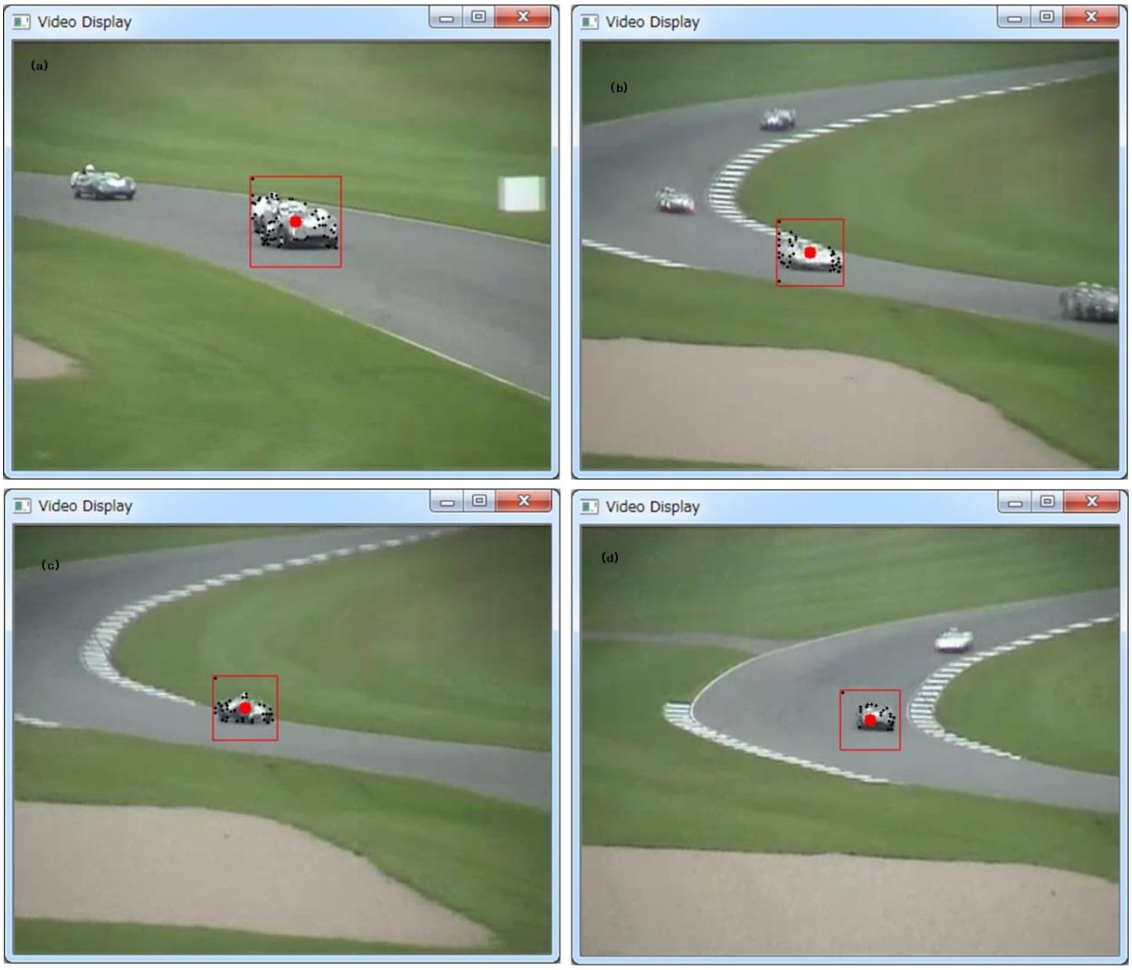

Figure 17 Feature point selection around an area of haptic interface point of the racing cars image sequence of (a) 40th frame (b) 400th frame (c) 800th frame (d) 1200th frame

Figure 18 shows the result of the optical flow information of some selected frames of the image sequence of racing cars. Optical flow represents the relative motion of objects felt by the viewer of the image sequence [59]. Hence, the direction of each arrow represents the relative direction of the object movement and the length of each arrow represents the magnitude of the object movement in two consecutive frames.

Figure 18 Flow information of the racing cars image sequence

3.2.3 Motion analysis

As shown in Figure 16, the length of a particular feature point in two subsequence frames at time *t* and *(t +Δt)* represents the flow details. We use velocity of a feature point to estimate flow details. The velocity of a feature point is calculated using the equation (9).

$$V_i(t) = \frac{P_i(t+\Delta t) - P_i(t)}{\Delta t} \qquad (9)$$

Here $p_i(t)$ and $p_i(t + \Delta t)$ represent the position of a particular feature point in two consecutive frames. Those feature points are within the ROI around the haptic interface point. If there are ***N*** feature points which have a motion, then the velocity is given by the average velocity of feature points, as shown in equation (10).

$$\overrightarrow{V_s(t)} = \frac{1}{N}\sum_{i=1}^{N}\overrightarrow{V_i(t)} \qquad (10)$$

3.2.4 Rendering of haptic motion

In this section, we discuss how motion force is rendered as a haptic feedback in relation with the selected object. In order to generate force feedback to the user through SPIDAR-G device, we use velocity-mapping approach. We use the nonlinear gain controller method proposed in section 3.1.4 for this purpose. As shown in Figure 10, the reason for selecting a nonlinear gain controller method is its ability to avoid haptic jitter by reducing force for high velocities and increasing force for low velocities. This brings down the feedback force into the sensible region of SPIDAR-G and enables a smooth and realistic sensation to user.

In the nonlinear gain controller method, we use a nonlinear function to map the velocity into force. The resulting feedback force to sense the motion of objects is shown in equation (11). In this case, the sigmoid function proved to be a good candidate for the nonlinear function ***f.*** However, as the velocity needs to be zero when changing the moving direction, we got an additional requirement such that the selected sigmoid function needs to go through the origin. Therefore, we selected the inverse tangent function, which is shown by equation (12).

$$\overrightarrow{F(t)} = f\left(\overrightarrow{V_s(t)}\right) \qquad (11)$$

$$F(t) = \frac{2\times F_{max}}{\pi}\tan^{-1}(\alpha \times V_s(t)) \qquad (12)$$

Here ***Fmax*** is the maximum force output level of the SPIDAR-G haptic device for better sensation for this application and ***α*** is chosen as 0.01.

3.3 Haptic Rendering of 6DOF Motion

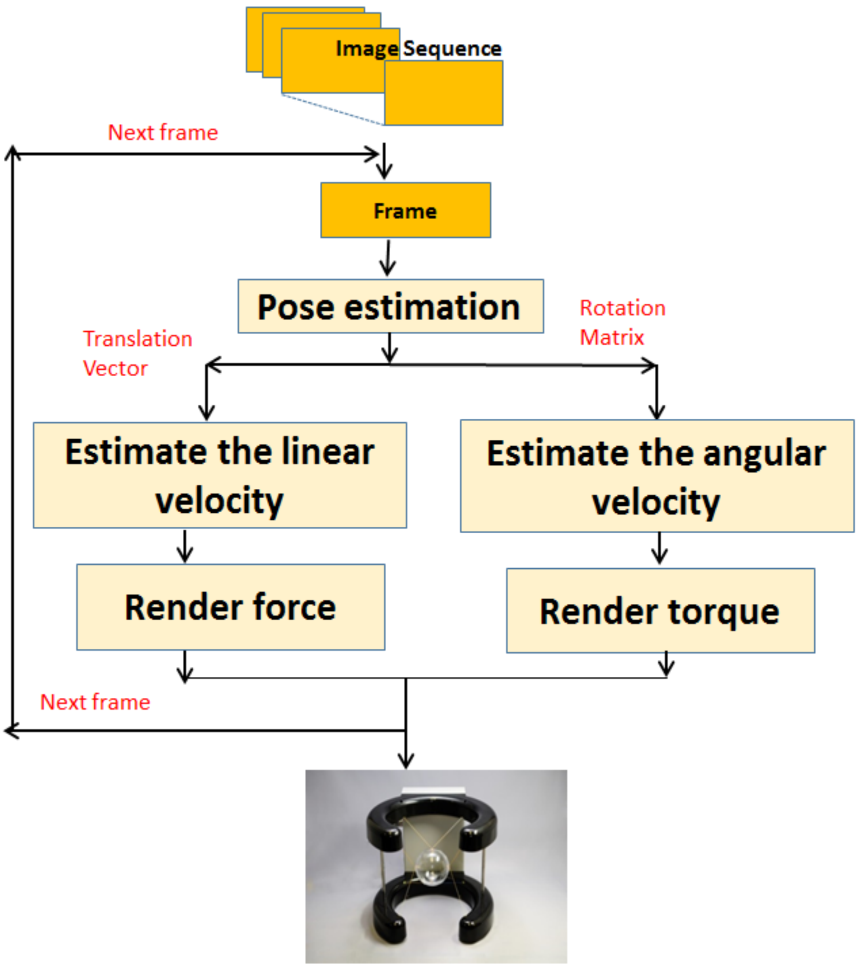

Figure 19 Proposed approach for 6DOF haptic motion rendering

The motions of the objects are not only translational but also rotational. In the real world, object motions are not only in two dimensions but also in three dimensions. So that it would be interesting and highly necessary to research on how to incorporate three dimensional translational and rotational features as 3D technologies are become increasingly popular. Since SPIDAR-G haptic interface has the capability of generate six degrees of freedom force feedback, this could be implemented through SPIDAR-G. Hence, we propose a method to feel the 3D translational and rotational motion of an object in the 2D image sequence using the SPIDAR-G haptic interface.

