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THE ROLE OF VISUAL FEEDBACK IN INTERACTIVE GRASPING SIMULATION

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ABSTRACT

Modern virtual reality system are composed by different devices (for visualization and force feedback) capable of deceiving the human sense in a way that the users has the impression of acting in a virtual world generated by the computer. However, haptic and tactile interaction is still in its infancy, if one is interested to feel the interaction with a computer generated virtual model and do not want to restrict the natural movement of the hand with different external devices. The presented approach is investigating the ability of humans to control with its hand a virtual hand model in manipulative tasks, following the interaction on a desktop virtual reality setup, but without haptic feedback, in order to determine the feasibility of user studies for this kind of user – virtual product interaction. Because no real force feed-back is provided, the user can decide upon the correctness of the grasping posture only from visual feedback. The hand and the virtual object interaction are computed from a simulation, so the accurate spatial position of the real hand and fingers are needed in real time. This simulation program is using the Nvidia PhysX SDK. The presented approach is linking a simulation software with a virtual environment and provides real time bi-directional communication of graphical information in a desktop environment: the user can see how its fingers are acting on a virtual product and how the virtual product is responding to different grasping postures and manipulation task. Using a visual display, the presented approach would allow a designer to evaluate a virtual product in a more intuitive way, using a rich perceptual paradigm, and also the simulation program is providing useful information for shape evaluation.

Keywords: interactive grasping simulation, visual feedback, stability of finger contact, accuracy of finger contact

1 INTRODUCTION

Handling of products during their life cycle (e.g. human powered devices, shampoo bottles, mobile phones, handheld cameras) requires intensive and often complex human-product interaction. Exchange of information and transfer of energy between the product and its user are needed in order to achieve proper operation of the available product functions. The hands of the users play an important role in this interaction. They facilitate communication by spatial movements and by taking up particular postures, and conveying energy and information by touching or forcing the interface of products. In addition, the hands are used as a tool to support and position products in their usage environments. Advanced interfacing techniques and technologies (e.g. gesture recognition, pressure sensors, touch displays) support the communication at semantic level by interpreting the motion of the hands and processing contextual information. Traditional interfaces based on buttons, joysticks, knobs, bottles of shampoos require sometimes particular movements that deliver the right energy to produce a mechanical motion in the interface of the product. Understanding the underlying physical and mental processes in these interactions requires an interdisciplinary research involving the wide areas of cognitive and engineering sciences.

Research focusing on the role of ergonomics, usability, design of the emotions for tactile and haptics sensory experiences provides knowledge, methods, and tools for designers in order to develop products that can be used safely and comfortably in the everyday life. Typically, user research and usability studies are done on physical prototypes and tested by potential users. These methods are rather time consuming and expensive in addition they require well defined product concepts that can be easily rapid-prototyped. As an alternative for usability studies, computer simulation of the use processes started to take a ground. However, computer simulation of usage of products still contains many challenges. From the hardware side, it requires adequate tactile and haptic feedback for the user and accurate and fast 3D visualization of product concepts (Doug and Dinesh, 2001). From, the software side, it needs more accurate contact models that considers contact zone update during grasping, non-linear deformations of the human body, micro-sliding displacements, and time dependent behavior, as well as real time simulation of product behavior.

To support realistic and accurate simulation of human-product interaction, our research focuses on a new method for interactive, real time graphic simulation of grasping. Our ultimate goal is to develop *a grasping simulation* control mechanism that (a) provides means for the user to control a virtual hand model in a natural way, (b) is able to simulate contact phenomena in various use scenarios in an interactive manner, (c) is able to compute and simulate the contact forces on each individual finger in grasping so that the forces are stable and accurately positioned according the intention of the user, and (d) enable minimum latency due to computation time and user responsiveness.

In order to achieve this goal, two crucial parameters need to be paid an increased attention, namely the accuracy of finger positioning with respect to the virtual product and the stability of grasping. Both are dependent on the correct contact phenomena computation and simulation during grasping. The first parameter refers to the accuracy of contact identification. For the case of real hand-virtual product simulation three conditions need to be fulfilled: (i) accurate tracking for the real hand in order to allow construction of an accurate virtual hand that will be tested for collision detection with the virtual product during the grasping simulation (ii) display technology that allows co-location of the virtual product with the real hand (iii) collision detection algorithms as accurate as possible. The second parameter is related to the grasping theory of stability, based on grasping itself that is an intensively cognitive process during which the user adapts continuously his/her finger actions according to the bio-feedback such as to achieve and maintain stability of grasping. Of course, the real grasping involves a multi-sensory human perception and clearly is a very complex process. An accurate grasping simulation would require taking into consideration the whole human sensory perception but this is beyond the scope of the present research.

