3D Interaction System with Multiple Identified,Small,Wireless,Battery-less,Occlusion-free Magnetic Markers

著者	武　越
学位授与機関	Tohoku University
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Abstract

This study proposes a 3D interaction system with the unity high performance 3D tracking system that supports small, wireless, battery-less, identified and occlusion-free multiple markers. The tracking system is designed for potential 3D user interface based on the wireless magnetic position tracker with LC resonance principle. The designed tracker overcomes the limitations of existing 3D tracking and innovates 3D user interface technologies with precise and real time motion tracking. Since the resonant frequencies of the markers with coil and condenser are designed to be different each other, the system can identify multiple markers simultaneously by measuring their resonance peak. This main principle also allows wireless, buttery-less, and small markers that are easy to be fastened on objects. Because of the basic feature of the magnetic flux, the markers occluded with something can be detected, meaning their complex movements and embedding markers are supported. A performance evaluation shows that the tracking system achieve a less than 1mm accuracy of position tracking, and more than 100Hz refresh rate even when using 10 markers simultaneously.

Based on the uniqueness of the tracking system (or in order to highlight the uniqueness of the tracking system), a 3D interaction system is developed with three different functions of tracking small free moving objects, direct modeling of deformation objects, and dexterous hand gestural interaction. Firstly, in the function of tracking small free moving objects, this study explores a scientific visualization in which the trajectories of moving insects (beetles) with a marker are measured and visualized on a screen in real time. Results show totally nine-hour position log of the insects, and observational behaviors of their movements including movements into the behind of trees. Secondly, this study develops a physical interaction system that allows users to directly build 3D virtual models by modeling real clay that embeds several markers in real time. A user study confirms that most of participants satisfy the quality of shape recognition with clay-embedded markers and the created virtual model. Finally, in dexterous hand gestural object manipulation, this study implements an efficient fingers-based virtual object interaction with finger identifications. The system allows users with markers to interact with virtual model with their fingers, and supports the fundamental manipulations of catch, release, RTS (rotation, translation, and scaling) and cutting that are separately trigged by identified fingers actions. A user study verified the effectiveness of the finger identifications as well as free and complicated finger movements.

Throughout the implementation and findings from the evaluations, the uniqueness of the tracking system is proved, and potential of the innovative 3D interface design is clearly shown. The study also discusses some ideas of the new hardware design to improve stability and extend the capture area, and future 3D user interface design with the novel tracking system.

Keywords: Human-Computer interaction, 3D interaction, 3D sensor, Objects manipulation, Shape recognition

Contents

Chapter 1

Introduction

Virtual Reality (VR) is an advanced human-machine interface which has the basic characteristics of immersion, interaction and imagination. The VR technology was presented by Jaron Lanier in the 1980s to comprehensive utilizes computer graphics, simulation technology, multimedia technology, multi-sensor technology to simulate the human's visual, auditory, tactile and other sensory organs which can make people be immersed in a computer-generated virtual realm, and through language, gestures and natural way to create a user-friendly multi-dimensional information space. Users through virtual reality system not only can feel the "immersive" realistic experience of objective world, and be able to break through the space, time and other objective limits to feel the undergo that cannot be experienced in the real world. However, it still has many requirements should be improved. One of the most important requirements is how to manipulate 3D virtual objects directly and conveniently. 3D tracking sensor is a vital composition of VR interaction which is a communication tool between users and computers. Although, researchers have used mechanical or electromagnetic field sensors to achieve the object manipulation. Users have to wear heavy complex sensors to detect their motions which are difficult to use that led to the inconvenience of the operating experience. With the development of optical tracking system, optical sensors reflect theirs advantages of high accuracy and small and light size markers. However, optical markers on human body are occluded easily, and the system frequently lose their exact positions, which significantly reducing efficiency and convenience. On the other hand, the user interface is also an important factor on the object manipulations. Existing 3D interactive systems had been focused on direct manipulation [1][2] where user's interaction space corresponds to that of the virtual object. For instance, users can touch virtual 3D objects and translating, scaling and rotating them with fingers [3][4]. But these operation are too single and stiff, cannot do complex elaborate operations such as cutting, combining, sometimes the efficiency is lower than indirect manipulation with keyboards and mice.

1.1 Objective

A high performance 3D tracking system is an important premise of an outstanding precise and fast 3D interaction system. For example markers of the tracking system must be small and wireless so that they are easily fastened on small and moving objects conveniently. To achieve this, buttery should not be placed on the marker. At the same time, in order to detect multiple objects simultaneously, the markers need to be identifiable. And For stable and continues tracking in complex environment, occlusion-free (Markers occluded by something from data acquisition side can be detected) marker is required. This study aims to design a new 3D tracking system to overcome the shortages of the existing tracking systems for 3D interactions, and meet the all requirements for such 3D interactions. The tracking system is designed based on the one of the possible ideal tracking system with LC resonant principle [5], and modified especially for finger-based interaction system.

This study also illustrates a novel 3D interaction which has three different functions of tracking small free moving objects, direct modeling of deformable objects, and dexterous hand gestural interaction to verify the features of the tracking system. The first example, tracking small free moving objects, this study explores a scientific visualization in which the trajectories of small free moving objects in a complex environment with a marker, in which tracking objects are easily occluded are detected and display with 3D technology in real time. The second example allows users to build 3D virtual models by molding real clay which embeds several markers in real time. The last example lets users to manipulate virtual models with their fingers which are fastened with markers, and supports the fundamental but dexterous manipulations of catch, release, RTS (rotation, translation, and scaling) and cutting that are based on identified fingers actions.

1.2 Contributions

This study contributes an outstanding 3D tracking system for 3D interaction which has more comprehensive advantages with small wireless identifiable occlusion-free markers. The principle, designing the specification and discussion on the system performance evaluation will clearly provide valuable information in the field of 3D tracking system. From the implementation of the three examples of the 3D interaction system, tracking small free moving objects, direct modeling of deformable objects, and dexterous hand interaction, the features (small, identifiable, battery-less, wireless and occlusion-free) of the tracking system is proved, and potential of the innovative 3D interface design is clearly shown. The implemented platform with the novel hardware, the 3D interaction software by high quality visualization, and network configurations will be expected to provide exceptional usability and wide applicability in present and future 3D user interface.

Chapter 2

Related Work

This chapter outstand several related researches in virtual reality 3D interaction [6] with 3D tracking systems and 3D interactions. These related researches given a lot of experience and knowledge which helped to formulate correct research goals and progress.

2.1 3D Tracking System

3D tracking system is the basis of 3D interaction which is a fatal communication tool between users and machines. There are five mainly kinds of tracking sensors (mechanical, acoustic, optical, image based and magnetic sensor) which are widely used at present. Mechanical sensor is most classical device to track position in 3D environment which through measure the angles or force between each connections to detect the positions of the objects. Ishi et al. [7] developed a 3D mechanical tracking interface using tensed strings which can force feedback. Suryanarayanan et al. [8] investigated the use of surface EMG to track elbow joint angle during flexion-extension of the arm applied to control of a virtual environment or an anthropomorphic telemanipulator. An intelligent system based on neural networks and fuzzy logic has been developed to use the processed surface EMC signal and predict the joint angle. The intelligent system has been tested on normal subjects performing flexion-extension of the arm of various angles and at several speeds. The joint angles predicted by the intelligent system were input to a computer-simulated model of an elbow manipulator. Acoustic sensor is also one of the earliest 3D tracking technologies,used by Ivan Sutherland [9] in his research which through ultrasonic time-of-flight ranging in air.The system employed a continuous-wave source, and determined range by measuring the phase shift between the transmitted signal and the signal detected at a microphone. Meyer et al. [10] point out that that acoustic sensor enables continuous measurement without latency, but can only measure relative distance and then keep track of number of accumulated cycles.There are a particularly large number of different designs with optical sensors. Two or more cameras are mounted on the walls or ceiling looking in on a workspace. The sensors detect the direction to the targets attached to the objects being tracked, and a computer then triangulates the 3D position of them using the bearing angles from the two nearest cameras. Wang et al. [11] developed a optical tracking scheme, where lateral-effect photo-diodes mounted on the user's helmet view flashing infrared beacons placed in the environment. Church's method uses the measured 2D image positions and the known 3D beacon locations to recover the 3D position and orientation of the helmet in real-time. Welch et al. [12] introduced a optical senor with less than on millisecond of latency, and less than 0.5 millimeters and 0.02 degrees of position and orientation noise. however, the system must use a very dense array of LEDs so that will always be beacons available within the field of view of several of the sensors.Image based sensor is a new kind of 3D tracking sensor through analysis image to compute the positions of objects. Kinect is a representative image based sensor which provides full-body 3D motion capture, facial recognition and voice recognition capabilities. Shotton et al. [13] presented the principle of Kinect which consist of a RGB camera, depth sensor (Figure 2.1). The depth sensor consists of an infrared laser projector combined with a monochrome CMOS sensor, which captures video data in 3D under any ambient light conditions. The sensing range of the depth sensor is adjustable, and the software is capable of automatically calibrating the sensor based on user's physical environment, accommodating for the presence of furniture or other obstacles.Magnetic tracking technologies have a long history which be used for 3D interactions.