The proposed approach for this research is shown in Figure 19. At the first step, it estimates the 3D pose of the object in the image sequence by using an existing computer vision algorithm. As the next step, it estimates the linear and angular velocity of the object. In this research our main contribution is in the final step i.e. six degrees of freedom haptic motion rendering. For that we modified the proposed two candidate methods namely linear gain controller method and a nonlinear gain controller method with the intention of feeling the 6DOF motion. The following sections broadly describe the above parts.

3.3.1 Pose estimation

Identification of specific objects in an image and to determine each object's position and orientation relative to some coordinate system is a typical task in the field of computer vision [63]. The combination of position and orientation is referred to as the pose of an object. The specific task of determining the pose of an object in an image or an image sequence is referred to as pose estimation [64]. Different methods and algorithms are proposed for pose estimation in the field of computer vision. Those methods can be categorized into three classes: analytic or geometric methods, genetic algorithm methods or learning-based methods.

In our research to estimate the pose information from the 2D image points, we adopt the common and most popular computer vision algorithm called “POSIT”. Pose from Orthography and Scaling with Iteration (POSIT) is a fast and accurate, iterative algorithm for finding the pose of an 3D model or scene with respect to a camera given a set of 2D image and 3D object points correspondences [65].

Figure 20 shows the pinhole camera model, with its centre of projection ***O*** and the image plane at the focal length ***f.*** A 3D model with feature points M_i is positioned at camera frustum. A M_i point has known coordinates (U_i,V_i,W_i) in the model frame and unknown coordinates (X_i,Y_i,Z_i) in the camera frame. The projections of M_i are known and called m_i, having image coordinates (x_i,y_i).

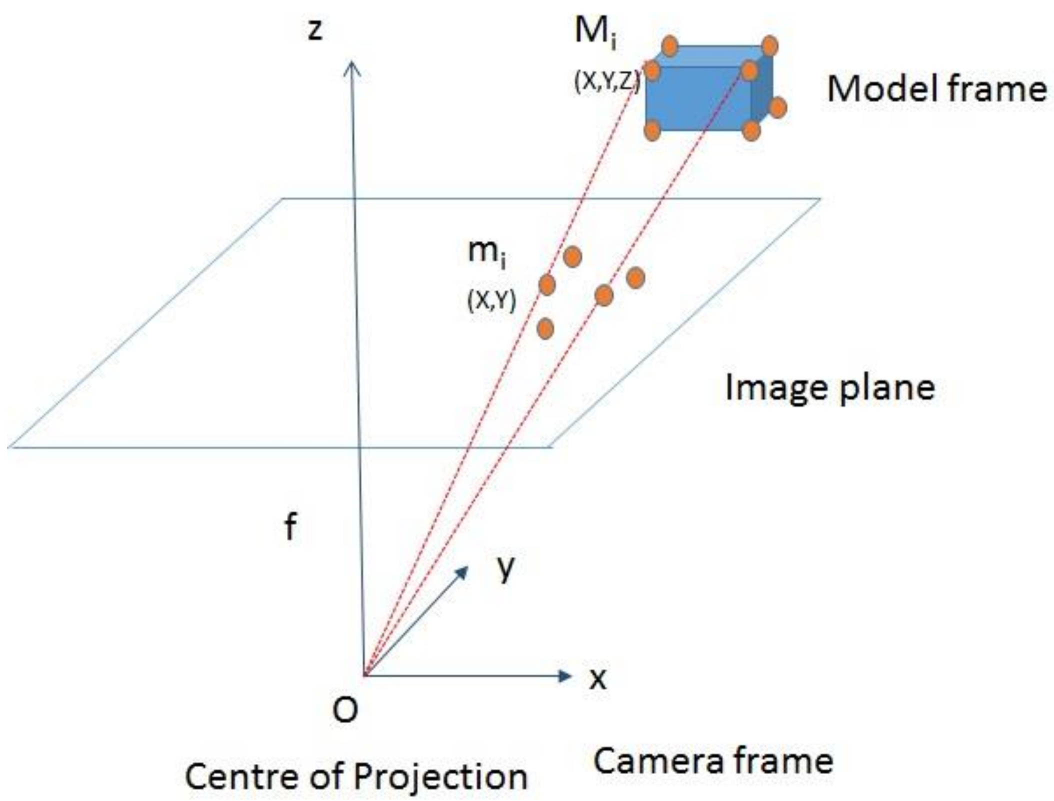

Figure 20 Perspective projections $\boldsymbol{m_i}$ for model points $\boldsymbol{M_i}$

The pose matrix ***P*** gives the rigid transformation between the model and the camera frame.

$$P = \begin{bmatrix} R \\ T \end{bmatrix} \tag{13}$$

Where ***R*** is the rotation matrix representing the orientation of the camera frame with respect to the model frame and ***T*** is the translation vector from the camera centre to the model frame centre.

Hence,

$$R = \begin{pmatrix} r_{00} & r_{01} & r_{02} \\ r_{10} & r_{11} & r_{12} \\ r_{20} & r_{21} & r_{22} \end{pmatrix} \tag{14}$$

$$T = (T_x, T_y, T_z) \tag{15}$$

Here, the rotation matrix ***R*** is a composite matrix, which represents the rotation around the ***x, y*** and ***z*** axis in sequence with respective rotation angles $\boldsymbol{\theta_x}, \boldsymbol{\theta_y}, \boldsymbol{\theta_z}$.

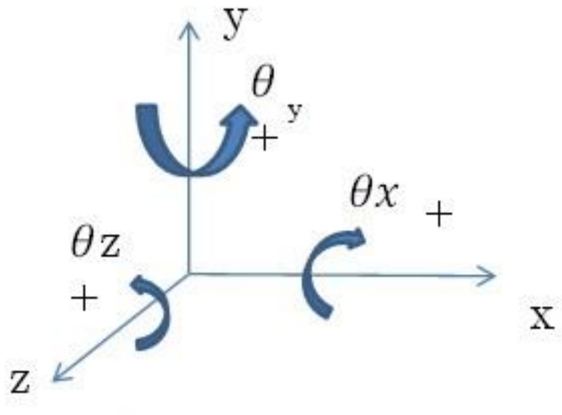

Figure 21 Rotation angles in x, y and z directions

Thus the result of the total rotation matrix R is given by the product of the three matrices, $\boldsymbol{R_x}(\boldsymbol{\theta_x}), \boldsymbol{R_y}(\boldsymbol{\theta_y})\ and\ \boldsymbol{R_z}(\boldsymbol{\theta_z})$, where,

$$R_x(\theta_x) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & \sin\theta_x \\ 0 & -\sin\theta_x & \cos\theta_x \end{pmatrix} \tag{16}$$

$$R_y(\theta_y) = \begin{pmatrix} \cos\theta_y & 0 & -\sin\theta_y \\ 0 & 1 & 0 \\ \sin\theta_y & 0 & \cos\theta_y \end{pmatrix} \tag{17}$$

$$R_z(\theta_z) = \begin{pmatrix} \cos\theta_z & \sin\theta_z & 0 \\ -\sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{18}$$

Thus,

$$R = R_z(\theta_z)\, R_y(\theta_y)\ R_x(\theta_x) \tag{19}$$

$$R = \begin{pmatrix} \cos\theta_z & \sin\theta_z & 0 \\ -\sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_y & 0 & -\sin\theta_y \\ 0 & 1 & 0 \\ \sin\theta_y & 0 & \cos\theta_y \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & \sin\theta_x \\ 0 & -\sin\theta_x & \cos\theta_x \end{pmatrix} \tag{20}$$

Hence we can estimate the rotation angles $\theta_x, \theta_y, \theta_z$ in the **x**, **y** and ***z*** axis as follows. If we assume,

$$a = \cos\theta_x\,,\ b = \sin\theta_x\ \ , c = \cos\theta_y\,, d = \sin\theta_y\,, e = \cos\theta_z\,, f = \sin\theta_z$$

$$R = \begin{pmatrix} \mathrm{e} & f & 0 \\ -f & \mathrm{e} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} \mathrm{c} & 0 & -d \\ 0 & 1 & 0 \\ d & 0 & c \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & \mathrm{a} & b \\ 0 & -b & \mathrm{a} \end{pmatrix} \tag{21}$$

$$R = \begin{pmatrix} \mathrm{ce} & af + bde & \mathrm{bf} - \mathrm{ade} \\ -cf & \mathrm{ae} + \mathrm{bdf} & be - adf \\ d & -\mathrm{bc} & ac \end{pmatrix} \tag{22}$$

From equation (14) and equation (22),

$$\frac{b}{a} = -\frac{\mathrm{r}_{21}}{\mathrm{r}_{22}} \tag{23}$$

$$\tan\theta_x = -\frac{\mathrm{r}_{21}}{\mathrm{r}_{22}} \tag{24}$$

$$\theta_x = \tan^{-1}\left(-\frac{\mathrm{r}_{21}}{\mathrm{r}_{22}}\right) \tag{25}$$

$$\frac{\mathrm{d}}{\mathrm{c}} = \frac{\mathrm{r}_{20}}{\mathrm{r}_{22}}\cos\theta_x \tag{26}$$

$$\tan\theta_y = \frac{\mathrm{r}_{20}}{\mathrm{r}_{22}}\cos\theta_x \tag{27}$$

$$\theta_y = \tan^{-1}\left(\frac{\mathrm{r}_{20}}{\mathrm{r}_{22}}\cos\theta_x\right) \tag{28}$$

$$\frac{f}{e} = -\frac{\mathrm{r}_{10}}{\mathrm{r}_{00}} \tag{29}$$

$$\tan\theta_z = -\frac{\mathrm{r}_{10}}{\mathrm{r}_{00}} \tag{30}$$

$$\theta_z = \tan^{-1}\left(-\frac{\mathrm{r}_{10}}{\mathrm{r}_{00}}\right) \tag{31}$$

Hence the values of the rotation angles $\theta_x, \theta_y, \theta_z$ in the **x**, **y** and **z** axis can be estimated from the equation (25), equation (28) and equation (31).