The main question this paper investigates is how visual feedback influences the accuracy and stability of interactive grasping simulation. For this purpose we have divided this fundamental question into a number of sub-questions for which we conducted 5 related experiments that allowed drawing up several conclusions presented in the last section of this paper. In all experiments the participants have been asked to use a grasping simulation system, which provided visual feedback only. Independent variables of our research are the size of the grasped object, the type of visual feedback, visibility of the contact points, and motion of the grasped object. The dependent variables of our research are the accuracy of positioning of the fingers with respect to the virtual object (which is of course display device dependent), and the stability of grasping. The measurements concern the response time of the users.

In the following sections, after a brief literature survey in the relevant area to our research, the grasping process is detailed as well as the typical stages of grasping simulation. The research instrument for the experimental research is then presented in section 4 followed by the description of experiments (section 5) and data analysis in section 6. In section 7 the conclusions and future work are presented.

2 STATE OF THE ART

Simulation proved to be an efficient means for product designers and engineers to develop and test various product concepts and manifestations. Conventionally, simulation of the use of products concentrated on the disposition of the product throughout its life cycle and on the understanding the critical events in the life of the product, rather than on modeling the user and the product together in given situations and on the evaluation of the actions in the interaction or manipulation processes. The current trend is to develop realistic virtual simulation environments, which make it possible to concurrently simulate the use and the behavior of products. From a computational point of view, proper representation and calculation of the physical phenomena and changes in real time is a complicated process. On the other hand, development of this kind of environments is also challenging because of (i) the complexity of the physical processes, (ii) the necessary coupling between the real and the virtual world, and (iii) the limitations of the available technologies and computational capacities.

Almost two decades ago, there were simulation languages developed, such as SLAM II, GPSS/H, SIMSCRIPT II.5 and SIMAN, which were able to represent and simulate process-interactions [1]. They opened up the 'digital age' in simulation, which is just developing into two branches, which are often referred to as 'mixed simulation' (combining the real world and the virtual world) and as 'entirely virtual simulation' (which is conducted exclusively in the virtual world). Grasping is an important element of interaction with and manipulation of physical object, consequently it has got into the focus of research in entirely virtual simulation environments.

Typically power grasping and precision grasping are differentiated [2]. As explained in [9], in the case of precision grasping, a hand grasps an object by means of its fingertips. In power grasping, a hand grasps an object by using both the palm and the fingertip. Power grasping intends to achieve an optimized form for stable grasping. For this reason, it is not advantageous for object manipulation.

Human fingers can grasp an object with many points of contact, each of which is pressed against the object as if wrapping up that object [5], proposed a point contact model for dynamic modeling and simulation of complete grasping tasks. It allows modeling of an arbitrary number and combination of contacts on the basis of LUGRE friction model. Okada and Kanade found that an appropriate arrangement of finger joints is very important since the stability of grasping an object greatly depends on that arrangement [10].

Peña Pitarch et al. reported on working with a hand model which included 25 degrees of freedom, and on using forward and inverse kinematic analysis for the above two types of grasping [11]. The simulation of the virtual grasp of human hand is based on iterative numeric computation- and optimization-based methods, so the computation times were probably much higher than that is requested for quasi real time simulations.

Garbaya and Zaldivar-Colado (2007), reported on the development of a virtual assembly system, which includes human interaction [6]. The system calculates contact force sensations by making their intensity dependent on the depth of penetration. However, the penetration is not visible to the user who sees a separate model, which does not intersect the mating part model. The two 3D models of the parts, the off-screen rendered model and the on-screen rendered model, are connected by a spring-dumper arrangement, and the force calculated is felt by the operator through the haptic interface. They also conducted a study to investigate the effects of contact force sensation on user performance and they found that the task completion time was reduced.

The simulation of grasping with one or two human hands has been widely studied in cognitive science, psychology and robotics. In most of the works, it is handled as a primarily tactile activity. In addition, the perceptive, cognitive, motor and reflective aspects of object grasping have also been studied [8]. The experiments of Gerard showed that subjects mentally simulated a manual reaching movement toward the perceived chess piece [7].

There are several low-level phenomena in grasping processes, which can not be described with the conventional Newtonian mechanics, but which should be correctly modeled if we want to get a high-fidelity simulation. These are: amount of the wrapped up area, contact zone rearrangement, non-linear deformations, micro-sliding displacements, and time dependent behavior.