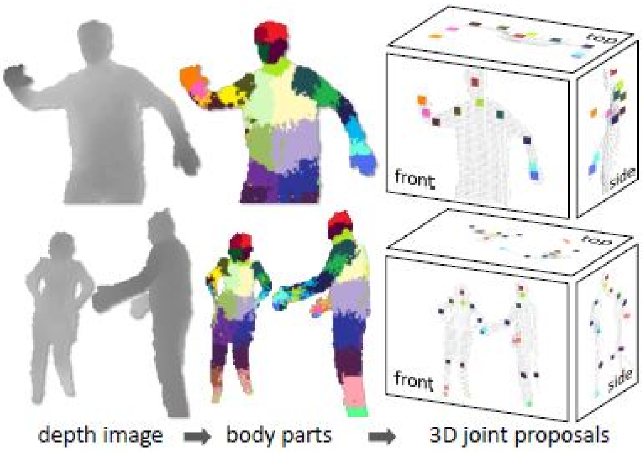


Figure 2.1: Princple of image based sensor

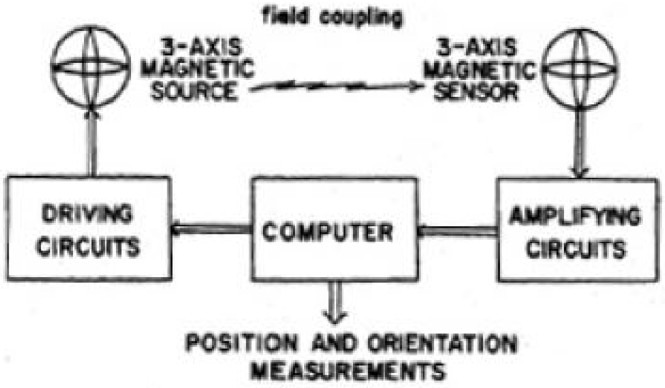


Figure 2.2: Princple of Raab's magnetic tracking system

Raab et al. [14] using AC magnetic field coupling from a 3-axis source to a 3-axis sensor to determine both the position and orientation (Figure 2.2) magnetic fields are generated by a source consisting of three orthogonal coils of wire activated in sequence by the electronics control unit to generate three orthogonal magnetic dipole fields.The magnetic sensor consist of a triaxial coil assembly that is able to measure components of these oscillating magnetic fields by inductive pickup.

2.2 3D Interaction

2.2.1 Objects Manipulation

With the development of 3D display technology, the performance has made great progress and the price has become much cheaper. 3D display technology has been used widely in to provide stereoscopic information which makes people to obtain and understand it more intuitively and realistically [15]. At present, 3D display devices are a large-scale application in industrial design, entertainment, and training, etc. 3D displays are divided to the following categories: stereoscopic monitor with 3D glasses, glass-free 3D display, Holographic display and head-mounted 3D display. There are two types of 3D virtual interactive system, single type and multiply type. Valkov et al. [16] presented 2D touching of 3D stereoscopic objects which provides touching and manipulating 3D objects on a plane for one user which tracks with two cameras and touch recognize touch motion with IR illuminators (Figure 2.3). Kitamura et al. [1] developed an multiply users interactive stereoscopic display (IllusionHole) which lets each user can see his/her own image with different viewpoints which computes with user's position (Figure 2.4). Nakashima et al. [2] integrated 2D and 3D user control interface with IllusionHole in order to support cooperative controlling and sharing. Lee et al. [17] introduced a depth-fused 3D Interaction which can display 3D images on arbitrarily viewpoint with two fog screen and projectors. The stereoscopic image is projected onto a mist of medium which is compared the traditional 3D display more realistic. Harish et al. [18] developed a

Figure 2.3: Touch 3D objects by fingers directly

Figure 2.4: IllusionHole. Collaborative 3D display with users' own viewpoints

simple and inexpensive 3D display made up of polygonal elements. They used a per-pixel transformation of images and depth to produce accurate 3D images on an arbitrary planar display facet which can see from any viewpoint. The system can be built to any size and can support any orientation of eyes of stereoscopy. Butler et al. [19] designed a novel interactive 360 degree viewable 3D display which provides viewpoints-corrected, stereoscopic 3D images to multiple users without any eye-wear or other users instrumentation.

Hachet et al. [20] developed a 3D interaction based on 2D unified multi-touch control which allows users to operate 3D objects straightway (Figure 2.5). It combines multi-touch input and immersive visualization into a single interaction. Lee et al. [21] presented a 3D vision-based natural hand interaction which segmented skin color to find hand direction to manipulate virtual objects with a stereo camera. This interaction allows users handle 3D virtual models in 3D environment by hand without fastening any tracking markers on hands. Vlaming et al. [22] proposed a fine grained interaction for information visualization which permits touch interaction with both the 3D windowing environment as well as with the contents of the individual windows contained therein. Wyss et al. [23] presented a direct bimanual object selection and manipulation interface using two ray pointers, one for each hand, and thus taking advantage of the user's natural control over his/her interhand-coordination. The interaction allowed controlled translation of virtual objects in an increased interaction volume. Song et al. [24] introduced a mid-air interaction allows users to manipulate the pose and scale of 3D virtual objects by their hand gestures in 3D environment with Kinect. One of the advantages is that users can manipulate 3D virtual objects in mid-air without any tracking sensors.

Hancock et al. [25] presented an interaction paradigm *Sticky Tools* that has the benefits of force-based interaction complete with full 6DOF manipulation. Stickt tools allowed users to pick objects and move them with other objects, and use these virtual objects as tools. Coffey et al. [26] created a method for exploring overview and detail visualization of volume datasets which consisted of two display surfaces, an interactive multi-touch table and a stereoscopic display wall. The system addresses current limitations of visualizations of volume data.Although current strategies support detailed spatial analysis of local data features, it is easy to become lost and disoriented in these immersive visualizations and it is also difficult to perform analysis at multiple scales. Duval et al. [27] designed a collaborative virtual interaction with non-immersive or semi-immersive environments for which users cannot afford to buy expensive devices neither for 3D visualization of their virtual environment nor for interaction. It provided to a users a 3D virtual ray allowing the user to only control the 2D position of the closest ray end, and calculating the orientation of the ray. M. Mollers et al. [28] afforded 3D virtual interaction methods for touch-enhanced displays which supported to give a prospectively correct view with movement of users and united the viewpoints of real world and virtual world. It depended on tracking the position of user's head to compute the viewpoints then correct the image on real time. Grossman et al. [29] presented a prototype collaborative 3D virtual model interaction, which served as platform to support users to see the models with their privacy viewing.

On basis of direct manipulate interaction, gestural control philosophy further simplify the direct manipulation. Shi et al. [30] presented a novel 3D virtual interaction based on gestural control of tracking both hands on real time which needs neither markers nor gloves. They use three cameras

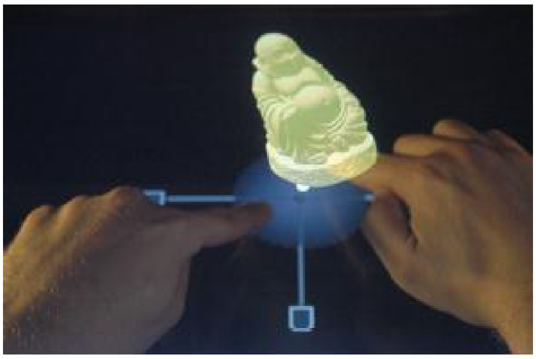


Figure 2.5: Toucheo. Direct multi-touch interaction with co-located 3D stereoscopic visualization

to analysis frames then detect skin color to get the positions of fingers which offered a 2D analysis to confirm 3D positions. Y. Boussemart et al. [3] introduced a gesture based 3D interaction for manipulation of 3D virtual environments in which users need not resort to the command vocabulary of traditional keyboard and mouse interaction. They implemented a bimanual gesture interpreter to recognize and translate a user's actions into gestural commands for manipulating virtual objects with purely video-based tracking techniques. Rado et al. [31] introduced a new interactive techniques which designed for users moving environment. They designed a novel menu which users press down a hand-held button attached to a 6 DOF, magnetic sensor. Grossman et al. [32] developed a 3D virtual interaction with volumetric displays for interactive manipulation of objects (Figure 2.6). The 3D tracking system provides direct manipulation of stereoscopic models which provides gestural manipulation around the display's hemispheric enclose with a Vicon motion tracking system is used to track the positions of markers placed on the user's fingers. It innovative integrated touch-sensitive display surface and direct manipulate in order to simplify user's operation.

In order to detect users' motion, have to fasten tracking markers on fingers or hands to get the positions of them. But no matter the weight and size of lighter and smaller, always restrict users with a certain extent. The motion senors are remarkable progress which detect motions without any device with users. Nickel et al. [4] introduced a 3D vision system capable of visually detecting pointing and gestures and estimating the 3D pointing

Figure 2.6: Gestural interaction with a volumetric display

detection on real time with a stereoscopic camera. By using dedicated Hidden Markov Models for different gesture phases, high detection tares were achieved even on defective trajectories to achieve manipulate directly without fastening any markers. Song et al. [33] developed a mixed reality interactive application which provided users with enhanced interaction experiences by integrating virtual and real world objects in mixed environment with a stereo camera which tracks the user's hands and fingers robustly and accurately in the 3D environment. Through this interaction a more realistic and immersive control method is achieved compared to the traditional input devices. Hilliges et al. [34] developed an interactive system (Figure 2.7) combining an optical see through display and Kinect camera to create the illusion that users are directly interacting with 3D virtual models. A virtual image of a 3D scene is rendered through a half silvered mirror and spatially aligned with the real environment for the viewer. Users easily reach into an interaction volume displaying the virtual image. This allows the user to get their hands into the virtual display and to directly interact with an spatially aligned 3D virtual environment without any 3D tracking devices.

2.2.2 Shape Recognition

Except display and manipulate stereoscopic 3D objects directly, it is another research topic to build 3D virtual models of reality objects more conveniently

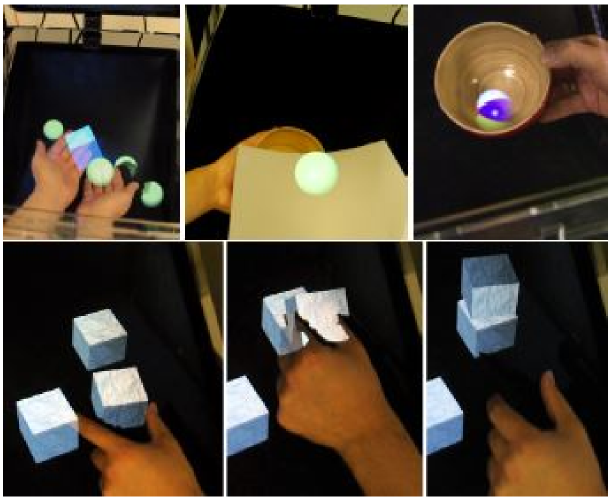


Figure 2.7: HoloDesk: allows direct freeform interactions with 3D graphics, without any bodyworn hardware

and rapidly. Kitamura et al. [35] developed a novel physical interaction that allows a users to construct and interact with a 3D environment by using cubes with a bi-directional user interface (Figure 2.8). It can recognize the 3D shape of connected cubes in real time by utilizing the real-time communication with the cubes. The cube has both input and output devices, and this makes the interface intuitive and helps to clarify the causal relationship between the input of the user's operational intention and the output of simulated results.