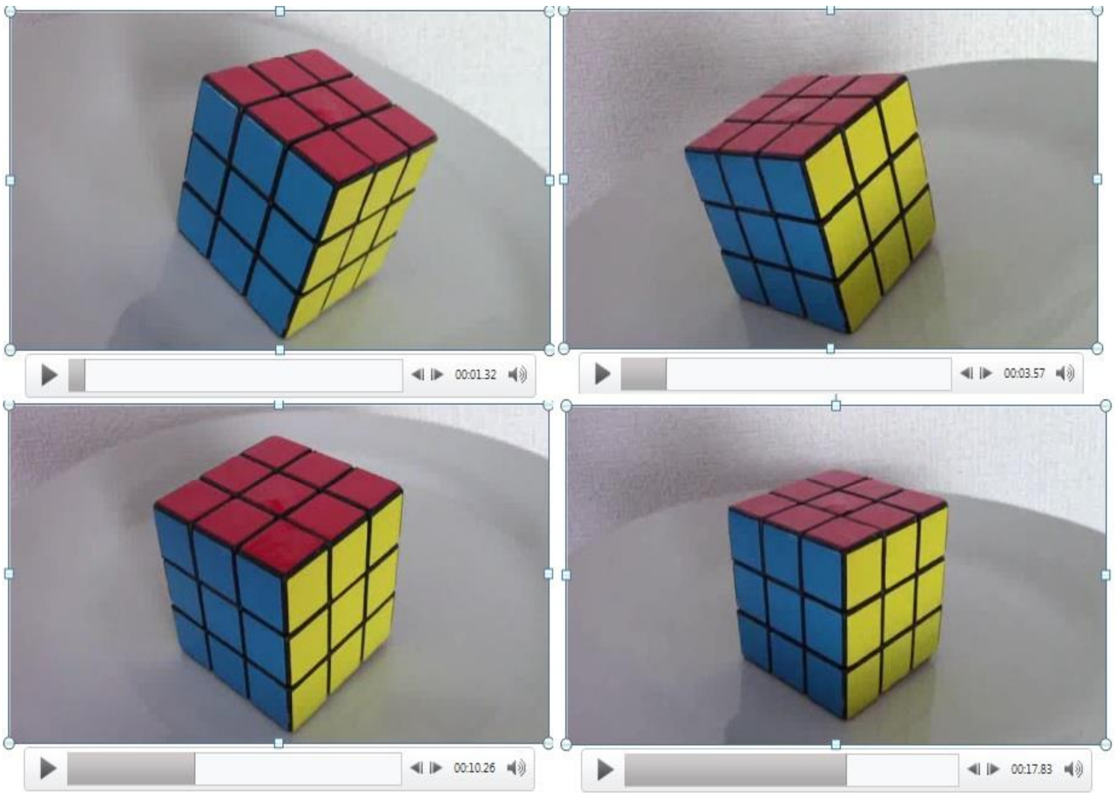

Figure 22 Image sequence of a rotating cube

To explain the result of this step, we used an image sequence of a rotating cube shown in Figure 22. The Figure 23 shows the estimated pose angles for θ_x, θ_y and θ_z during the video run. Figure 24 shows the results of the translation of the object with respect to the camera frame. Those results are compiles with the motion of the image sequence. According to Figure 23 and 24, we can give the information regarding the object movement in the image sequence. Since there is no big difference of pixels in the translation data in the x, y and z axis, we can conclude that mainly the object has a rotation than the translation. Object rotation is high with respect to z axis. Object is rotating around x axis with little angles. There is no big difference in the rotation angles in y direction. It means there is no big rotation of the object in the y direction.

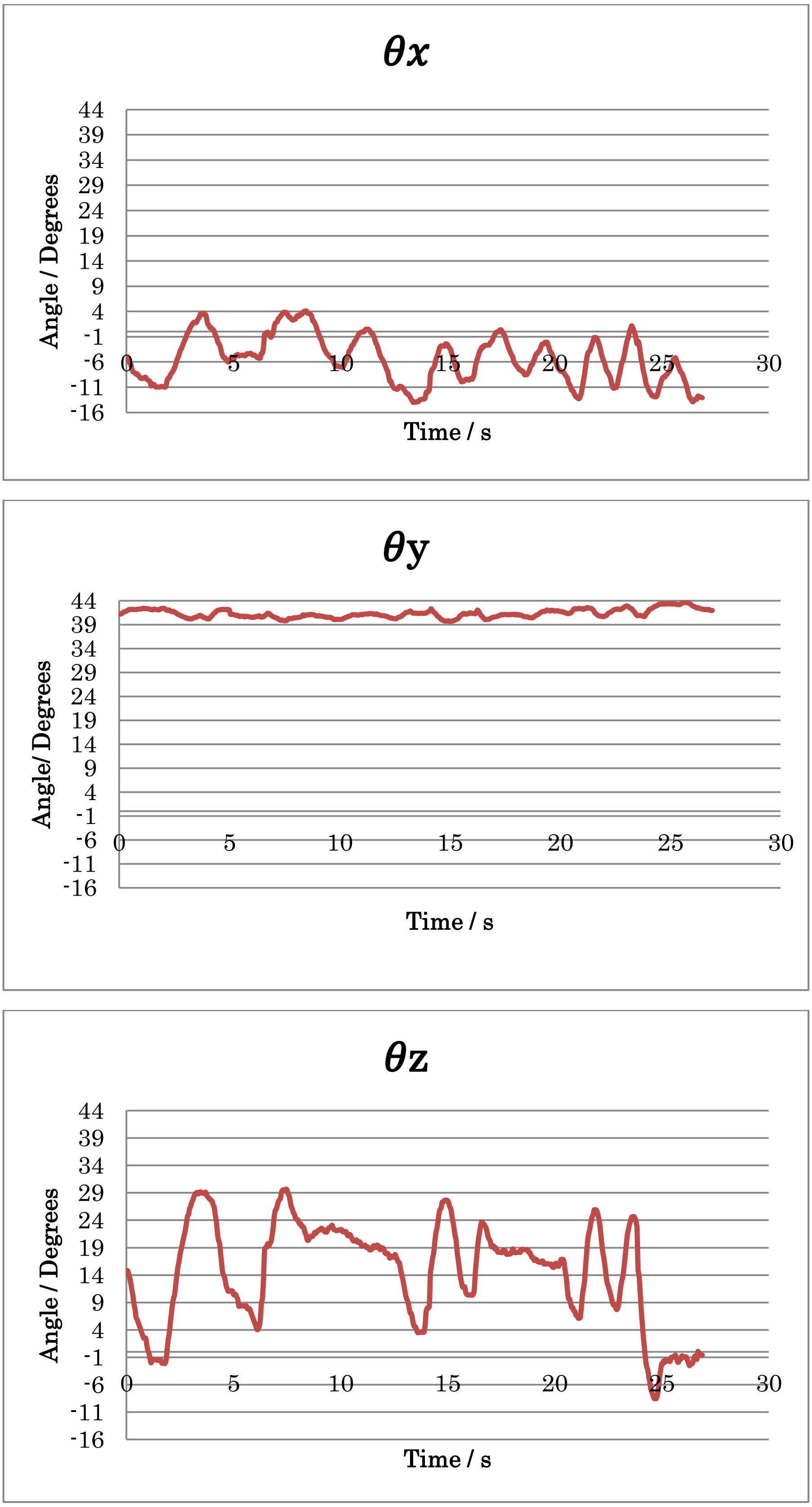

Figure 23 Estimated pose angles for θ_x, θ_y and θ_z (top to bottom)