3 A WORKFLOW FOR GRASPING SIMULATION

Figure 1 presents the concept of our interactive grasping simulation method. Although there are different approaches to grasping simulation, they share several commonalities. For instance, all grasping simulation approaches distinguish the following three phases of grasping: (a) approaching the object, in which there is no contact between the hand and the grasped object, (b) touching the object, in which there are contacts between the hand and the object, but the configuration of contact points does not form a grasping posture, and (c) grasping phase, when the configuration of contact points forms a grasping posture. As we have earlier discussed in several cases grasping simulation need to be

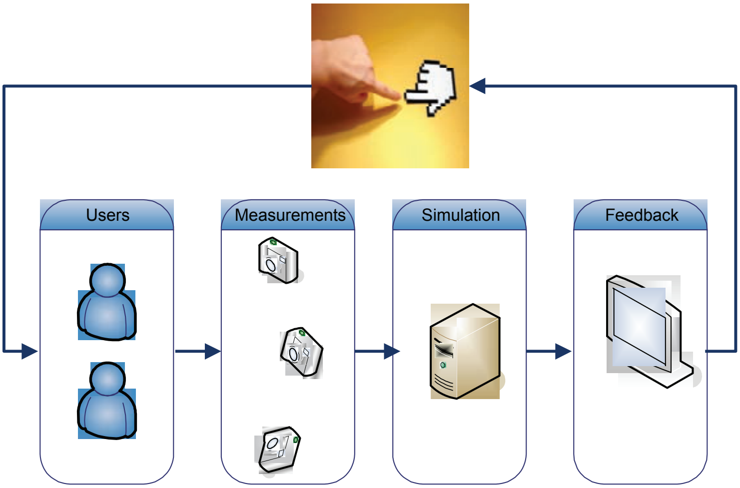


Figure 1: A process of interactive grasping simulation

executed on non-existing, virtual objects. In these cases, grasping forces cannot or limitedly be measured, thus they have to be determined by a different method. This is especially true for cases, where direct contact is simulated between the physical hand and the grasped virtual object in the same 3D space. This concept is supported by current virtual technologies, where the virtual object as an airborne image is visualized by volumetric displays. These airborne images are directly accessible for the users of such a system.

In the phase of approaching only motion phenomena is computed for the hand via a kinematic simulation. When the grasping process is starting the program is switching to a forward dynamics simulation. In this faze the torque in the joints are calculated in order to impose the motion of the virtual fingers according to the measured positions of phalanges of the real hand. When a grasping posture is recognized, a manipulation interval for possible forces is created based on anthropometric rules and data, which provides the platform for interactive grasping force manipulation. The user of the system can influence the grasping forces if he moves his hand in such a way that the hand penetrates into the grasped object. This penetration is used to determine the contact forces, which are exerted by the user at each contact point on the grasped object. By mapping the possible penetration range to the manipulation interval of the contact force, the user can also directly manipulate the values of the normal forces. The friction between the hand and the object is computed based on the normal forces for the case of both static and kinetic frictions. Finally, the motion of the grasped object is determined as a resultant of the grasping and friction forces.

4 RESEARCH INSTRUMENT

In order to investigate, how visual feedback influences the stability and accuracy of grasping in virtual reality environments, we have developed a tool to measure the effect of several variables (i.e. size of grasped object, visibility of the intended contact points, static vs. dynamic behavior of the grasped object, and orientation of grasping) on the stability and accuracy of contact control. The hardware setup contains a motion tracking system, a high-end computer, and a 2D display. The application used for the measurements is programmed with help of Nvidia PhysX SDK, and it was running on a Geforce 8800GTX graphics card.

For the purpose of hand motion and position measurement, a passive optical tracking system is used. A camera system using infrared light measures the position of retro-reflective markers, which are attached to specific landmarks of the user's hand. The tracking system enables the free movement of the user, since there are no cables connected to the user, to the detection device or to the computer. Previous approaches put several limitations on the hand postures and motions due to the insufficient technical capabilities of the tracking system. These limitations forced the user to use simple, but - from the point of view of grasping - unnatural hand postures and motions. Our six camera based system

Figure 2: Hardware setup of the experiments

enables the recognition of complex hand postures and motions with an accuracy of 0.1 mm. The position data measured by the tracking device serve as the input for controlling the virtual hand in simulation and for hand posture recognition.