Izadi et al. [36] presented a 3D physical interaction named KinectFusion that build high-quality 3D virtual models on real time from a moving Kinect camera. The system took the live depth from Kinect and converts from image coordinates into 3D points and normals in the coordinate space of the camera to build the 3D virtual model with a novel GPU-based implementations for both cameras tracking and surface reconstruction allow users to interactive in real time that have not previously been demonstrated.

Jota et.al [37] designed a seamless interaction between physical world and virtual world. They guided a simple idea to let users build virtual models using physical objects, similar to scale models, where a virtual models could be build, step by step. using simple daily objects and visualized side-by-side to the construction blocks which combined a Kinect depth camera with 3D

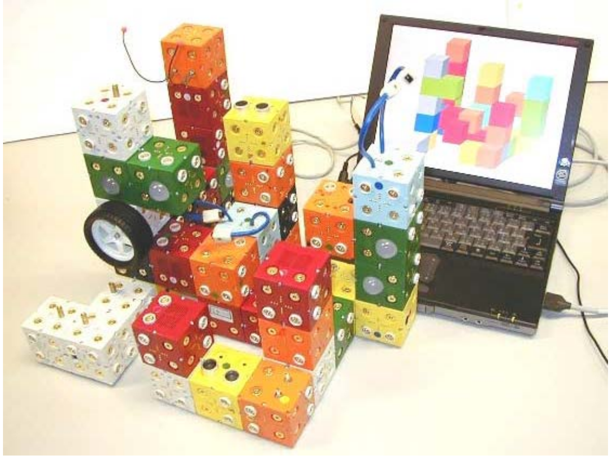


Figure 2.8: ActiveCube: An example of 3D structure with 39 cubes

Figure 2.9: StereoBlock: shape recognition based on Kinect

stereoscopic projector. Wibowo et al. [38] introduced DressUp, a physical interaction for designing dresses with 3D input use the human body as a model. It consisted of a body-sized physical mannequin, a screen, and tangible prop tools for drawing in a 3D on and around the mannequin. As the users draws, he/she modifies or creates pieces of digital cloth. Pai et al. [39] described a system for constructing 3D virtual models of several aspects of physical interaction (Figure 2.10). It used a highly automated robotic facility to scan behavior models of whole objects which provided a comprehensive view of the modeling process. Compare other systems, the system can scan the structure and section with a high accuracy.

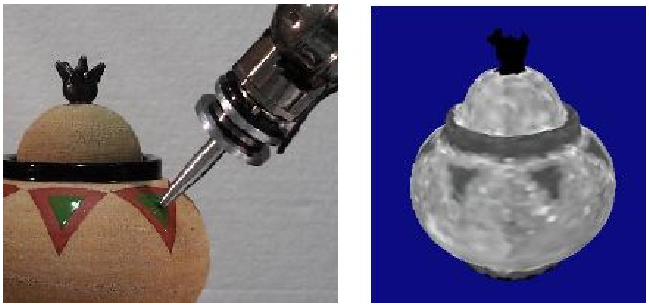


Figure 2.10: Examples of behavior models scanned

2.3 Wireless magnetic motion capture system using multiple LC resonant magnetic markers

2.3.1 System Component and Principle

Hashi et al. [5][40] develop a novel magnetic tracking system (Figure 2.11). Wireless magnetic multi-position tracking system that uses multiple LC resonant magnetic markers. The marker consists of a Ni-Zn ferrite core ($4mm$ in diameter and $10mm$ in length) with a wound coil and a chip capacitor, representing an LC series circuit with no battery, driven wireless by electromagnetic induction. The system is composed of measurements equipment and a coil assembly consisting of an exciting coil and an array of newly designed pickup coils. The pickup coils array consists of 25 pickup coils placed at intervals of $60mm$ on an acryl board. Each coil consists of 40 turns of polyester enameled copper wire (PEW) wound around an acryl bobbin of $30mm$ in diameter. An excitation voltage of 25 Vp-p is applied to the exciting coil (10 turns of PEW around a $50mm \times 500mm$ Teflon coil) and the markers are strongly excited at its resonant frequency by electromagnetic induction. Then the system becomes slow as the number of markers increases, owing to the time required to switch frequencies and marker multiple measurements. Therefore, a superposed wave including all of the resonant frequency components of the markers if used to realize simultaneous excitation. The induced voltage wave measured by the pick-up

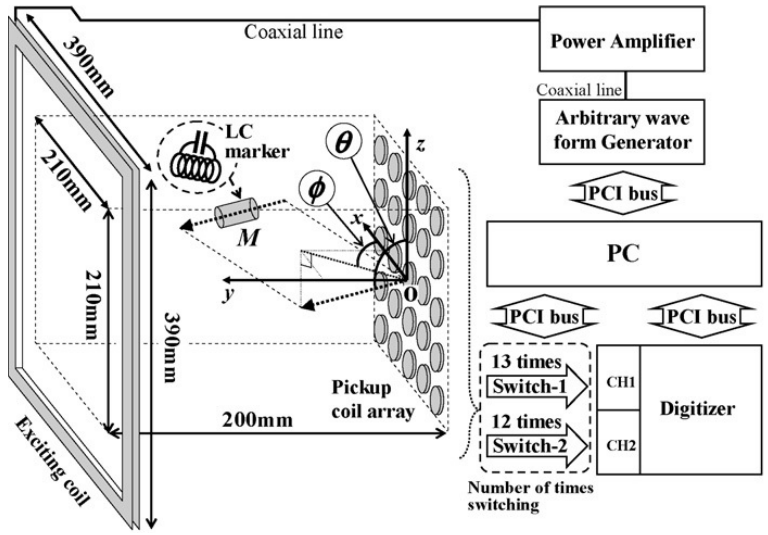


Figure 2.11: Schematic diagram of theproposed wireless motion capture system

coils is analyzed in each frequency spectrum by FFT analysis [41] (Figure 2.12). The spectra are first measured without the marker and are then measured with the marker. The induced voltage of the marker contributes VMK, which can be obtained by vector subtraction of the amplitude of the spectrum without the marker from the amplitude of spectrum with the marker. The amplitude VMK measured by each pickup coil varies in proportion to the flux density *B* that the marker produces for the location of the pickup coil.

2.3.2 Position Calculation

The position and orientation of the markers is obtained by solving an inverse problem [42]; more than six values (in this paper, 32 values are used) of the flux density at known locations are needed to determine both the position and orientation of the marker as the magnetic flux source (six degrees of freedom). To solve this problem, the flux density generated from the marker is considered as a magnetic dipole field. Based on this assumption, the position and orientation of the marker is calculated using the following equations (Eqs. 2.1 - 2.3) and the nonlinear method of least squares, which

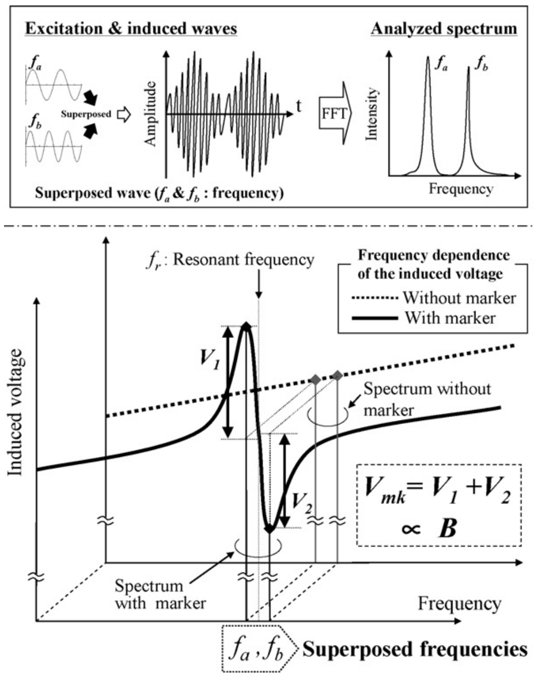


Figure 2.12: Signal of LC marker acquisition technique (superposed wave excitation and FFT analysis)

effect an optimization using the Gauss-Newton method.

$$\S(\vec{p}) = \sum_{i=1}^{n} \| \vec{B}^{(i)}_{meas} - \vec{B}^{(i)}_{cal}(\vec{p}) \|^2 \tag{2.1}$$

$$\vec{B}^{(i)}_{cal}(\vec{p}) = \frac{1}{4\pi\mu_0} \left\{ -\frac{\vec{M}}{\gamma_i^3} + \frac{3(\vec{M}\vec{\gamma}_i)\vec{\gamma}_i}{\vec{\gamma}_i^5} \right\} \tag{2.2}$$

$$\vec{p} = (x, y, z, \theta, \phi, M) \tag{2.3}$$

Here, $S(\vec{p})$ is the objective function (the residual sum of squares), i is the coil number, n is the total number of coils, $\vec{B}^{(i)}_{meas}$ is the measured flux density, $\vec{B}^{(i)}_{cal}$ is the theoretical flux density that takes the magnetic dipole field into account, $\vec{p}$ is the parameters of the marker. $\vec{M}$ is the magnetic moment, and $\vec{r} = (x, y, z)$ is the position of the marker. Eq. 2.2 is the equation of an ideal dipole field expressed as a function of position and orientation. Position and orientation of the marker is expressed in polar coordinates (Figure 2.12): ϕ is the angle between the x-axis and the and the direction vector when the moment is projected onto the xy-plane, and θ is the angle between the direction of the moment and the z-axis.

Chapter 3

3D Tracking System with Small, Wireless, Battery-less, Identifiable and Occlusion-free Markers

Based on the principle of 3D measurement explained in 2.3, we developed new tracking system for 3D finger manipulation with small, wireless, battery-less, identifiable and occlusion-free markers. (Figure 3.1).