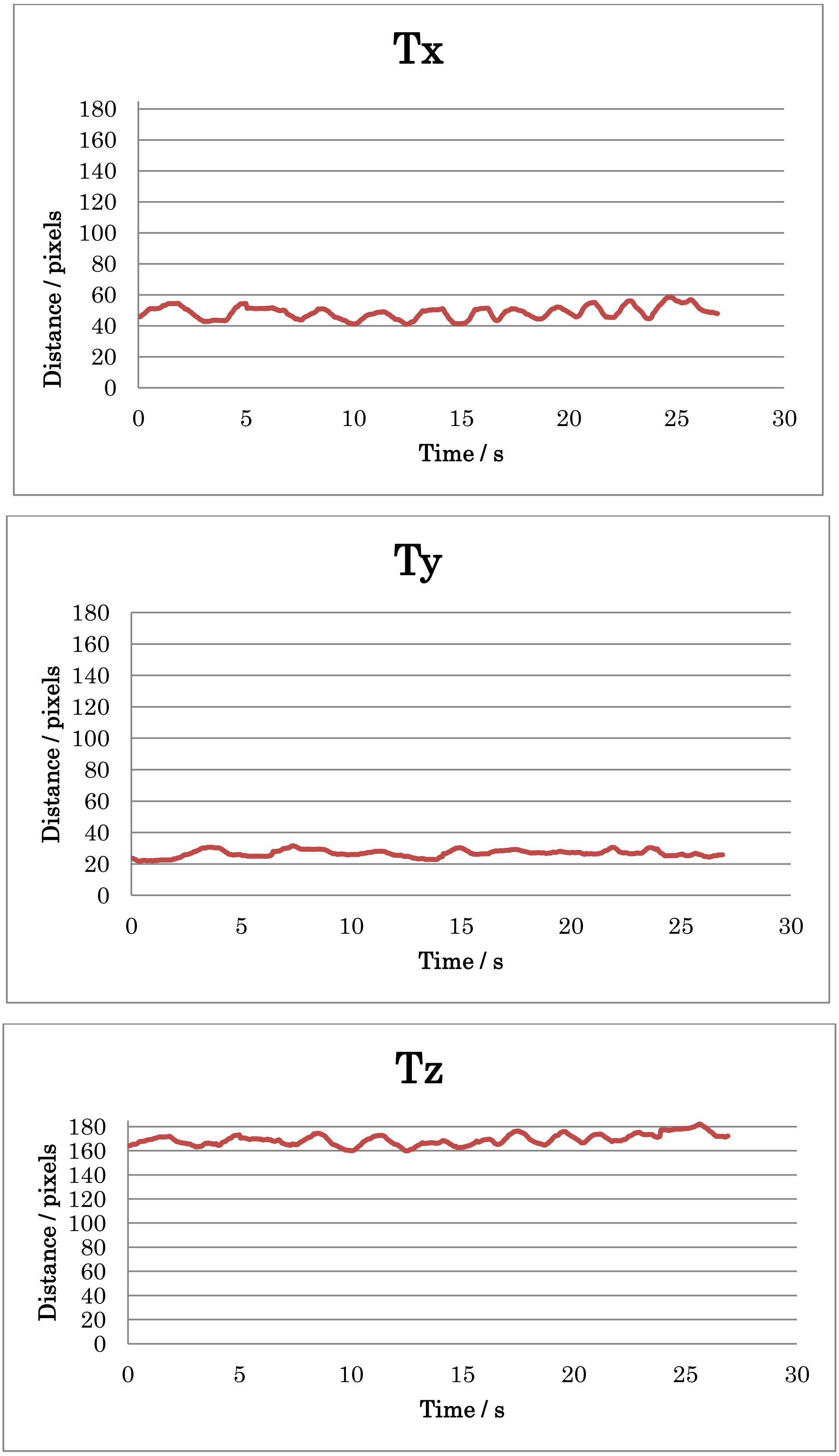

Figure 24 Estimated translation values in x, y and z directions (top to bottom)

3.3.2 Estimation of the linear velocity and the angular velocity

This section explains how we calculate the linear velocity and the angular velocity of an object in the image frame.

Translation of the object in two subsequent frames at time ***t*** and ***(t+***Δt***)*** can be represented as $T_{(x,y,z)}(t)$and $T_{(x,y,z)}(t+\Delta t)$. Hence, the linear velocity $(V(t))$ of the object in the image sequence at time ***(t+***Δt***)***, is calculated using the equation (32).

$$\overrightarrow{V(t)} = {\Delta T_{(x,y,z)}}/{\Delta t} \tag{32}$$

Where,

$$\Delta T_{(x,y,z)} = T_{(x,y,z)}(t+\Delta t) - T_{(x,y,z)}(t) \tag{33}$$

Orientation of the object in two subsequent frames at time ***t*** and ***(t+***Δt***)*** can be represented as $\theta_{(x,y,z)}(t)$and $\theta_{(x,y,z)}(t+\Delta t)$. Hence, the angular velocity $(\omega(t))$ of the object in the image sequence at time ***(t+***Δt***)***, is calculated using the equation (34).

$$\overrightarrow{\omega(t)} = {\Delta \theta_{(x,y,z)}}/{\Delta t} \tag{34}$$

Where,

$$\Delta \theta_{(x,y,z)} = \theta_{(x,y,z)}(t+\Delta t) - \theta_{(x,y,z)}(t) \tag{35}$$

3.3.3 Haptic rendering of the force and torque

Haptic rendering means rendering of forces related to the moving objects in the scene. In this section we explain how we calculated forces and torques in 3D space based on the above linear velocity and the angular velocity in the image sequence. We used SPIDAR-G haptic device, which generates six degrees of freedom force feedback sensation to users by controlling the tension of each string in the device.

However, the high velocities produced by high force and low velocities produced by low force lead to an unrealistic sensation. To overcome this problem and to get a realistic force feedback sensation to the user we need to reduce force for high velocities and increase the force for low velocities. For this purpose, we proposed and evaluated two alternative methods: linear gain controller method and nonlinear gain controller method.

Linear gain controller method:

Automatic gain controller is a feature found on many electric circuits that automatically controls the gain of a signal. We used this concept to control the force of the haptic device.

Using the linear gain controller method, the feedback force related to the linear velocity and the angular velocity is calculated from equation (36) and equation (37). This enables user to get the feeling of the 3D movement of the object.

$$\overrightarrow{F(t)} = k_1 * \overrightarrow{V(t)} \qquad (36)$$

$$\overrightarrow{\tau(t)} = k_2 * \overrightarrow{\omega(t)} \qquad (37)$$

Here $\boldsymbol{k_1}$ and $\boldsymbol{k_2}$ are gain controllers.

Calculation of $\boldsymbol{k_1}$ and $\boldsymbol{k_2}$ is done as in equation (38) and equation (39) to control the feedback force and torque within a sensible region for all velocity levels. In other words, the purpose of the gain controller $\boldsymbol{k_1}$ and $\boldsymbol{k_2}$ is to increase the feedback force and torque for weak changes in velocity and decrease the feedback force and torque for strong changes in velocity.

$$k_1 = \frac{F_{max}}{V_{max}(T)} \qquad (38)$$

$$k_2 = \frac{\tau_{max}}{\omega_{max}(T)} \qquad (39)$$

Here $\boldsymbol{F_{max}}$ and τ_{max} are the maximum force and torque output level of the SPIDAR-G for better sensation for this application. $\boldsymbol{V_{max}(T)}$ is the maximum linear velocity of the dynamic image sequence at a time T and the $\omega_{max}(T)$ is the maximum angular velocity of the dynamic image sequence at a time ***T***, which can be expressed as in equation (40) and equation (41).

$$V_{max}(T) = \{V_{max}(t) \quad 0 \leq t \ \leq T \qquad (40)$$

$$\omega_{max}(T) = \{\omega_{max}(t) \quad 0 \leq t \ \leq T \qquad (41)$$

Nonlinear gain controller method:

Similar to the previous method, the purpose of using a nonlinear gain controller method is to maintain the feedback force in the sensible region by decreasing the feedback force for high velocities and increasing the feedback force for low velocities.

In the nonlinear gain controller method, we use a nonlinear function to map the velocity into force. The resulting feedback force to sense the motion of objects is shown in equation (42) and equation (43).

$$\overrightarrow{F(t)} = f\left(\overrightarrow{V(t)}\right) \qquad (42)$$

$$\overrightarrow{\tau(t)} = f\left(\overrightarrow{\omega(t)}\right) \qquad (43)$$

In this case, the sigmoid function proved to be a good candidate for the nonlinear function ***f***. However, as the velocity needs to be zero when changing the moving direction, we got an additional requirement such that the selected sigmoid function needs to go through the origin. Therefore, we selected the inverse tangent function to map the velocity into force, which is shown by equation (44) and equation (45).

$$F(t) = \frac{2\times F_{max}}{\pi} \tan^{-1}(\alpha \times V(t)) \qquad (44)$$

$$\tau(t) = \frac{2\times \tau_{max}}{\pi} \tan^{-1}(\beta \times \omega(t)) \qquad (45)$$

Here $\boldsymbol{F_{max}}$ and τ_{max} are the maximum force and torque output level of the SPIDAR-G device for better sensation and the parameters α and β are chosen as in the discussion of section 3.1.4. Hence α and β is chosen as 0.01 to get a smooth feeling of the force and torque change.

We have implemented and experimentally evaluated the three proposed methods for 2DOF, 3DOF and 6DOF haptic motion rendering. Chapter 4 presents the results of experimental evaluation.

Chapter 4

Experimental Evaluation

This chapter presents the results of the experimental evaluation involving the feedbacks of real users regarding their viewing experience of image sequences with the involvement of active and passive user scenarios and their experience with feeling 6DOF motion.

4.1 Evaluation of the 2DOF and 3DOF Motion Rendering Systems

In order to evaluate whether our research has a benefit of adding 3D interactivity to an image sequence and allow user to be active, such as allowing them to interact with the system to feel the motion of a desired object in the image sequence , we performed a qualitative experiment by getting the involvement of real users. We evaluate three systems i.e. without haptics, with haptics passive user involvement (i.e. 2DOF motion rendering) and with haptics active user involvement (i.e. 3DOF motion rendering).

A total of seven users participated in the experiment. All the participants were laboratory members and experienced users of the SPIDAR-G system. Moreover, all users were mostly young at the age between 20 and 26. Therefore, we assumed that this sample is capable of evaluating an enhanced feature of digital multimedia content, as most users in that age group are early adopters of technology and also enthusiasts of digital multimedia content.

We use four different image sequences, a video of a moving leaves, a video of a fish tank, a video of bouncing balls and a video of a car race which are shown in the Figure 25. All the four image sequences include multiple objects, which have different motions. Table 1 summarizes each video in two aspects, object richness in the environment and the variation of the motion direction. We selected those videos to match with our objective of enhancing their viewing experience by letting them to point and feel the movement of the object or objects in the image sequence. For example, we expected the haptic feedback of object movement in the video of bouncing balls to increase the excitement of the viewer by letting them to feel the motion of a specific ball instead of getting the feeling of the collective motion of all balls. Each video has duration of one minute. Moreover, the camera is not moving in first three videos except fourth.