The camera system used is offered by the Motion Analysis Corporation (www.motionanalysis.com). The Hawk Digital System consists of Hawk Digital Cameras, the EagleHub, and EVa Real-Time (EVaRT) software that can capture complex motion with extreme accuracy. Real-time capabilities allow users to see capture results at the same instant as the subject is performing a specific task. The Hawk Digital Camera has a 640 x 480 full resolution at up to 200 frames per second. The camera signal goes directly to the tracking computer via an Ethernet connection, and the signal processing is embedded in the camera. The EagleHub consists of multi-port Ethernet switch (100 Mbps) and provides power for the cameras. A single Ethernet Cat 5 Cable is used for all signals and power between the camera and the EagleHub. EVaRT software provides users with a simple and powerful interface. Under a single software environment users can set up, calibrate, capture motion in real-time, capture motion for post processing, edit and save data in several formats. The retro-reflective markers are available in different sizes from 4-25 mm. The limiting factor in which marker works in the capture volume is the distance of the marker from the camera. The Software Development Kit (SDK) helps to connect EVaRT with user developed applications and stream data in real-time through the network.

We have developed and implemented a simulation model for the right hand in PhysX SDK. Each joint of the user contains a marker that is measured by the motion tracking system. From the 3D position of the markers the angles of the finger joints are calculated in the following way:

The spatial position and orientation of the hand can be obtained from the position of three markers (marker 1, 7 and 10, fig. 3): marker 7 is defining the origin of the hand's coordinate system; marker 10 gives the x axis direction and marker 7 (together with marker 10) is used to define the xy plane of the same coordinate system. The origin and three axis of the coordinate system attached to the hand (O_h, x_h, y_h, z_h, fig. 2) can be obtained by:

$$\begin{cases} (x_{Oh}, y_{Oh}, z_{Oh}) = (x_{M7}, y_{M7}, z_{M7}), \\ \bar{x}_h = \overline{M_7 M_{10}}, \\ \bar{z}_h = \overline{M_7 M_{10}} \times \overline{M_7 M_1}, \\ \bar{y}_h = \bar{z}_h \times \bar{x}_h. \end{cases} \tag{1}$$

The relative position of the phalanxes against the hand and each other can be obtained from the markers attached to them. During the grasping process or other movement of the fingers, the position of the points where the fingers are articulated to the hand is not a fixed one in the hand's coordinate system. For accurate tracking of the fingers a marker is required for each one to recognize the proximal phalangeal joint position. Once this joint position is known, then other three markers are required for each finger for computing the rotation of each phalangeal joint. These markers are located on the two interphalangeal joints and on the tip of the fingers. Because is important to keep the number of markers as low as possible and from the reason that the distal interphalangeal (DIP) rotation can be obtained from an approximation of 2/3 of the proximal interphalangeal rotation (Yin et al., 2003), the marker from tip can be left out. So, for tracking the hand and the fingers' positions 18 markers are needed: 3 markers for the spatial position of the hand and 1 for each phalanges (totally 15 for the 5 finger). If the index and the middle finger's proximal phalangeal markers are used also for the hand position's computation (fig. 2), than the markers number can reduced to 16. Furthermore, if only three fingers are considered in the simulation process (thumb, index and the middle finger), than 10 markers are enough.

The three markers attached to each finger are defining the fingers' own coordinate system. For example the middle finger's coordinate system (O_f, x_f, y_f, z_f, fig. 2) origin is located on marker 10. The three markers (marker 8, 9 and 10, fig. 2) are defining the yz plane of the finger; the y axis of the coordinate system is perpendicular to the plane defined by the z axis of the hand's coordinate system and x axis of the finger's coordinate system. The origin and three axis of the coordinate system attached to the finger (O_{f2}, x_{f2}, y_{f2}, z_{f2}, fig. 2) can be computed by:

$$\begin{cases} (x_{Of}, y_{Of}, z_{Of}) = (x_{M10}, y_{M10}, z_{M10}), \\ \qquad \bar{x}_f = \overline{M_8 M_{10}} \times \overline{M_9 M_{10}}, \\ \qquad\qquad \bar{y}_f = \bar{z}_h \times \bar{x}_f, \\ \qquad\qquad \bar{z}_f = \bar{x}_f \times \bar{y}_f. \end{cases} \tag{2}$$

From the measured position of the markers a computer program is constructing the kinematic model of the virtual hand. The hand is linked to the ground with a 6 degree of freedom (general) joint, in which the displacement and rotations are computed from the previously mentioned 3 points (markers 1, 7, 10). In this joint the displacements are corresponding with the position of marker 7. The three rotation are computed by first transforming the coordinate system's axis orientation in direction cosine matrix and then into a rotation sequence: a z axis rotation, y axis rotation and x axis rotation (measured in the global reference frame) for the three rotations.