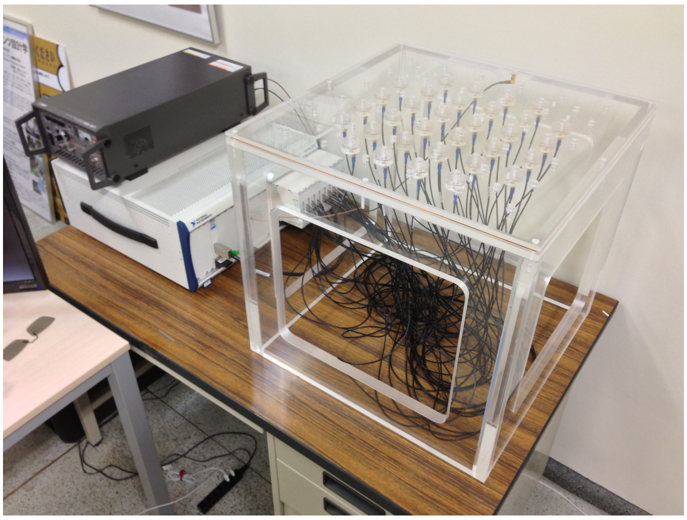


Figure 3.1: 3D tracking system with small, wireless, battery-less, identifiable and occlusion-free markers

Because we aim to track fingers' motions, the size of the marker must be very small and light. If the tracking system can distinguish ten fingers simultaneously, the markers should be identifiable. In order to detect the wispy motions of the fingers and keep working stable, the markers must be high accuracy and occlusion-free. We want the motions of the fingers cannot be limited, so the markers will be wireless. Through calculation, the range of activity of hands is about $30cm$ length and width, $20cm$ height. So this is the requirement of detecting area.

3.1 System Overview

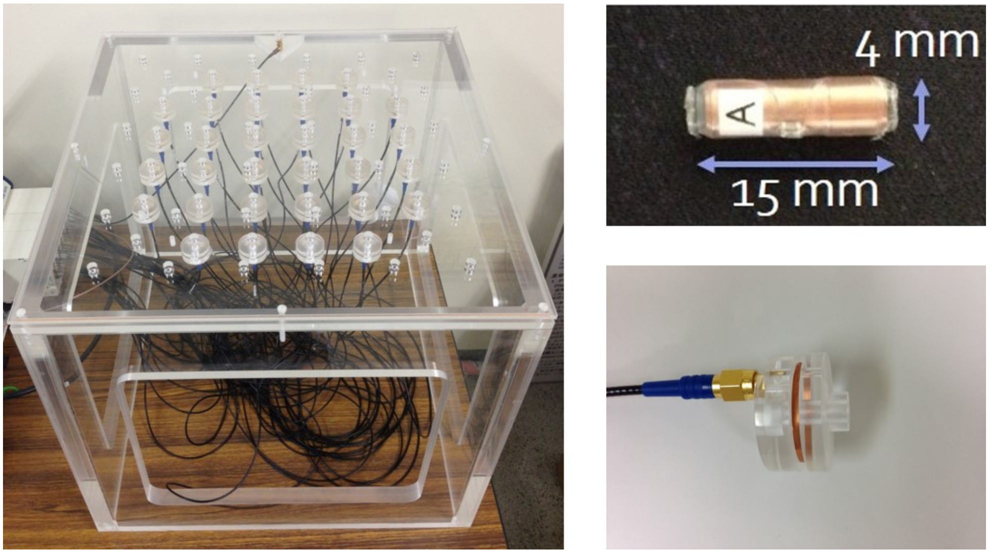


Figure 3.2: Left: Table Type with Exciting coil and Pickup coils
Right: LC marker and pickup coil

Wireless magnetic multi-position tracking system was developed for 3D interaction to satisfy the above requirements based on Hashi's novel magnetic tracking system. The system is composed of measurements equipment and a coil assembly consisting of an exciting coil, pickup coil array and LC markers. Exciting coil and pickup coil array are integrated in the same plane forming "Table Type" (Figure 3.2). The marker consists of a Cu ferrite core ($4mm$ in diameter, $15mm$ in length and $4g$ weight) with a wound coil and

Figure 3.3: NI PXIe-1075 Data Processor

Figure 3.4: NF HSA-4011 Power Amplifier

a chip capacitor, representing an LC series circuit without battery, driven wireless by electromagnetic induction.

NI PXIe-1075 (Figure 3.3) is used for controlling the exciting coil in order to produce exciting voltage and analysis induced voltage from pickup coils. The pickup coils then process the induced voltage to digital data and send it to the computer. It provides 8 hybrid slots to connect 8 NI TB-2706 direct connectivity terminal blocks. Each blocks can link four pickup coils. So the system allows 32 pickup coils to receive the induced voltage from the markers simultaneously.

Because the exciting voltage cannot excite the markers effectively which

NI PXIe-1075 control the exciting coil to produce, a power amplifier is necessary to strengthen the exciting voltage. NF HSA-4011 (Figure 3.4) is used to strengthen the exciting voltage which can produce high voltage and adjust output voltage flexibly.

3.2 System Working Principle

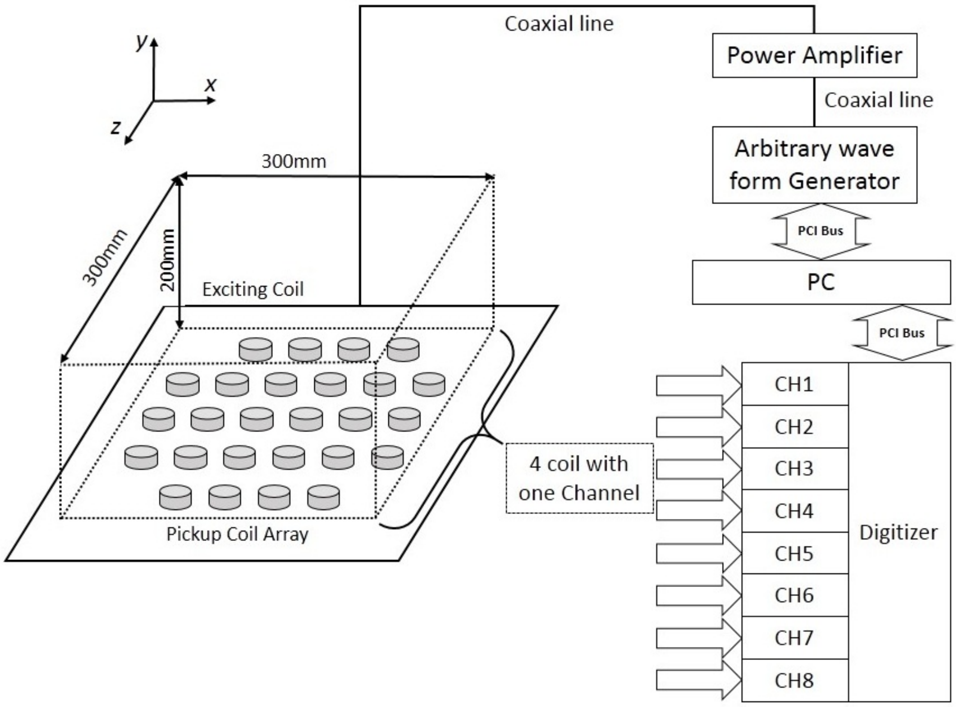


Figure 3.5: Structure chart of 3D tracking system with small, wireless, battery-less, identifiable and occlusion-free markers

The new 3D tracking system (Figure 3.5) is improved and strengthened from Prof. Hashi's magnetic tracking system. Because the tracking system aims to 3D interaction manipulation, exciting coil and pickup were integrated in the same plane in order to facilitate the users' motion. Also, the number of the pickup coils was increased from 25 to 32 in order to extend the detecting area. The current detecting area is $300mm$ lengthy, $300mm$ wide and $200mm$ tall which can satisfy tracking small objects with high accuracy in a complicated environment which meets the requirement of the detecting area.

Because the limitation with data processor and algorithm, the refresh rate of Prof. Hashi's tracking system is only $10Hz$ (1 marker working situation) which cannot fulfill the speed requirement of 3D interaction. After update a new data processor (NI PXIe-1075) and optimized algorithm, the refresh rate was increased to $100Hz$ (1 marker working situation). This speed is sufficient to meet the requirement of 3D interaction.

Larger detecting area facilitates user operations. The data processor (NI PXIe-1075) supports 32 connect point. Compared with the 25 pickup coils of Prof. Hashi's tracking system, this system has made substantial progress. How further extend the detecting area with 32 pickup coils is a important challenge. Striking a balance between accuracy and the distance of each two pickup coils is the key. We tested three distance with two pickup coils, $45mm$, $60mm$, $75mm$. The test result shows, in 45mm situation, the accuracy is very high but the detecting area is too narrow. In $75mm$ situation, the accuracy has fallen considerably. $60mm$ was showed to be the best balance between accuracy and detecting area.