Figure 25 Evaluated image sequences (a) moving leaves (b) fish tank (c) bouncing balls (d) car race

In order to compare the usefulness of adding haptic technology into image sequence and to compare the motion rendering system with and without involvement of the user, we performed a qualitative experiment using the above image sequences.

Variation of the motion Direction	**Object richness in the environment**	
	Small	Large
Small		
Large		

Table 1 Categorization of the image sequences

At first, we let them to watch the original video. Then we let them to feel the motion of the image sequences just by gripping the SPIDAR-G haptic device (i.e. passive user scenario). Finally, we let them to interact with the same image sequences using our haptization system three dimensionally and feel the movement of the desired object in it (i.e. active user scenario). We used a questioner to evaluate the experience of each participant in this experiment. All participants experienced each video at least twice and they took at least 15 minutes for the evaluation. We asked them to rate the system based on their viewing experience with each video in three situations i.e. without haptic feedback, with haptic feedback involving passive user and with haptic feedback involving active user. In order to record the responses of users, we asked them to rate the system in each category based on their feeling of the motion of objects in the image sequence on a scale of 1 to 5, which represents 'Very Bad', 'Bad', 'Average', 'Good' and 'Very Good'. Figure 26 shows a demonstration setup of the system, which shows a user experiencing an image sequence of bouncing balls using the SPIDAR-G haptic interface.

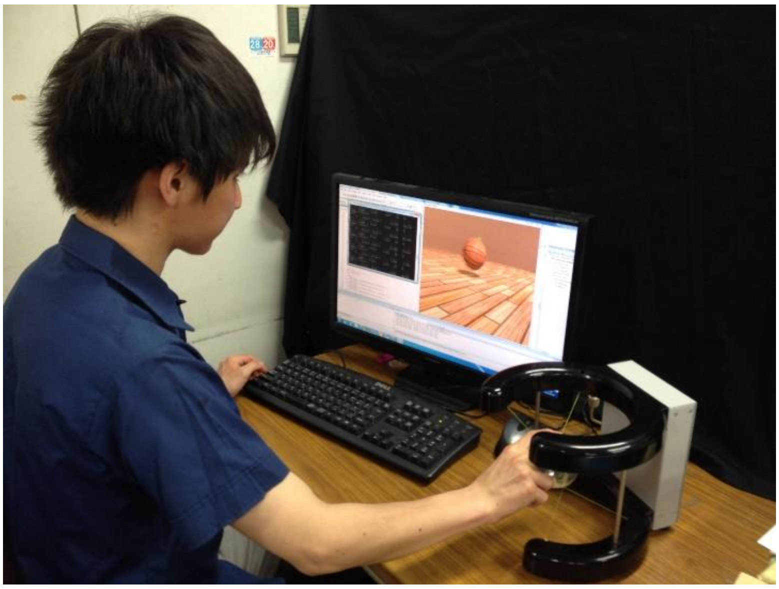

Figure 26 Demonstration of the system

4.1.1 Results of the experiment

A compilation of users' feedbacks regarding the feeling of the objects movement in three situations for each image sequence is shown in Table 2, Table 3, Table 4 and Table 5.

		With Haptic	
Participant	**Without Haptic**	**Passive user**	**Active user**
1	2	4	5
2	5	2	3
3	2	3	4
4	3	4	4
5	2	3	5
6	1	3	5
7	2	3	4

Mean	2.43	3.14	4.29
Variance	1.62	0.48	0.57

Table 2 Users' feedback for the image sequence of moving leaves

		With Haptic	
Participant	Without Haptic	Passive user	Active user
1	1	3	2
2	5	1	1
3	2	2	2
4	4	2	2
5	1	1	1
6	1	3	3
7	2	2	2
Mean	2.29	2.0	1.86
Variance	2.57	0.67	0.48

Table 3 Users' feedback for the image sequence of fish tank

		With Haptic	
Participant	Without Haptic	Passive user	Active user
1	2	5	4
2	4	3	4
3	3	2	4
4	3	2	3
5	2	4	3
6	1	3	5
7	2	4	4
Mean	2.43	3.29	3.86
Variance	0.95	1.24	0.48

Table 4 Users' feedback for the image sequence of bouncing ball

Participant	Without Haptic	With Haptic Passive user	Active user
1	1	4	4
2	4	1	3
3	3	4	5
4	3	2	3
5	1	3	3
6	1	2	3
7	2	3	3
Mean	2.14	2.71	3.43
Variance	1.48	1.24	0.62

Table 5 Users' feedback for the image sequence of car race

4.1.2 Discussion of the experiment

Table 6 and Table 7 compile the overall results of the user's feedback using the mean and variance values for each image sequence with and without haptic feedback.

Image Sequence	Without haptic	With haptic	
		Passive user	Active user
Moving leaves	2.43	3.14	4.29
Fish tank	2.29	2.0	1.86
Bouncing balls	2.43	3.29	3.86
Car race	2.14	2.71	3.43
Mean	2.32	2.78	3.36
Variance	0.02	0.33	1.12

Table 6 Result of the mean values of users' feedback

Image Sequence	Without haptic	With haptic	
		Passive user	Active user
Moving leaves	1.62	0.48	0.57
Fish tank	2.57	0.67	0.48
Bouncing balls	0.95	1.24	0.48
Car race	1.48	1.24	0.62

Table 7 Result of the variance values of users' feedback

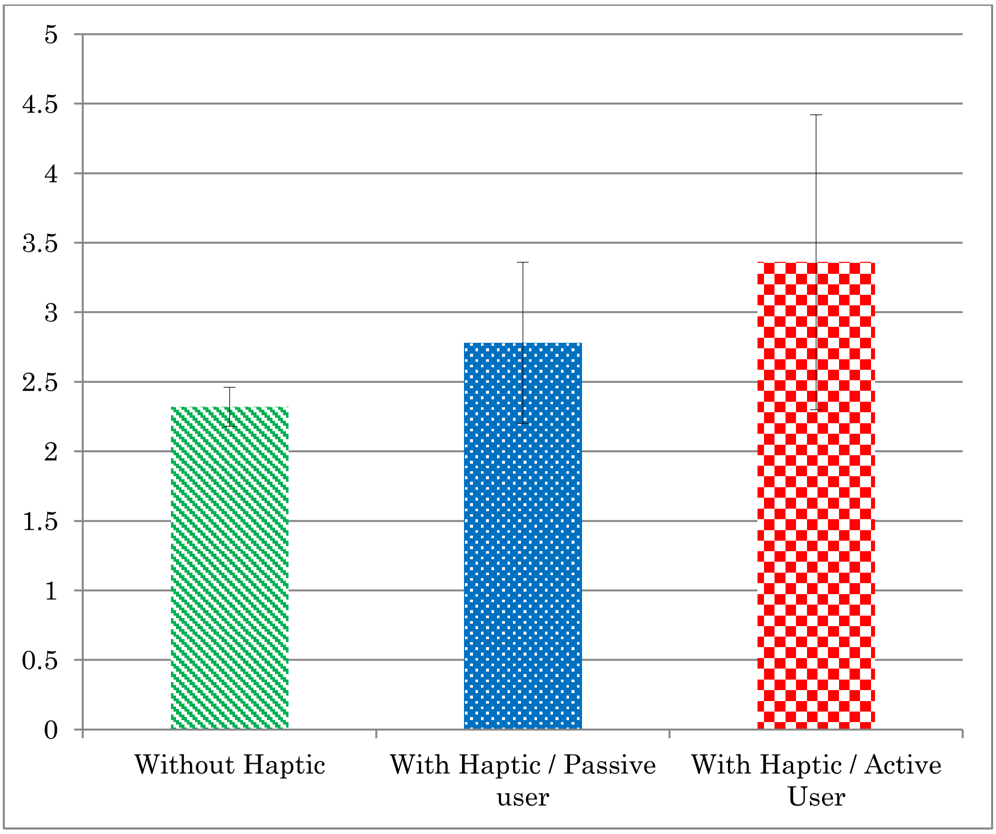

Figure 27.Results of the users' mean response for each category

Figure 27 shows the overall results of the users' response for each category of the system graphically. According to Figure 27, it is clear that the results of with haptic scenarios are higher than seeing the video without haptics. Therefore we can conclude that the feeling of object movements through haptic interface significantly enhances the viewing experience of user. Moreover, the scenario with haptic feedback that involves active users outperforms the other two cases; i.e. without haptic feedback and with haptic feedback but passive users. Hence we can conclude that the users experienced an increased appreciation of the image sequence by adding 3D interaction by allowing user to active with the use of our proposed object haptization method on a 2D image sequence.

Moreover we compare the results of the users' feedback in three situations with respect to each image sequence. Figure 28, Figure 29, Figure 30 and Figure 31 show the mean values of the users' response for each image sequences graphically.

According to Figure 28, Figure 29 and Figure 30, it is clear that the scenarios with haptic feedback are higher than seeing the video without haptics. Moreover, it is clear that the scenarios with haptics that involve active users outperforms the other two cases; i.e. without haptic feedback and with haptic feedback but passive user. Furthermore, we can notice that the performance of the proposed approach for with haptic, active user scenario decreased based on the speed of the objects in the image sequence. That is, if the objects have fast motion like the case of image sequence of the car race, the users' mean response value decreases compared to the objects that have slow motion like in the case of the image sequence of moving leaves.

According to the Figure 31 reveals that just watching the video is better than using haptics. This occurs because of the large number of small fish in the tank and the difficulty for the users to point and feel the motion of a particular fish due to this object richness of the environment.