Each finger is linked to the hand with a spherical joint, although the rotation around the finger's longitudinal axis is insignificant The three rotations in each spherical joint is obtained in the same way as previously presented, but the coordinates of the finger's markers are first transformed into the hand's coordinate system, so the direction cosine matrix of each finger is obtained relative to the hand's coordinate system. The phalanxes are linked to each other (interphalangeal joints) with one

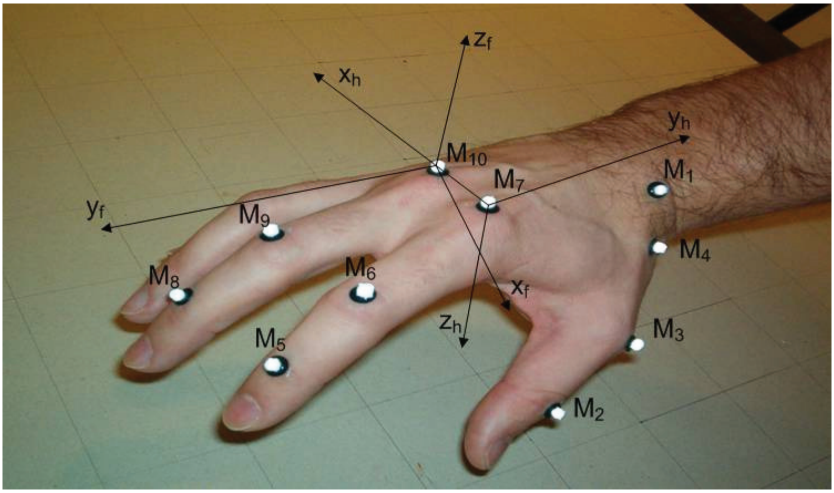


Figure 3: The markers and the real hand

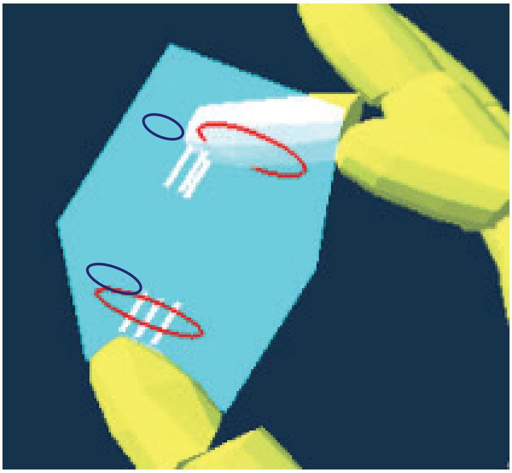


Figure 4: Accuracy of contact area positioning

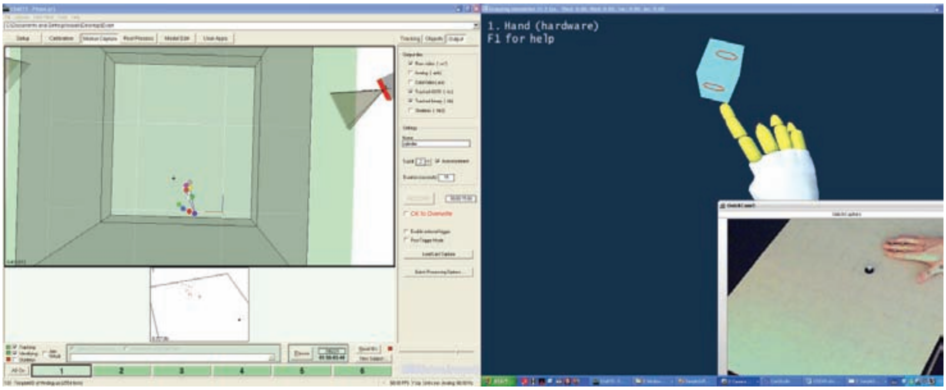
degree of freedom revolute joints, so the proximal interphalangeal rotation angle is obtained by computing the angle between the three markers (for example, in the case of the middle finger this angle is between $M_{10}M_9$ and M_9M_8).