Chapter 4

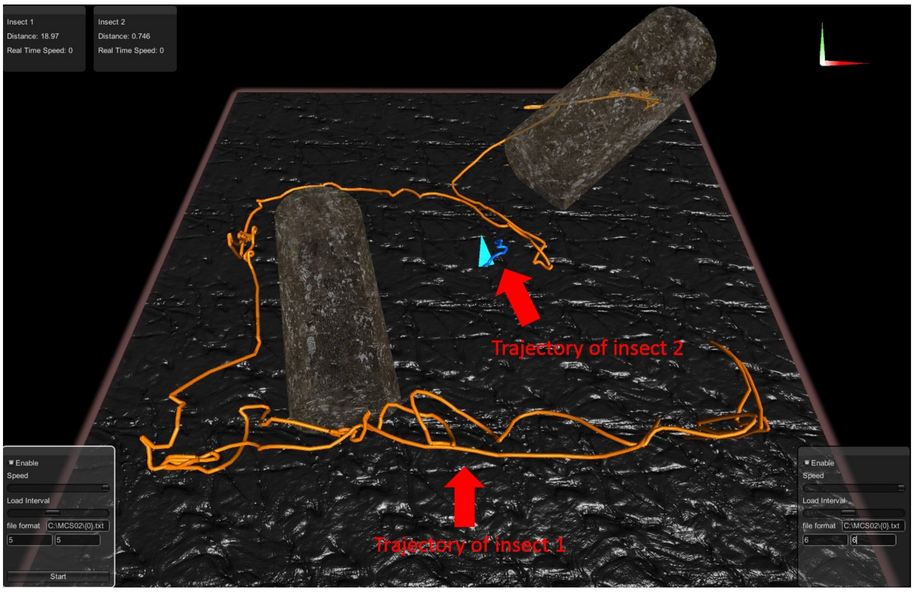
3D Interaction based on the Developed 3D Tracking System

We developed a novel 3D interaction using the modified 3D tracking system to achieve three examples of 3D interaction field (tracking small free moving objects, direct modeling of deformable objects, and dexterous hand gestural interaction) on same tracking hardware. Based on the outstanding features of the tracking system, the research 3D interaction simplifies the complexity of operation and allows more intuitive observation. It also reduces the using cost and increases the applicability to realize the three functions (Tracking small objects, building 3D virtual objects and gestural manipulation) on one hardware operation. And also through developing the 3D interaction, it was tested and verified that the tracking system is really suitable for 3D interaction.

4.1 Tracking Small Free Moving Objects

4.1.1 Function Overview

Track objects, especially small objects more conveniently is an important research theme of 3D interaction. Because the size of the objects to be tested is usually very small, it is required that the size of markers of the tracking system to be even smaller than the objects. Also, if the tracking



Insect 1
Distance: 18.97
Real Time Speed: 0

Insect 2
Distance: 0.746
Real Time Speed: 0

file format C:\MCS02\{0}.txt
5 5

file format C:\MCS02\{0}.txt
6 6

Figure 4.1: Tracking with two insects

system will be used in a complex environment, it should be able to track the targets without any occlusion. For example, as explained in the Chapter 2 related work, if optical sensor or image based sensor are used to detect the position, markers can be easily to occluded, so that it is not suitable with the development objective. The acoustic sensor also has this problem that if the sound wave is occluded by other objects, the tracking system will lost the target. On the other hand, magnetic and mechanical sensors are not easy to be occluded but they all need battery or a wired power source to provide energy, which led the size of the markers to be too large to be fastened on the small objects that will be tested.

The proposed 3D interaction provides a much more convenient and direct way to track the small moving objects (Figure 4.1). Based on the new magnetic tracking system, users just fasten the markers on the objects and the system will detect their positions and orientations in real time. Because the markers have no battery, they can be very small and light to be fastened on the small objects. And because the markers cannot be occluded, the users do not need to worry about the system losing position. The 3D interaction supports tracking 10 identifiable objects simultaneously. With 3D display technology, users will recognize trajectories more readily comparing with

Insect 1

Distance: 4.425

Real Time Speed:
0.224

Insect 2

Distance: 4.661

Real Time Speed:
2.974

Figure 4.2: Information display interface with the real-time distance and speed

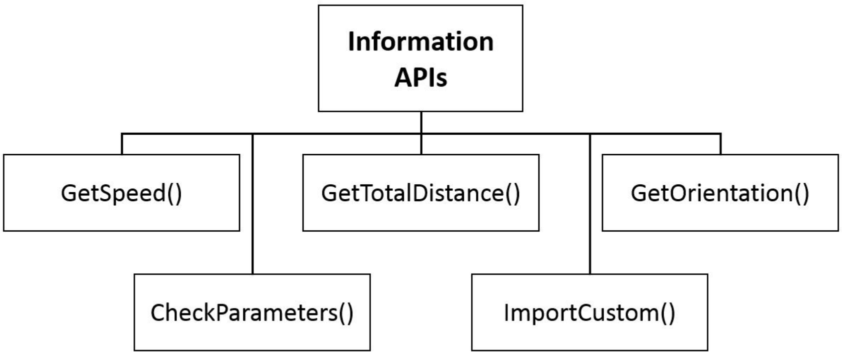


Figure 4.3: Thestructurechart of information APIs

2D mode.

4.1.2 Algorithm and APIs

In the tracking function, the 3D interaction will display the parameters (Figure 4.2) of the tested objects on real time. In the current implementation, it provides the average speed, total distance and preset threshold value.

When computing the average speed and total distance, harmonic mean is used to get more accurate statistics. The formula is:

$$H = \frac{n}{\frac{1}{x_1} + \frac{1}{x_2} + \frac{1}{x_3} + \cdots + \frac{1}{x_n}}$$

The computing algorithm can greatly reduce statistical error in order to keep the stability of statistic.

The system also allows users to custom statistics with the APIs (Figure

Figure 4.4: Marker fasten schematic diagram

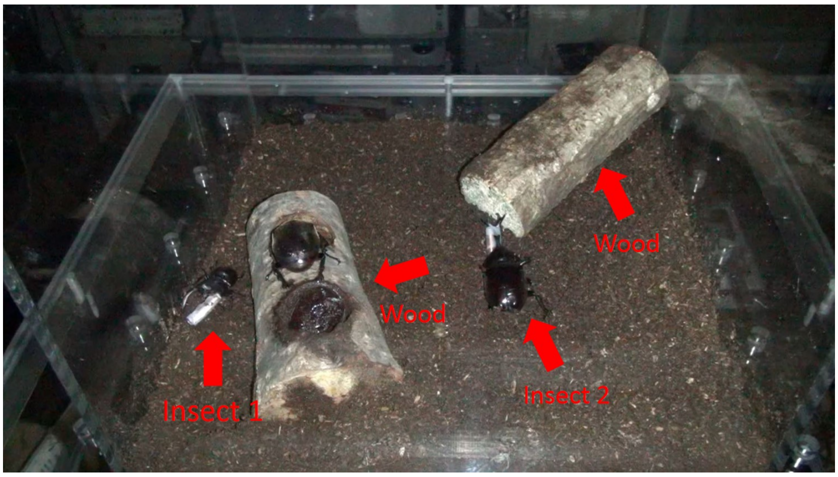


Figure 4.5: Real testing environment

4.3) of the 3D interaction. For instance, the user can preset a threshold value before tracking in order to make more flexible. If the threshold value is exceeded, the interaction will warn the users. It is very useful for test some sensitive objects with certain parameters.

We used two insects to test and verify the tracking function. The marker was fastened on the horn of the insect (Figure 4.4) which was placed the on soil with two wood piles to simulate a complex environment (Figure 4.5). The movement of the insects was tracked the two insect during 9 hours and display their trajectories in real time (Figure 4.1). The system showed to provide a stable measurement and plotted trajectory. The results above proved that the tracking function of the 3D interaction can afford a stable and accurate position detection without any occlusion. This means that users only need fasten the small markers on the objects and can get their trajectories without worrying about occlusion problem.

4.2 Direct Modeling of Deformable Objects

4.2.1 Function Overview

In addition to obtaining trajectory, to build 3D virtual models of realistic objects is also a primary function of 3D interaction. From Chapter 2 related work, if users want to build the virtual models of real objects in real time, often use assembled module to do. But this method cannot be used for getting complex shapes. Optical or mechanical scanning method can get complex shapes, but not in real time and the equipment cost is very high. The building 3D virtual models function of the proposed 3D interaction achieved a good balance in the precision and real-time.

The markers are packed in plastic shuttles and then put the shuttles are placed in a clay (Figure 4.6). U Users can mold the clay to change the shape of it. The 3D interaction builds the virtual model of the clay in real time.

4.2.2 Algorithm and Performance

Each shuttle is regarded as a virtual ball. With the current version, there are ten shuttles in the clay. There are 14 extend points around a ball. When

Figure 4.6: Left: A marker in a plastic shuttle
Right: A clay parceled markers

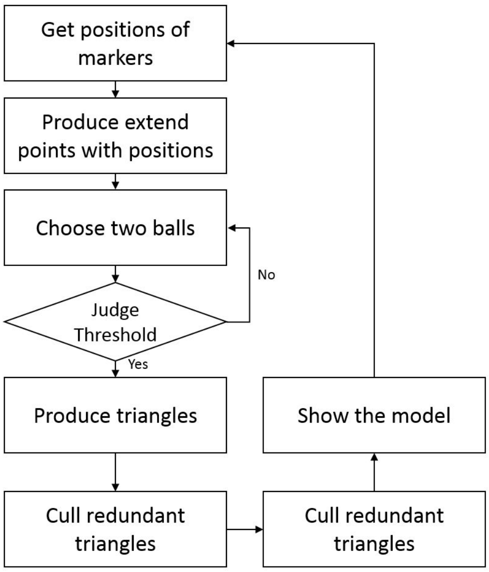


Figure 4.7: Building algorithm flow chart

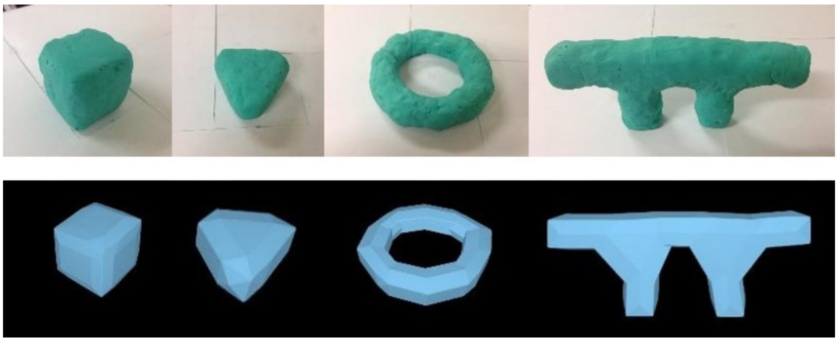


Figure 4.8: Comparison chart with four shapes

the distance of two balls is less than a threshold value, we take three points from the 28 points in order to form a triangle. After judged and calculated all of the balls, the triangles form in the shape of the object (Figure 4.7).

However, if calculated in the most extreme case, two million triangles will be formed, which causes a huge pressure to the graphics card with rendering. To overcome this, we only draw the surface in order to reduce graphics card pressure and use ray analysis method to cull redundant triangles.