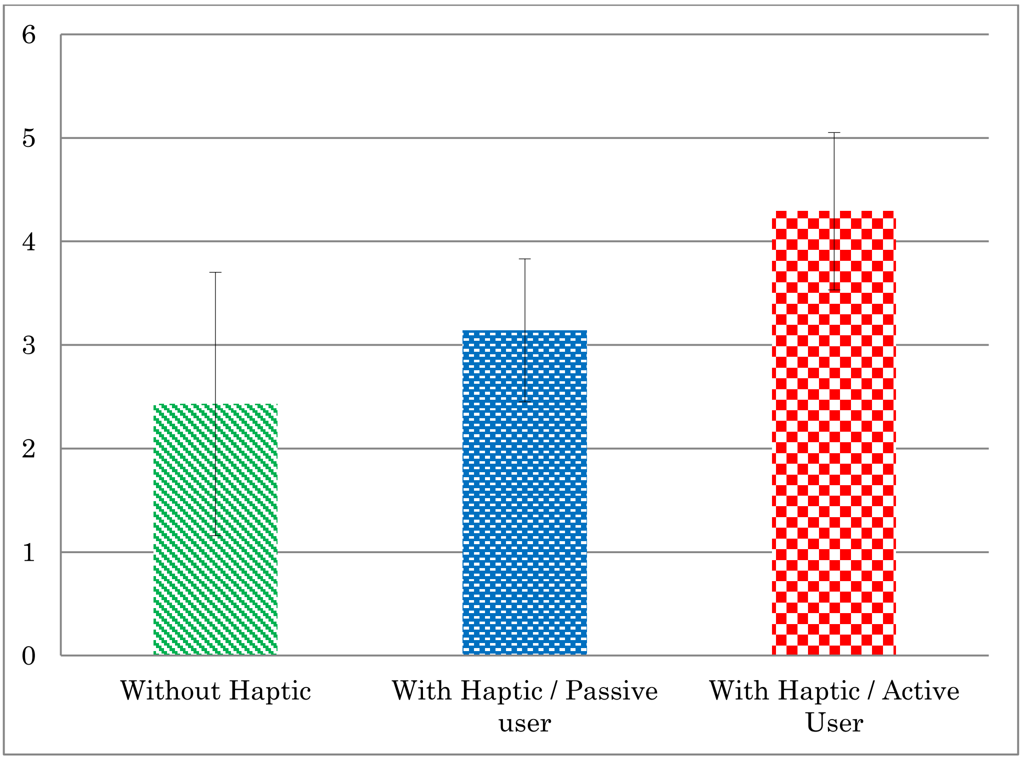

Figure 28.Results of the users' mean response for the video of moving leaves

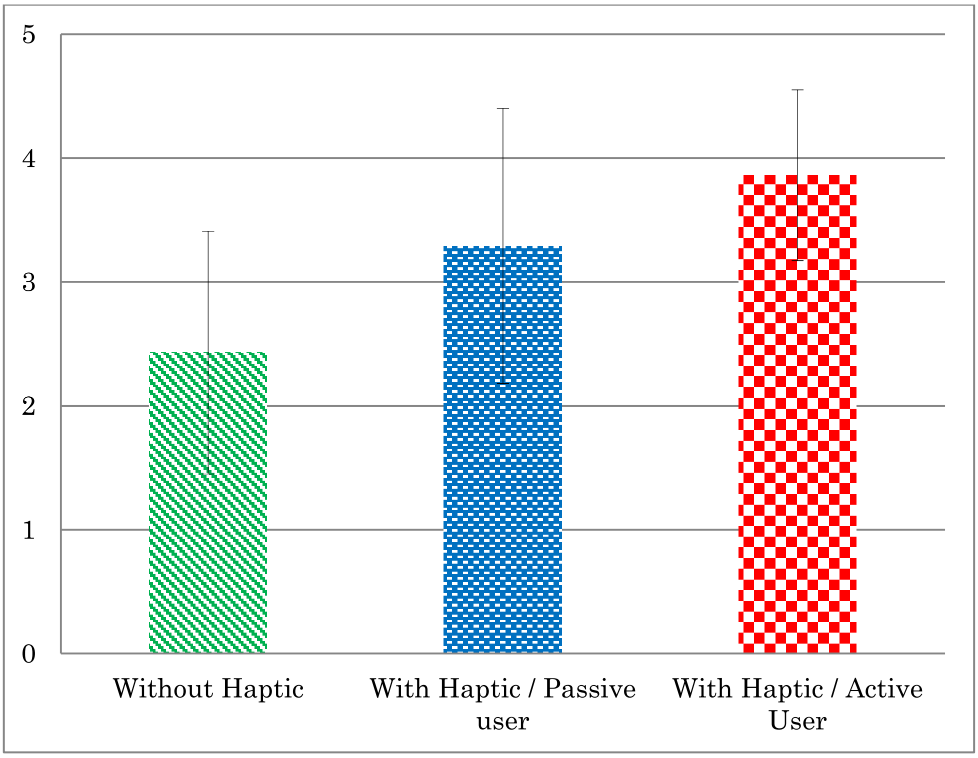

Figure 29.Results of the users' mean response for the video of bouncing balls

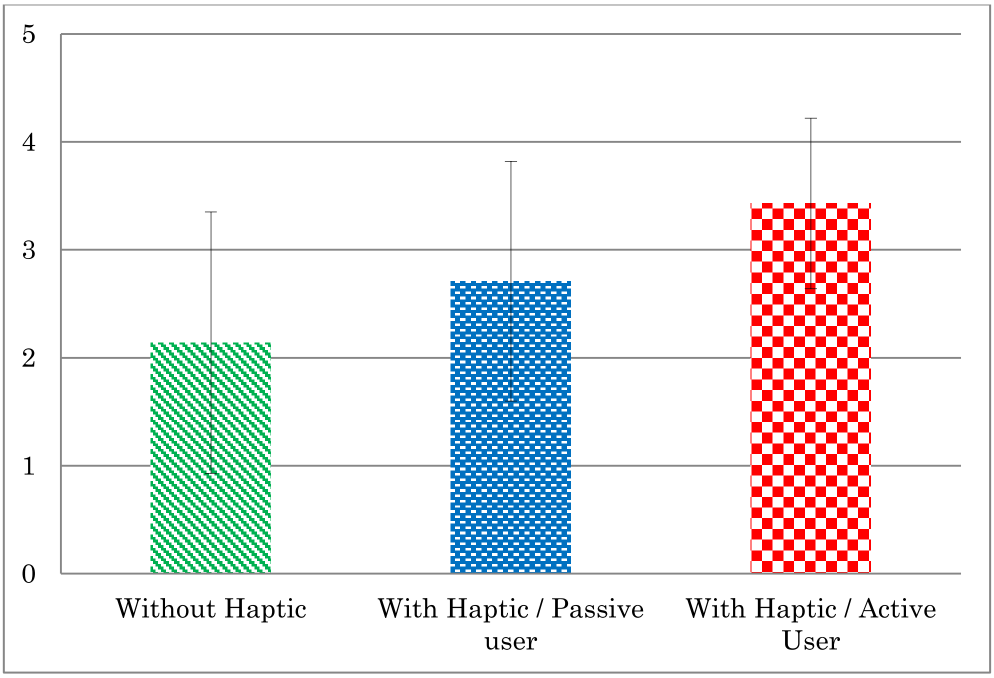

Figure 30.Results of the users' mean response for the video of car race

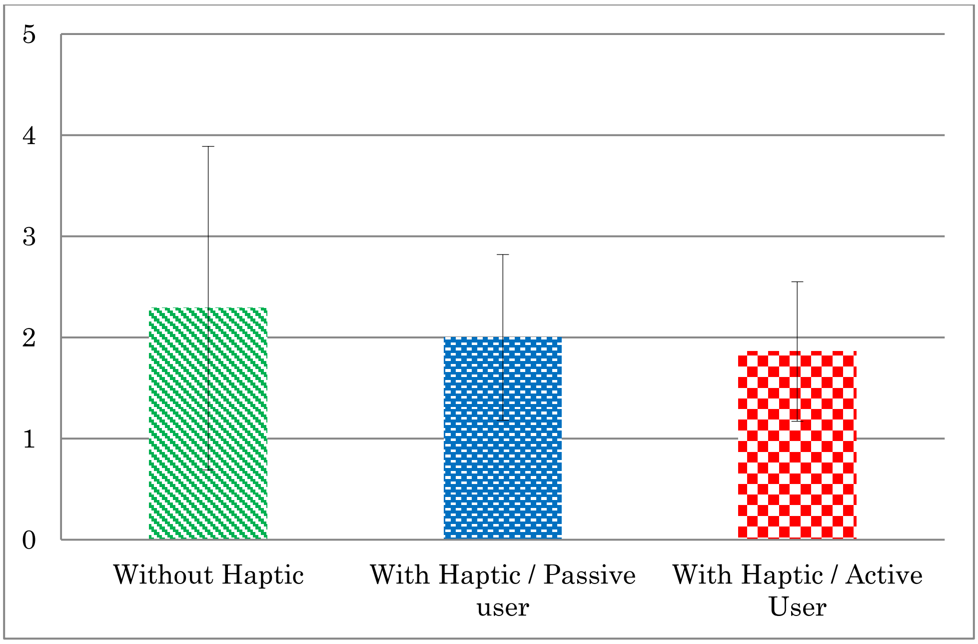

Figure 31.Results of the users' mean response for the video of fish tank

In order to verify our results statistically, we compare the difference of means between the two groups without haptic and with haptic/ passive user, without haptic and with haptic / active user, with haptic/ passive user and with haptic/ active user situations. At first we perform F- test to examine the differences between variances of the two groups. Table 8 shows the results of the p-values obtained from the F-test. Result shows that the variances are equal between two groups for each image sequences in the 0.05 significance level except the image sequence of fish tank in without haptic and with haptic, active user scenario.