The geometric model of the hand is constructed from convex meshes in order to facilitate real time collision detection supplied by PhysX. PhysX returns the set of pairs of colliding triangles P_k $\{\{t_{1,0};t_{2,0}\}, \{t_{1,1};t_{2,1}\},\ldots \{t_{1,n-1};t_{2,n-1}\}, \{t_{1,n};t_{2,n}\},\}$, the distance between the triangles D{d1; d2;}, and the list of contact forces $F\{f_1, f_2\ldots f_n\}$. For two intersecting convex meshes we define stability of grasping as follows. Let's denote d_{12} the Euclidian distance of triangles t_1 and t_2. The stability of a grasping simulation is defined as the variation of the maximum penetration of shape that is the variation of the value of the maximum Euclidian distance

$$\sigma_{[t_1..t_2]} = V_t(\max_k(d_k(P_k)) \qquad (3)$$

The accuracy of the positioning of fingers is defined as the overlap of the contact patch and the intended contact patch. As shown in Figure 4, the intended contact patch is defined by a red circle $C_i(r_i, \mathbf{p}_i)$ and the actual contact patch, which is best fitting circle, $C_i(r_i, \mathbf{p}_i)$ for the set of contact points $P\{p_1\ldots p_n\}$. We define accuracy as the Euclidian distance of the center of the intended contact patch and the actual contact patch for the time interval $[t_1..t_2]$.

$$A_{[t_1..t_2]} = \left|\mathbf{p_a} - \mathbf{p_i}\right|_{t_1}^{t_2} \qquad (4)$$



1. Hand (hardware)
F1 for help

Figure 5: Setup of stability calibration for resting hand

5 SETUP OF THE EXPERIMENTS

In our experiments 12 users had participated. The group of users consisted mostly of industrial design students with some background knowledge on computers but no or only limited knowledge on motion tracking systems and VR technologies. Only right handed participants have been selected for the experiments since the virtual hand model is also right handed. In the first step of the experiment each user was asked to play with the system for three minutes, in order to get used to the markers and to the control of the virtual hand model. There were no tasks assigned to the users in this stage.

In the first measurement, the users were asked to place their hand on the table and hold it still comfortably next to a stationary marker placed on the table. With this experiment, we measured the accuracy and stability of the motion tracking system as a reference base. The measurements of the resting hand have been compared to the reference base in order to measure the accuracy and stability of the resting hand. Also the position of the virtual hand and the physical hand is compared in order to identify the accuracy and stability of the virtual hand compared to the real hand.

In the second set of experiments, the users were asked to do a two finger pinching on a virtual block. As illustrated by figure 5, the block has been rendered in two ways, first as a semi-transparent object and then as a non transparent block. When the virtual object is rendered with a semi-transparent material, the users are able to see the location of the intended contact points on both sides of the block. In case of a non-transparent block, only one or none of the intended contact points can be seen. We assume that the users are able to position their hand on the block with approximately the same

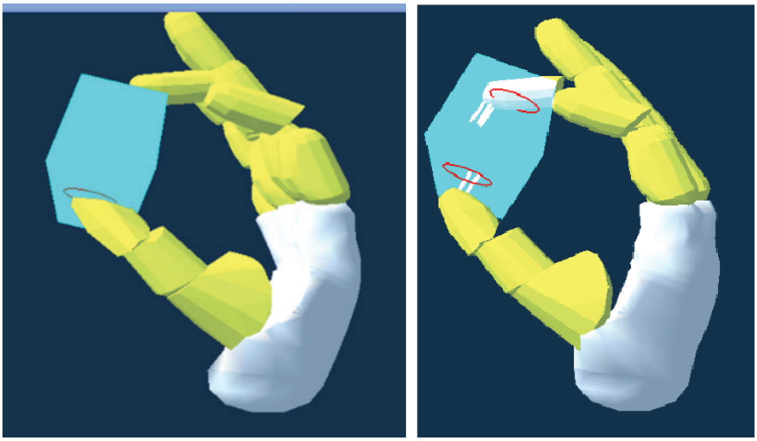


Figure 5: Visible and invisible intended contact area

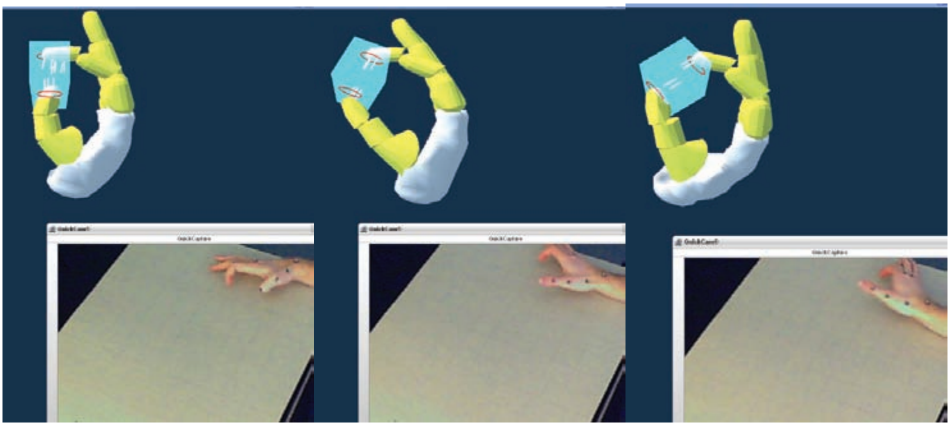


Figure 6 : Experiment setup for changing the orientation of grasping tasks

accuracy in both cases.