We created four basic shapes in order to test the performance of the function. From the comparison chart it was shown that the 3D interaction can build the shape of the clay roughly (Figure 4.8). It provides a new method to let users get the virtual model of the reality object.

4.3 Dexterous Hand Gestural Interaction

4.3.1 Function Overview

There are many researches about manipulating virtual objects with fingers (Figure 4.9). But because of the limitations of the tracking system, they have their own shortcomings, as detailed in Chapter 2. Precise manipulation of virtual objects is hard and mutual occlusion between fingers occurs often, resulting in misuse easily. The proposed tracking system provides an excellent platform to develop an outstanding finger-based manipulation function. Because the size of the markers is very small, which makes them easy to fasten on fingers. The markers are wireless so that they does not limit the fingers' actions. And because they are occlusion-free, the system will keep working properly even if there are occlusions between two fingers.

In the current version, there are six markers which are fastened on thumb, forefinger and middle finger of each hand (Figure 4.9). Right hand is responsible for translating, rotating and scaling objects. And left hand is responsible for other commands (Figure 4.10). Users can swap the commands as their wish.

Figure 4.9: Finger with markers

Figure 4.10: Manipulte a virtual object with 6 fingers

4.3.2 Gestural Commands

With this 3D interaction, the user can perform gestural commands to manipulate virtual models conveniently. If only the thumb and forefinger of right hand catch the object, the user can move and rotate it. If the the thumb ,forefinger and middle finger of right hand catch the virtual object simultaneously, the user can scale the virtual object as the fingers' open and close. If the user wants to release the virtual object, just need let middle finger leave the object then loosen thumb and forefinger of right hand, the object will be released (Figure 4.11). The 3D interaction not only has the above commands. If the object is in not be caught situation, the left hand can cut the object in two parts. The three fingers of left hand can form a plane that the system can compute the cutting angle and direction (Figure 4.12).

The Nvida's PhysX, which can provide a real physical world environment, is used for physical calculation. For instance, if the user releases the object, it will fall to the table. If the user cuts the object, the object will split according to the cutting angle and direction.

The interaction above shows that the proposed system can provide a precise direct manipulation platform for virtual models. The system overcomes the shortcomings of the existing 3D interactions and offer a physical environment very close to reality for users.

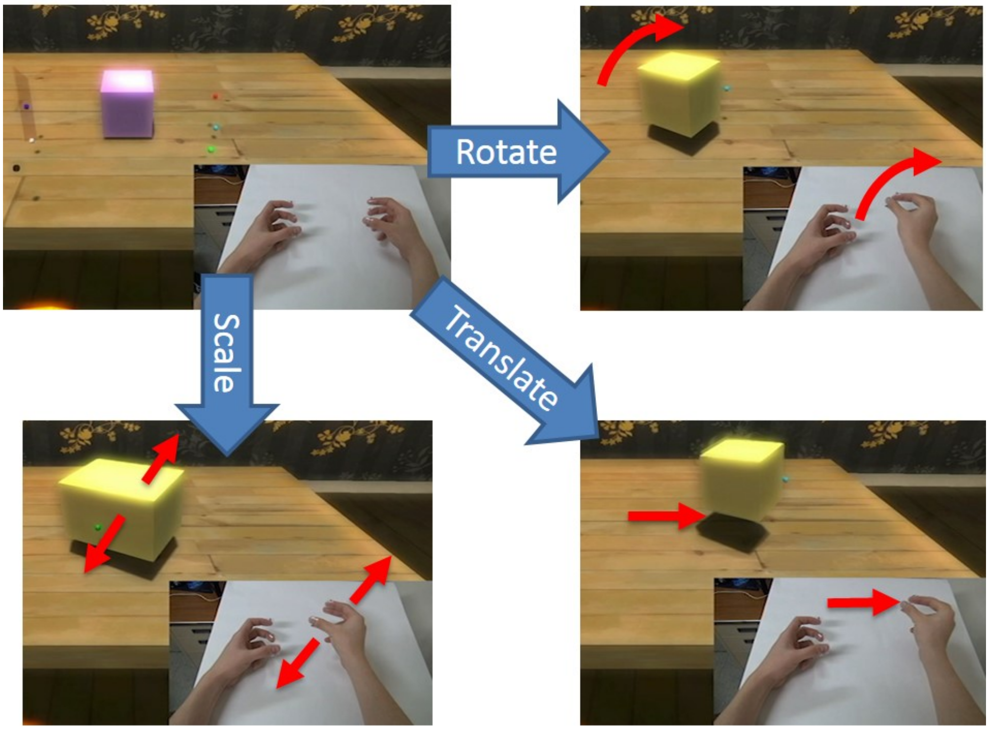


Figure 4.11: Translate, scale and rotate with fingers

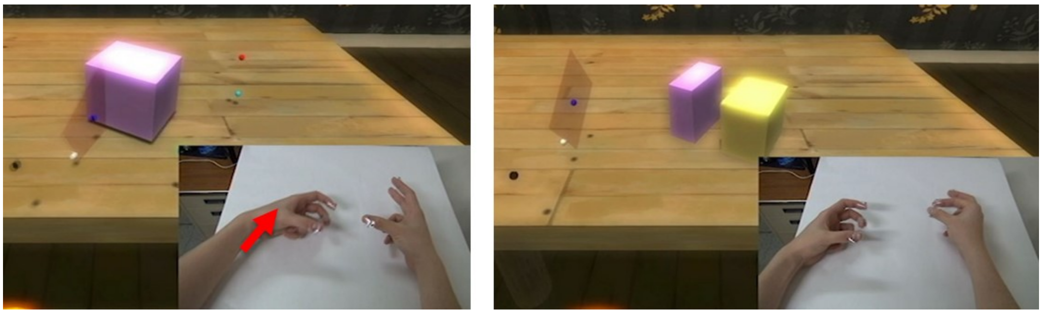


Figure 4.12: Cut according to a plane formed with three fingers

Chapter 5

Evaluation and Discussion

In order to verify the real performance and applicability of the tracking system, objective and the subjective evaluations are necessary. In the objective evaluation, the position accuracy and the detection speed were tested to evaluate system performance. In the subjective evaluation, 5 users were invited to try the tracking system with building virtual objects function. Also gestural interaction design function was evaluated through a questionnaire.

5.1 Objective Evaluation and Result

5.1.1 Position Accuracy

The position accuracy was verified experimentally for the system when the marker was arranged parallel to y-axis as shown in figure 5.1. The white cube points shown the actual positions of marker, blue cross points shown the detected positions of the marker. The marker was swept from $x = 0mm$ to $150mm$ at $y = 50mm$ and $100mm$ in $10mm$ steps along in the xy-plane at $z = 0mm$. The movement of the marker was done by a precision three-dimensional-axial manual scanner with position accuracy. Each point represents 100 measurements at every marker position, with squares for actual position and crosses for detected position. The figure 5.1 shows that the differences between actual positions and detected positions are all less than 1mm which means that the position accuracy less than 1mm.

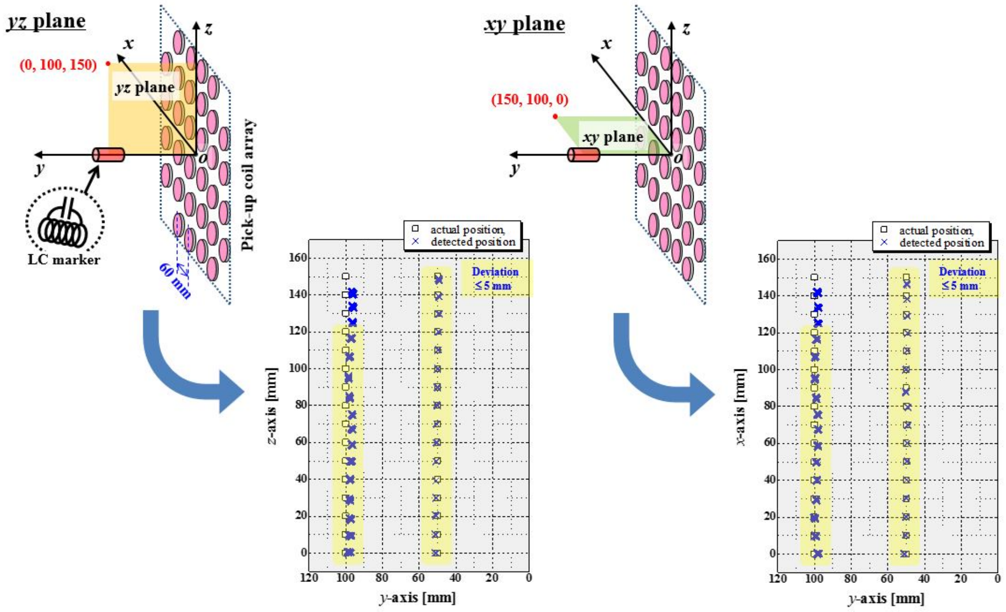


Figure 5.1: Position accuracy evaluation map

5.1.2 Orientation Accuracy

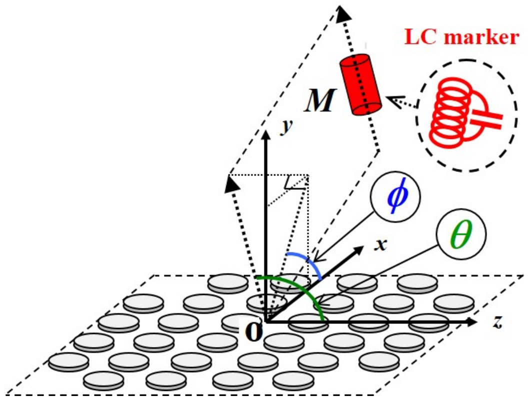


Figure 5.2: Test schematic

The orientation accuracy was verified experimentally for the system when the marker was arranged above the pickup coil array as shown in figure 5.2 5.3.The white cube point shown the actual angles of the marker, and the cross points shown the detected angle of the marker. The marker was placed at $y = 50mm$ and $y = 100mm$ to test the orientation accuracy.