	Without haptic and With haptic, passive user	**Without haptic and with haptic, active user**	**With haptic, passive user and with haptic, active user**
Moving leaves	0.081011	0.11531	0.415241
Bouncing ball	0.379097	0.209877	0.134951
Car race	0.418184	0.157119	0.209877
Fish tank	0.062537	0.029765	0.346619

Table 8 p-values obtained from F-test

	Without haptic and With haptic, passive user	**Without haptic and with haptic, active user**	**With haptic, passive user and with haptic, active user**
Moving leaves	0.216171	0.006111	0.01205
Bouncing ball	0.151387	0.008186	0.27069
Car race	0.376871	0.036709	0.190739
Fish tank	0.681848	0.534203	0.729807

Table 9 p-values obtained from Student's t-test

In order to evaluate the significant difference in the means of the two groups, we perform a student's t-test. The results of the p-values obtained from the student's t-test are shown in Table 9.

Results shows that there is a significant difference in the mean of the two groups without haptic and with haptic, active user in the 0.05 significance level for the image sequences of moving leaves, bouncing balls and car race. So it is clear that the users experienced an increased appreciation of the image sequence by adding 3D interaction by allowing user to active with the use of our proposed object haptization method on a 2D image sequence. Moreover, we can conclude that there is a significant difference in the mean of the two groups with haptic, passive user and with haptic, active user when the objects have slow motion. Further we can conclude that there is no significance difference between each two groups for the image sequence of the fish tank in the 0.05 significance level. We can summarize the performance of the active user interaction obtained from this experiment as in Table 10.

Variation of the motion direction	**Object richness in the environment**	
	Small	Large
Small	○	○
Large	○	X

Table 10 Performance of the active user interaction of the experiment

Result of the experiment leads to an interesting finding such that the proposed active user interaction is not suitable for the image sequences which have large variation of motion and object rich environments. Therefore, we have to define another kind of interaction, such that without selecting a particular object in every frame, it allows users to select the object at first and then track the motion of that object. Or else, it has allowed users to set the haptic point and get the feeling around that without selecting a particular object. This idea is shown graphically in Figure 32.

Figure 32 Suggestions to overcome

4.2 Evaluation of the 6DOF Motion Rendering System

Experiments discuss so far considers only the translational force. However 6DOF means that it enables to consider both translational and rotational forces. Therefore, we evaluate the proposed approach for 6DOF and test whether it enables the user to feel the motion of translation and rotation. We evaluate the performance with respect to the two proposed approaches: linear gain controller and nonlinear gain controller.

We performed a qualitative experiment by getting the involvement of real users.
A total of seven users participated in the experiment. All the participants were laboratory members and experienced users of the SPIDAR-G system.

We use the image sequence of a rotating cube shown in Figure 20 which has translation and rotation motion. In that image sequence, visually user can see object rotation. At first, we let them to watch the original video. Then we let them to feel the motion of the image sequence using haptic device using the two methods i.e. linear gain controller method and the nonlinear gain controller method. At first we allow them to feel only the translational and rotational motions separately. Then we allow them to feel the translational and rotational forces together. In order to record the responses of users, we asked them to rate the two methods based on their feeling of the motion of objects in the image sequence on a scale of 1 to 4, which represents 'Very Bad', 'Bad', 'Good' and 'Very Good'.

4.2.1 Results of the experiment

The resulting responses are shown graphically in Figure 32, Figure 33 and Figure 34.