In order to investigate the effect of the size of the grasped object on stability and accuracy of grasping, the width of the block was set to 10, 20 and 30mm. With this test we wanted to investigate whether there is a relation between the size of the grasped block and the accuracy and stability of contact. It is our hypothesis that the stability and accuracy of the contact manipulation is better in the middle range, where it is more comfortable to manipulate the block.

In the next step, the orientation of the block has been manipulated in three different positions. By changing this variable the users were forced to grasp the objects from a comfortable and two uncomfortable orientations. In case of the comfortable orientation, the orientation of the users' hand was inline to the orientation of the lower arm. In case of the two uncomfortable positions, the users palm were tilted inward and outward with approximately 30 degrees as it is illustrated on Figure 6.

In the last variable, the response of the grasped block was manipulated. The tests were conducted on static and dynamic blocks. By using static blocks the effect of the finger penetration have been neglected, while in case of dynamic blocks the grasped virtual objects responded to finger penetration. Our assumption was that the contact control of dynamic blocks will be more difficult for the users, than the contact control of static blocks.

6 DATA AND DATA ANALYSIS

In the first test the users were asked to place their hands on a table in such a way that the tip of their index finger touches the virtual object. Figure 7 illustrates an average result of these measurements. We have observed that on average the computed penetration is fluctuating in a range of 0.15-0.2mm around the nominal value. At the same time the measured position of the markers at the distal phalange joint of the index finger fluctuated with an error of 0.05-0.15mm. This means that the implementation of our virtual hand model amplifies the measured errors with discrete jumps. This is due to the fact that the geometry of the hand is represented by a discrete triangular mesh and some of the discrete elements are/are not in the contact with the virtual object depending on the fluctuation of the measurements.

In the second set of experiments, we have observed that the visibility of the intended contact area had influence on the accuracy of positioning but no significant influence on the stability of finger penetration. As it is shown in Figure 8, the user positioned the index finger mostly outside the intended contact area, when the contact was not visible for him/her. Stability of the finger penetration for both cases was in the range of 1-3 mm.

Due to the limitations on the extent of the paper, we are not able to illustrate the results on the effect of the grasping orientation and the size of the grasp object on the stability and accuracy of grasping. In terms of grasping orientation our results showed that both inward and outward tilting of the wrist had negative influence on the stability and accuracy control of the contact points. On average, the stability

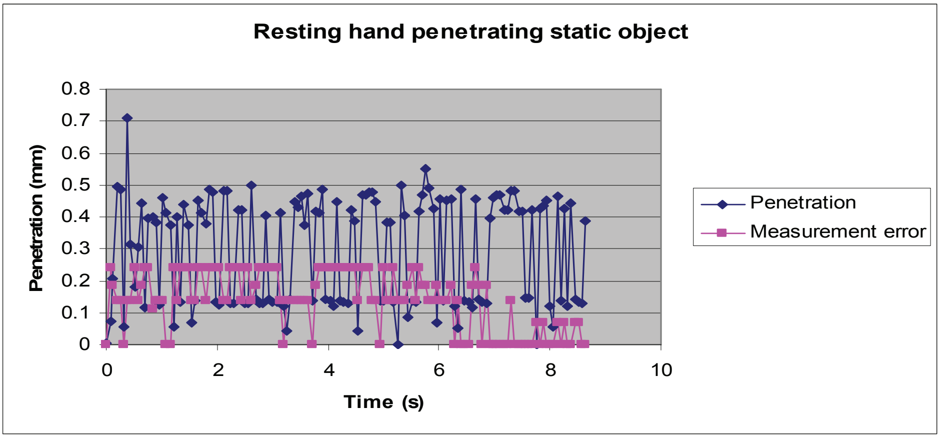


Figure 7: Penetration and measurement error of a resting hand positioned next to a static virtual object