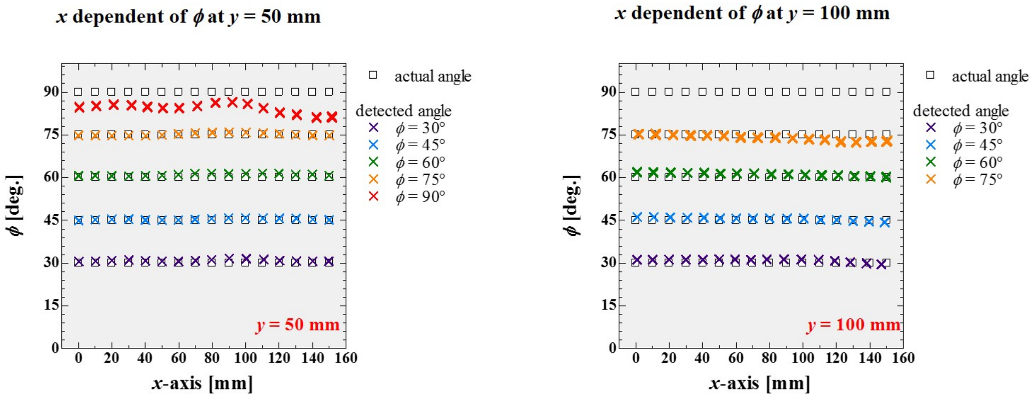


Figure 5.3: Orientation Accuracy Analysis

The movement of the marker was done by a precision three-dimensional-axial manual scanner. From the figure 5.3, no matter which angle of the marker (except more than 75 degree), the difference values between actual angle and detected angle are all less than 3 degree. But if the angle more than 75 degree, the orientation error will dramatically increase.

5.1.3 Detection Speed

By calculating the times of runs in one minute, the detection speed can be obtained as shown in figure 5.4. The red triangle points show the detection speed with 8 core CPU. The blue circle points show the detection speed with 6 core CPU. And the black cross point show the detection speed with 4 core CPU. Because the detection speed is determined by the number of the markers and the performance of the computer, three different performance computers were used to test the detection speeds with different numbers (1 to 10) of markers working simultaneously. The result (figure 5.4) showed that the tracking system requires a high performance computer. With more than 5 markers working simultaneously, the 4 cores computer runs under a very huge pressure. And with the 6 cores and 8 cores computer, the detection speeds with 10 markers working simultaneously are around 20Hz which are ideal for the speed requirement of the development purpose.

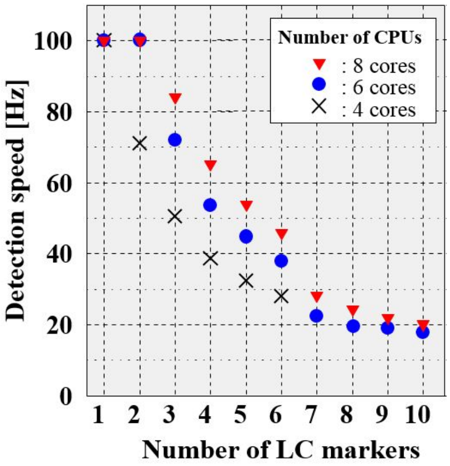


Figure 5.4: Detection Speeds with different performance computers and different numbers of markers

5.2 Subjective Evaluation and Result

5.2.1 Direct Modeling of Deformable Objects

Five users were invited to mold the clay into four shapes (Triangle, Cube, Ring and Cone) and let them compare the virtual shape with the actual shape. Then answer these six question with five options (Very good, Good, Ordinary, No-good, Bad).

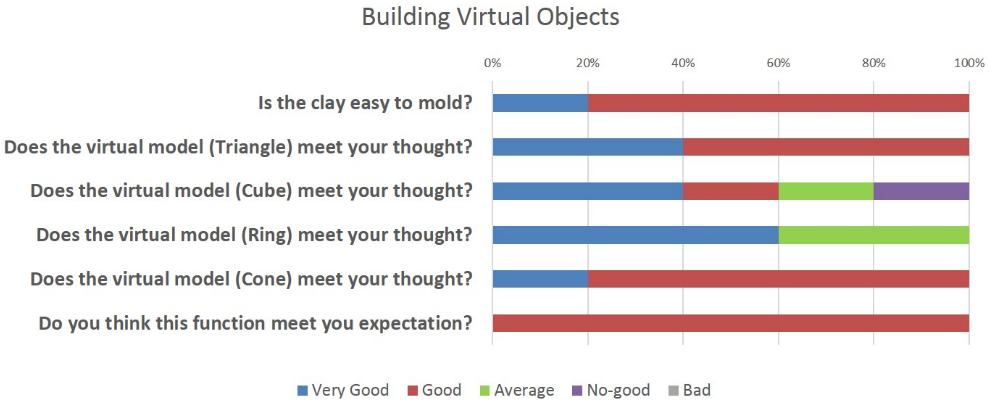


Figure 5.5: Percentage diagram of building virtual objects

Through the statistical result (figure 5.5), it can be said that all of the users were satisfied with the building virtual objects function of 3D interaction. In particular 100 percent of the users were satisfied with it according to question 6. They thought that the clay was easy to mold, and the virtual shapes were in line with their expectations according to the question 1 to 5. The results show that the function has achieved the desired effect based on the study 3D tracking system.

5.2.2 Dexterous Hand Gestural Interaction

The gestural interaction design function was evaluated by 5 users. The users were requested to catch, translate, rotate and scale the virtual object, then release it. They were also asked to use another hand to cut it into two parts. Finally, they were asked to answer ten questions. The first three questions are about the users' intuitive feels for the markers. The remaining three questions are about the 3D interaction.

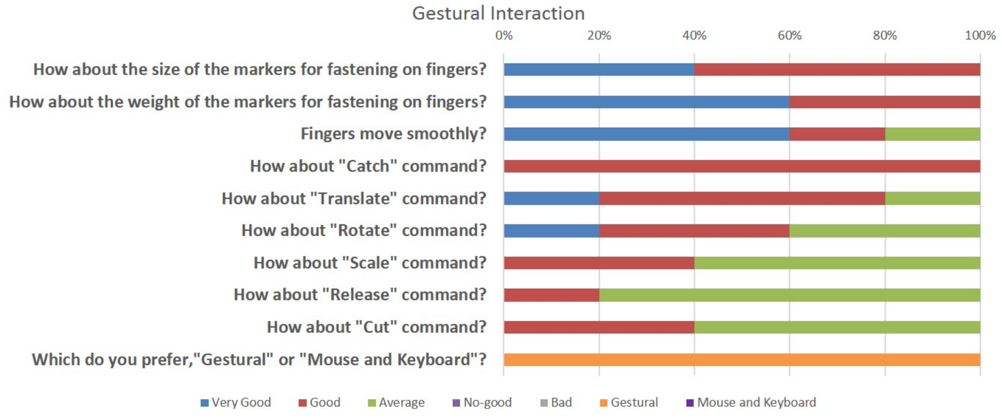


Figure 5.6: Percentage diagram of gestural design interaction

We can see that all of the users are satisfied with the size and weight of the markers (figure 5.6). The users also thought that the markers allow them to smoothly move their fingers. And the users think that the gestural commands are easy to manipulate the virtual objects. Compare with the mouse manipulation method, the users are inclined to the gestural manipulation method.

5.3 Integrated Discussion

The above objective evaluation and subjective evaluation have proved that the study 3D tracking system meets all of the requirements of the research objective (Small, wireless, identified, buttery-less and occlusion-free). It has more comprehensive features than the existing 3D tracking systems. The lightweight small-size and wireless markers are easily fastened on small objects. The feature of occlusion-free makes sure that the markers can work stably in a complex environment. And the study 3D interaction based on the 3D tracking system can provide more direct and convenient manipulation functions with high accuracy.

Based on the overall features, the study tracking system can support many fields.

- Object tracking under complicated environment
- Shape Recognition by the embedded markers
- Complicated and intelligent 3D manipulations
- Others such as medical applications

The study tracking system also has limitations. If the angle of marker and exciting coil is between 75 degree and 115 degree, the magnetic flux through the marker will decay very intensely which is not enough to excite the marker. This situation will occur a position error that the system cannot detect the position and orientation of the marker.

And because the coil of the markers are wound along Y-axis, there is unchanged of the induced magnetic flux in Y-axis. This situation led that the system cannot detect the angle of Y-axis.

Chapter 6

Conclusion and Future Work

In this paper, a new magnetic tracking system designed for 3D interactions was presented. It provides small-size, wireless, battery-less, identify and occlusion markers. These features make it more applicable and easy to use than the existing tracking systems. From the performance evaluation, it was verified that the position error is less than $1mm$ and the refresh rate is better than $100Hz$. It shows that the research tracking system has a high accuracy and fast speed. And from the user evaluation, the result proved the usability of this tracking system. The small wireless markers can be fastened on any objects conveniently and do not limit users' activities. We also developed a 3D interaction with three functions with the modified tracking system. Users can track small moving objects, build virtual models and manipulate virtual models by fingers directly. The 3D interaction solved three mainly requirements of 3D interaction field which also verifies that the research tracking system is a high performance unity motion detecting tool for 3D interaction systems.

We will continue to improve the structure of the markers with "two-coil" type to solve the dead angle problem and cannot detect angle of y-axis. Moreover, update the power amplifier and arbitrary wave form generator to extend the detecting area.

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Bibliography

[1] Y. Kitamura, T. Konishi, S. Yamamoto, and F. Kishino, "Interactive stereoscopic display for three or more users," in *Proceedings of the Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '01, pp. 231–240, ACM, 2001.

[2] K. Nakashima, T. Machida, K. Kiyokawa, and H. Takemura, "A 2D-3D integrated environment for cooperative work," in *Proceedings of the Symposium on Virtual Reality Software and Technology*, VRST '05, pp. 16–22, ACM, 2005.

[3] Y. Boussemart, F. Rioux, F. Rudzicz, M. Wozniewski, and J. R. Cooperstock, "A framework for 3D visualisation and manipulation in an immersive space using an untethered bimanual gestural interface," in *Proceedings of the Symposium on Virtual Reality Software and Technology*, VRST '04, pp. 162–165, ACM, 2004.