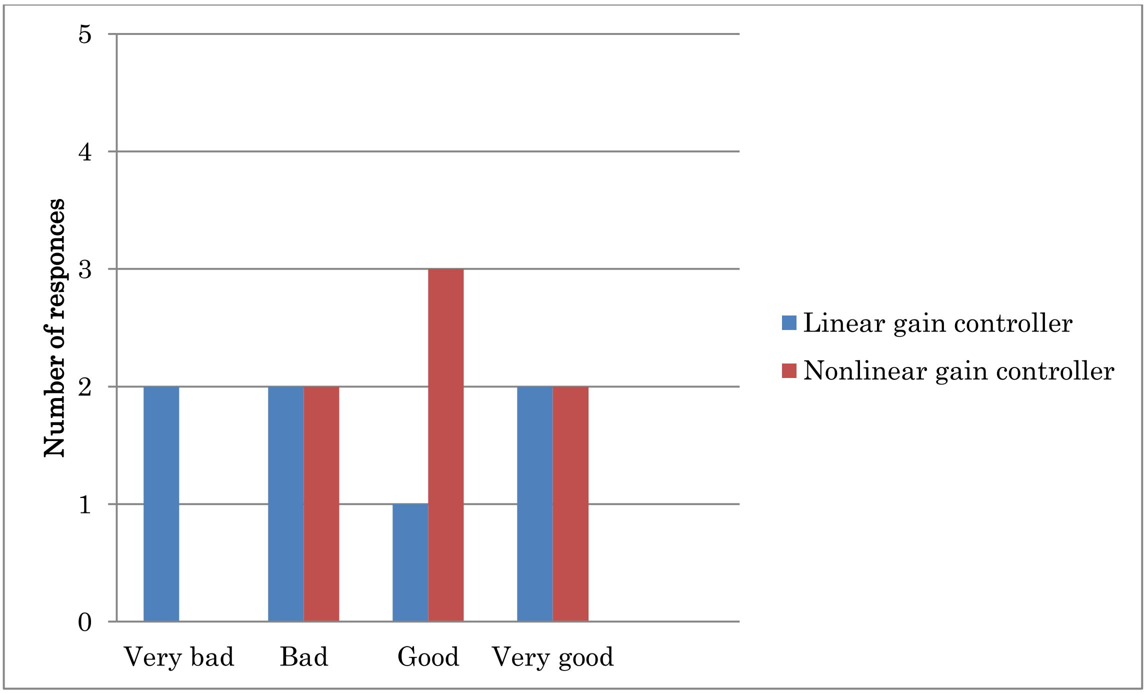

Figure 33 Distribution of users' responses when they feel translational motion

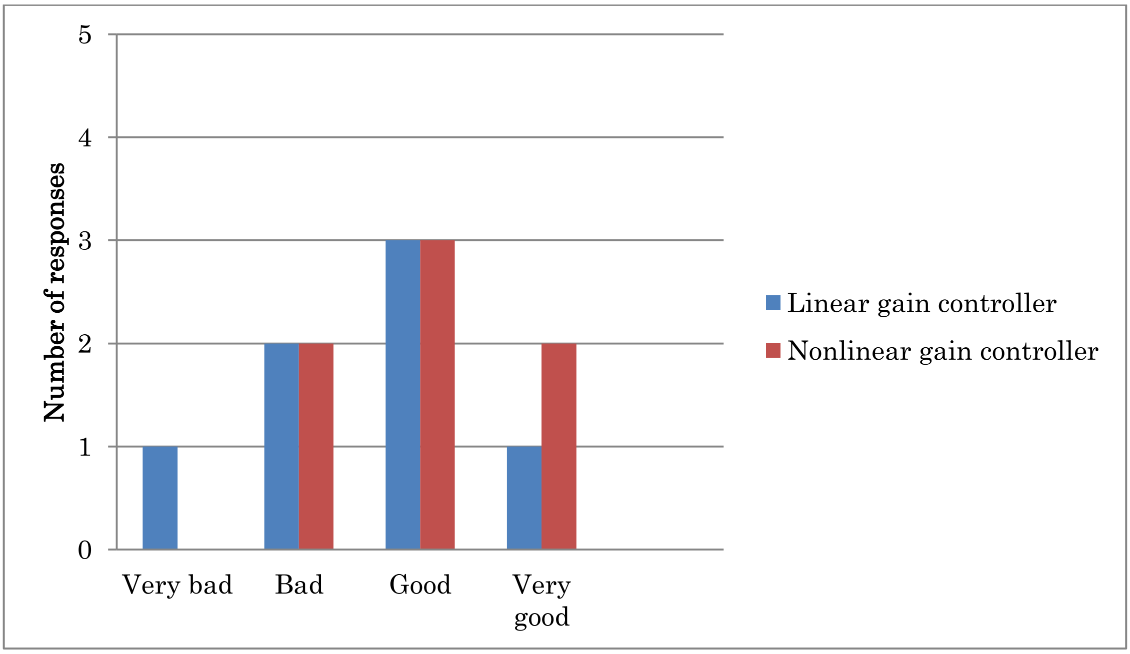

Figure 34 Distribution of users' responses when they feel rotational motion

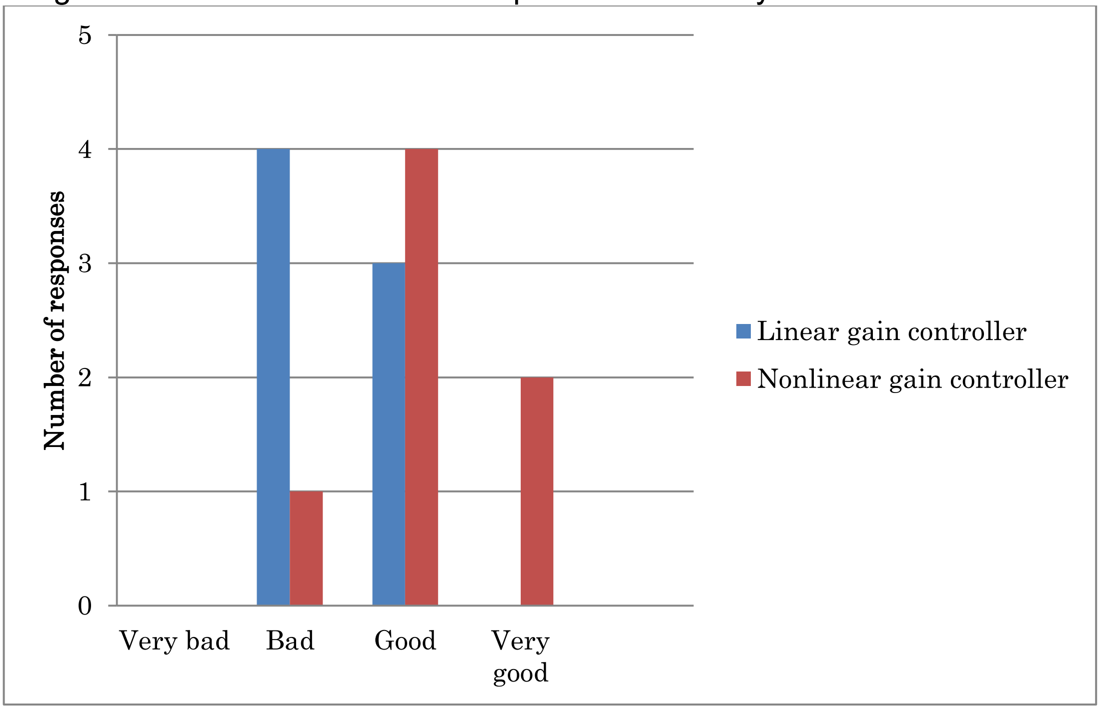

Figure 35 Distribution of users' responses when they feel translational and rotational motion together

4.2.2 Discussion of the experiment

According to Figure 33, Figure 34 and Figure 35, it is clear that the users not only get the feeling of the translational motion, they get the feeling of the rotational motion too in the image sequence. Hence we can conclude that our proposed approach is suitable for 6DOF motion rendering.

Further to that we evaluate which method i.e. linear gain controller method or nonlinear gain controller method is better for 6DOF motion rendering. However to simplify the analysis, we generally consider the responses of `Very bad` and `Bad` as negative responses such that the feeling of the movement is not satisfactory for the respective method. On the other hand, the responses of `Good` and `Very good` are considered as positive responses such that the feeling of the movement is satisfactory for the respective method. These two categories of negative and positive responses are denoted by `Negative responses` and `Positive responses` respectively.

The result of the positive responses is shown in Table 11. We tested with the involvement of seven numbers of real participants and it is clear that more than 70% of users responded that using the nonlinear gain controller method is better than using a linear gain controller method for translational as well as rotational motion rendering. .

	Translation only	Rotation only	Translation+ Rotation
Linear gain controller method	3	4	3
Nonlinear gain controller method	5	5	6

Table 11 Users' positive responses for each motion rendering method

Chapter 5

Conclusion and Future Work

5.1 Conclusion

In this research we explore different perspectives of getting the haptic perception of feeling the movement of objects in an image sequence, with the objective of enhancing the viewing experience of viewers to the near real world level.

At first we research on how to associate haptic signals with an image sequence to feel the movement of objects in it. There we focus on feeling the movement of objects along the x and y dimensions using the SPIDAR-G haptic interface. One of the best examples for such a feeling is feeling the wind in an image sequence. Here we propose two methods for haptic motion rendering: Linear gain controller method and a Nonlinear gain controller method. The experimental evaluations involving real users convince that the feeling of object movements through the haptic interface significantly enhanced the viewing experience of an image sequence.

However, some limitations exist in the work such as the users are purely passive users, not suitable for object rich environments and background noise affected to the final solution. Hence, we extend our research to active user perspective of the haptic perception of feeling the movement of objects in an image sequence by incorporating 3D haptic interactivity on 2D image sequence. There, we propose to interact with the multiple objects in an image sequence along the third dimension and feel the movement of desired object(s) in it using the SPIDAR-G haptic device. We have implemented and experimentally evaluated the proposed system for four different kinds of image sequences using real users. Feedback of the users reveal that their viewing experience with the image sequence have increased by adding such kind of interactivity to feel the motion.

Despite that, the motions of the objects are not only translational but also rotational. Therefore, we further propose a method to feel the 6DOF motion of objects. In our approach, we use and evaluate two methods for haptic motion rendering, i.e. linear gain controller method and a nonlinear gain controller method. We have experimentally evaluated and shown that the users are able to feel the 6DOF motion from 2D image sequence from our proposed method. Our evaluations further reveal that the nonlinear gain controller method outperforms the linear gain controller method.

5.2 Future Work

Result of the experiment, i.e. comparison of the motion rendering system without haptics, with haptics in passive user environment and with haptic in active user environment, shows that active user interaction is not suitable for the image sequences which have large variation of motion and object rich environments. Therefore, we have to define another kind of interaction, such that without selecting a particular object in every frame, it allows users to select the object at first and then track the motion of that object. Or else, it has allowed users to set the haptic point and get the feeling around that without selecting a particular object.

The method we use in the 6DOF system to estimate pose has some drawbacks. It must have at least four non-coplanar feature points with the assumption that we approximately know the 3D object model and its correspondence. Therefore, it's better to adopt a more advanced method to estimate the pose information from the image feature points. Furthermore, since 6 DOF system is passive, defining active user interactions for that for object rich environments is another future direction of this research.

Moreover since SPIDAR-G is a grip type haptic device, user can feel the movement of the object only to the gripping hand. Haptic sensation get into a single hand and the haptic sensation get into a full body are different. For some kind of image sequences (Such as feeling of the nature) , the feeling would be more interesting and become realistic, if the user get the feeling of the motion in the image sequence to the whole body rather than getting the feeling into a single hand. Therefore, another possible direction of future work would be to improve the system by identification of a suitable device such that it enables the user to point the object and get the whole body sensation. Moreover, there exist commercially available 6DOF motion based systems. They are being used in the flight simulation and motion ride applications. Hence, in the future, we will find the possibilities to expand our research to feel the such kind of image sequences by using commercially available 6DOF system.

In the experimental evaluation we didn't perform a quantitative experiment. We performed a qualitative experiment based on the users' feedback about the system.
In order to do a quantitative experiment, we want to collect the physiological or psychological data of the users during the experiment. For example, if we can measure how many times a video was viewing replayed by each user to feel the wind; it shows their interest to the system physiologically. Or else if we can compare the measures of brain activity using fMRI system during visual feedback and during haptic feedback, we can collect data psychological. In the future, we are looking for such kind of experimental evaluation.

Further to that, users' happiness to the system is measured by their satisfaction. Based on the users' feedback we can conclude that the users are satisfied about the system, hence they are happy. However, not all users are happy with haptic interaction. Some may prefer without haptics is better because if the force feeling is too strong then it becomes very noisy to users. Therefore improvements to the system in the future need to be done by getting measure of users' happiness also into consideration.

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Appendix A - Related Publication List

Journal papers

1. Anusha Jayasiri, Katsuhito Akahane, Makoto Sato: ` Adding 3D Interactivity to a 2D Image Sequence using the String-based Haptic Device', IIEEJ Transactions on Image Electronics and Visual Computing, Vol.2 , No.2, pp.159-167, 2014 12 .

2. Anusha Jayasiri, Katsuhito Akahane, Makoto Sato: `Object Motion Rendering with the String-based Haptic Interface SPIDAR for Enhanced Video Viewing Experience', International Journal on Advances in ICT for Emerging Regions , Vol.5 & 6, No.1, pp.48-58, 2013 12 .

International conferences

Full paper(s) (Reviewed)

1. Anusha Jayasiri, Kenji Honda, Katsuhito Akahane, Makoto Sato: ` Feeling Wind: An Interactive Haptization System for Motion Rendering in Video Contents using SPIDAR' , Proceedings of 23rd International Conference on Artificial Reality and Telexistence (ICAT 2013), pp.54-60, 2013 12.11-13 ＊

2. Anusha Jayasiri, Katsuhito Akahane, Makoto Sato: `Feeling the Motion of Object in a Dynamic Image Sequence through Haptic Interface' , Proceedings of International Conference on Advances in ICT for Emerging Regions (ICTer2012), pp.19-26, 2012 12.13-14＊

3. Anusha Jayasiri, Katsuhiko Akahane, Makoto Sato: `Haptic Rendering of Dynamic Image Sequence Using String based Haptic Device SPIDAR', Proceedings of Joint Virtual Reality Conference of ICAT-EGVE-EuroVR (JVRC2012), 2012 10.17-19

Short paper(s) (Reviewed)

1. Anusha Jayasiri, Katsuhito Akahane, Makoto Sato: `3D Translational Haptic Motion Rendering from an 2D Image Sequence' , Proceedings of Three Dimensional Systems and Applications (3DSA2014), 2014.5.28-30 http://www.3dsa.kr/program/sub_4.asp

2. Anusha Jayasiri, Katsuhito Akahane, Makoto Sato: `A Proposal of 3D Haptic Motion Rendering of an Object in a Video', Proceedings of Three Dimensional Systems and Applications (3DSA2013), CD, 2013.6.26-29

Domestic conferences

1. ジャヤシリ アヌシャ, 赤羽 克仁, 佐藤 誠: `Rendering of Moving Information using Haptic Feedback in Dynamic Image Sequence', 2012 年映像情報メディア学会年次大会, CD, 2012.8.29-31

* Cited and indexed in the IEEE Xplorer

Appendix B – Used Image Sequences for Evaluation

Moving leaves	Bouncing balls	Car race
		
		
		
		

Fish tank	Rotating cube