[4] K. Nickel and R. Stiefelhagen, "Pointing gesture recognition based on 3D-tracking of face, hands and head orientation," in *Proceedings of the International Conference on Multimodal Interfaces*, ICMI '03, pp. 140–146, ACM, 2003.

[5] S. Hashi, M. Toyoda, S. Yabukami, K. Ishiyama, Y. Okazaki, and K. Arai, "Wireless magnetic motion capture system for multi-marker detection," *Magnetics, IEEE Transactions on*, vol. 42, pp. 3279–3281, 2006.

[6] K. Stanney, *Handbook of Virtual Environments: Design, Implementation, and Applications*. Human Factors and Ergonomics Series, Taylor & Francis Group, 2002.

[7] M. Ishii and M. Sato, "A 3D spatial interface device using tensed strings," *Teleoperators and Virtual Environments*, vol. 3, pp. 81–86, 1994.

[8] S. Suryanarayanan and N. P. Reddy, "EMG based interface for position tracking and control in VR environments and teleoperation," *Presence*, pp. 282–291, 1997.

[9] I. E. Sutherland, "A head-mounted three dimensional display," in *Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, part I*, AFIPS '68, pp. 757–764, ACM, 1968.

[10] K. Meyer, H. L. Applewhite, and F. A. Biocca, "A survey of position trackers," *Presence: Teleoper. Virtual Environ.*, vol. 1, pp. 173–200, May 1992.

[11] J. fang Wang, R. Azuma, G. B. V. Chi, G. Bishop, V. Chi, J. Eyles, and H. Fuchs, "Tracking a head-mounted display in a room-sized environment with head-mounted cameras," 1990.

[12] G. Welch, G. Bishop, L. Vicci, S. Brumback, K. Keller, and D. Colucci, "The hiball tracker: high-performance wide-area tracking for virtual and augmented environments," in *Proceedings of the symposium on Virtual Reality Software and Technology*, VRST '99, pp. 1–ff., ACM, 1999.

[13] J. Shotton, A. Fitzgibbon, M. Cook, T. Sharp, M. Finocchio, R. Moore, A. Kipman, and A. Blake, "Real-time human pose recognition in parts from single depth images," in *In In CVPR, 2011. 3*, 2011.

[14] F. Raab, E. Blood, T. Steiner, and H. Jones, "Magnetic position and orientation tracking system," *Aerospace and Electronic Systems, IEEE Transactions on*, vol. AES-15, pp. 709 –718, sept. 1979.

[15] D. A. Bowman, E. Kruijff, J. J. LaViola, and I. Poupyrev, *3D User Interfaces: Theory and Practice*. Redwood City, CA, USA: Addison Wesley Longman Publishing Co., Inc., 2004.

[16] D. Valkov, F. Steinicke, G. Bruder, and K. Hinrichs, "2D touching of 3D stereoscopic objects," in *Proceedings of the Conference on Human Factors in Computing Systems*, CHI '11, pp. 1353–1362, ACM, 2011.

[17] C. Lee, S. DiVerdi, and T. Höllerer, "An immaterial depth-fused 3D display," in *Proceedings of the Symposium on Virtual Reality Software and Technology*, VRST '07, pp. 191–198, ACM, 2007.

[18] P. Harish and P. J. Narayanan, "A view-dependent, polyhedral 3D display," in *Proceedings of the International Conference on Virtual Reality Continuum and its Applications in Industry*, VRCAI '09, pp. 71–75, ACM, 2009.

[19] A. Butler, O. Hilliges, S. Izadi, S. Hodges, D. Molyneaux, D. Kim, and D. Kong, "Vermeer: direct interaction with a 360 degree viewable 3D display," in *Proceedings of the symposium on User Interface Software and Technology*, UIST '11, pp. 569–576, ACM, 2011.

[20] M. Hachet, B. Bossavit, A. Cohé, and J.-B. de la Rivière, "Toucheo: multitouch and stereo combined in a seamless workspace," in *Proceedings of the symposium on User interface software and technology*, UIST '11, pp. 587–592, ACM, 2011.

[21] M. Lee, R. Green, and M. Billinghurst, "3D natural hand interaction for AR applications," in *Proceedings of the Conference Image and Vision Computing New Zealand (IVCNZ 2008)*, pp. 1–6, IEEE Computer Press, 2008.

[22] L. Vlaming, C. Collins, M. Hancock, M. Nacenta, T. Isenberg, and S. Carpendale, "Integrating 2D mouse emulation with 3D manipulation for visualizations on a multi-touch table," in *Proceedings of International Conference on Interactive Tabletops and Surfaces*, ITS '10, pp. 221–230, ACM, 2010.

[23] H. P. Wyss, R. Blach, and M. Bues, "isith - intersection-based spatial interaction for two hands," in *Proceedings of the conference on Virtual Reality*, VR '06, pp. 123–127, IEEE Computer Society, 2006.

[24] P. Song, W. B. Goh, W. Hutama, C.-W. Fu, and X. Liu, "A handle bar metaphor for virtual object manipulation with mid-air interaction," in *Proceedings of the Conference on Human Factors in Computing Systems*, CHI '12, pp. 1297–1306, ACM, 2012.

[25] M. Hancock, T. ten Cate, and S. Carpendale, "Sticky tools: full 6DOF force-based interaction for multi-touch tables," in *Proceedings of the International Conference on Interactive Tabletops and Surfaces*, ITS '09, pp. 133–140, ACM, 2009.

[26] D. Coffey, N. Malbraaten, T. Le, I. Borazjani, F. Sotiropoulos, and D. F. Keefe, "Slice wim: a multi-surface, multi-touch interface for overview+detail exploration of volume datasets in virtual reality," in *Proceedings of the Symposium on Interactive 3D Graphics and Games*, I3D '11, pp. 191–198, ACM, 2011.

[27] T. Duval and C. Fleury, "An asymmetric 2D pointer/3D ray for 3D interaction within collaborative virtual environments," in *Proceedings of the International Conference on 3D Web Technology*, Web3D '09, pp. 33–41, ACM, 2009.

[28] M. Möllers, P. Zimmer, and J. Borchers, "Direct manipulation and the third dimension: co-planar dragging on 3D displays," in *Proceedings of the International Conference on Interactive Tabletops and Surfaces*, ITS '12, pp. 11–20, ACM, 2012.

[29] T. Grossman and R. Balakrishnan, "Collaborative interaction with volumetric displays," in *Proceedings of the Conference on Human Factors in Computing Systems*, CHI '08, pp. 383–392, ACM, 2008.

[30] J. Shi, M. Zhang, and Z. Pan, "A real-time bimanual 3D interaction method based on bare-hand tracking," in *Proceedings of the International Conference on Multimedia*, MM '11, pp. 1073–1076, ACM, 2011.

[31] D. Rado and D. F. Keefe, "rair flow menus: toward reliable 3D gestural input for radial marking menus," in *SIGGRAPH '09: Posters*, pp. 26:1–26:1, ACM, 2009.

[32] T. Grossman, D. Wigdor, and R. Balakrishnan, “Multi-finger gestural interaction with 3D volumetric displays,” in *ACM SIGGRAPH 2005 Papers*, SIGGRAPH ’05, pp. 931–931, ACM, 2005.

[33] P. Song, H. Yu, and S. Winkler, “Vision-based 3D finger interactions for mixed reality games with physics simulation,” in *Proceedings of the International Conference on Virtual-Reality Continuum and Its Applications in Industry*, VRCAI ’08, pp. 7:1–7:6, ACM, 2008.

[34] O. Hilliges, D. Kim, S. Izadi, M. Weiss, and A. Wilson, “Holodesk: direct 3D interactions with a situated see-through display,” in *Proceedings of the Conference on Human Factors in Computing Systems*, CHI ’12, pp. 2421–2430, ACM, 2012.

[35] Y. Kitamura, Y. Itoh, and F. Kishino, “Real-time 3D interaction with activecube,” in *Extended Abstracts on Human Factors in Computing Systems*, CHI EA ’01, pp. 355–356, ACM, 2001.

[36] S. Izadi, R. A. Newcombe, D. Kim, O. Hilliges, D. Molyneaux, S. Hodges, P. Kohli, J. Shotton, A. J. Davison, and A. Fitzgibbon, “Kinectfusion: real-time dynamic 3D surface reconstruction and interaction,” in *ACM SIGGRAPH 2011*, SIGGRAPH ’11, pp. 23:1–23:1, ACM, 2011.

[37] R. Jota and H. Benko, “Constructing virtual 3D models with physical building blocks,” in *Extended Abstracts on Human Factors in Computing Systems*, CHI EA ’11, pp. 2173–2178, ACM, 2011.

[38] A. Wibowo, D. Sakamoto, J. Mitani, and T. Igarashi, “Dressup: a 3D interface for clothing design with a physical mannequin,” in *Proceedings of the Conference on Tangible, Embedded and Embodied Interaction*, TEI ’12, pp. 99–102, ACM, 2012.

[39] D. K. Pai, K. v. d. Doel, D. L. James, J. Lang, J. E. Lloyd, J. L. Richmond, and S. H. Yau, “Scanning physical interaction behavior of 3D objects,” in *Proceedings of the Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH ’01, pp. 87–96, ACM, 2001.

[40] S. Hashi, K. Ishiyama, S. Yabukami, H. Kanetaka, and K. Arai, "Analysis and improvement of detection accuracy for a wireless motion sensing system using integrated coil component," *Journal of Applied Physics*, vol. 107, pp. 107–110, 2010.

[41] M. Toyoda, S. Hashi, S. Yabukami, M. Ohya, K. Ishiyama, and K. Arai, "Development of wireless magnetic multi-position detecting system using fft anaysis," *Journal of Magnetics Society of Japan*, vol. 30, pp. 391–395, 2006.

[42] S. Hashi, M. Toyoda, S. Yabukami, K. Ishiyama, Y. Okazaki, K. I. Arai, and H. Kanetaka, "Wireless magnetic motion capture system using multiple lc resonant magnetic markers with high accuracy," *Sensors and Actuators A: Physical*, vol. 142, pp. 520 – 527, 2008.