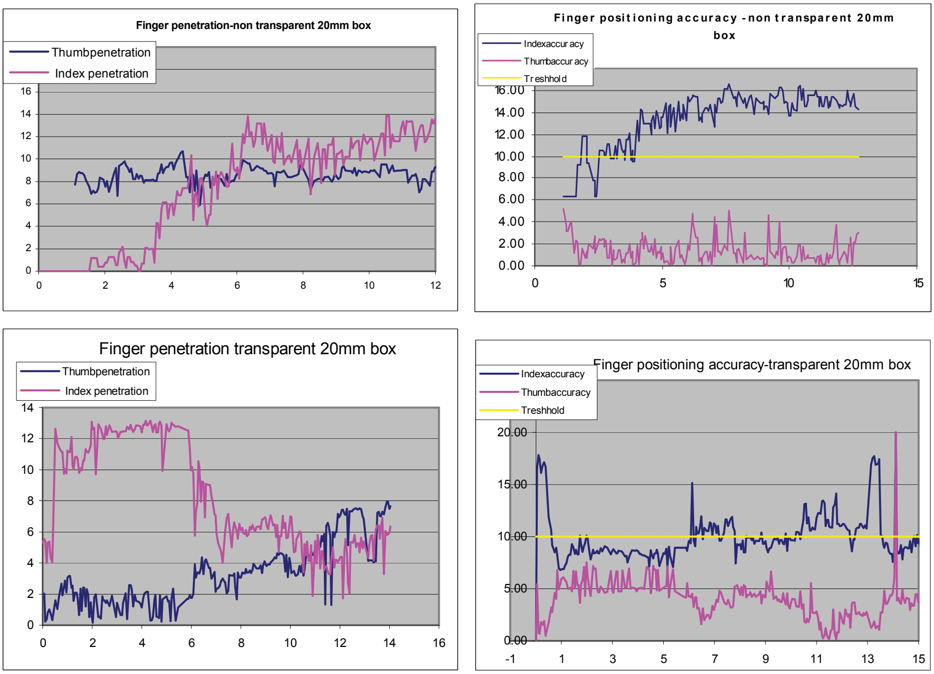


Figure 8: Experimental results of transparent and non-transparent object grasping

fluctuation has increased to a range of 3-4mm, while positioning of the contact point has proved to be extremely difficult for the thumb. On the index finger, this negative effect was not that significant.
As far as the size of the grasping object is concerned, we have not observed significant difference in terms of the stability control of the contact penetration for different dimensions of the grasped object. However, the accuracy control of the contact area was found to be more difficult for object with larger dimensions. In these cases, the center of the actual contact area was outside the intended contact area in several cases.

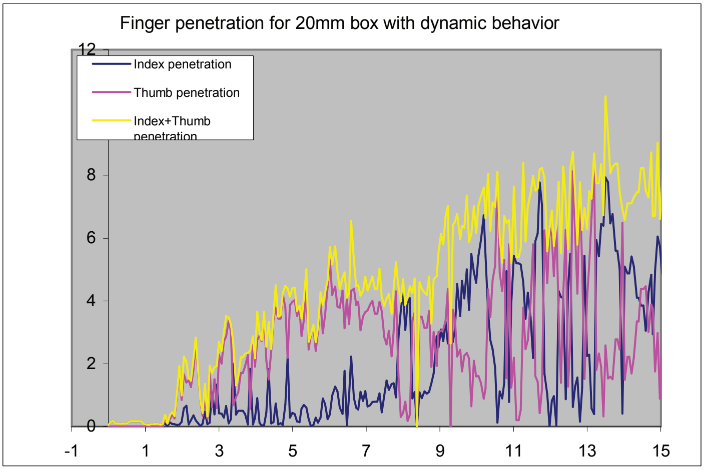


Figure 9: A typical finger penetration for dynamic virtual object

In the final test, when the object behaved dynamically, its position has changed in response to the penetration of the fingers. In a situation, when the object was between the thumb and index finger, a wiggling effect has been observed in all cases. As shown in figure X, the fluctuation of stability were in the range of 2-6mm both for the index finger and for the thumb. However, the sum of the penetration of the thumb and index finger remained in the range of 2-3 mm similar to the range measured for static virtual objects. This means that in fact the users were able to control the virtual hand in the same way independently from the virtual object behavior. However, the penetration of fingers have changed due to the wiggling motion of the grasped object

7 CONCLUSIONS

Developing high quality products requires designers to anticipate even from the design stage the possible interactions between the user and the product. Grasping is one of the most complex process during human-product interaction. In this context realistic and accurate simulation of user grasping virtual products has a considerable potential to improve the quality of the design and ultimately the product quality. During grasping the user receives a considerable amount of fused information from the human multi-sensory system. To achieve accurate grasping simulation requires knowledge on the human sensory feedback and how each individual sensorial channel influences the grasping precision and stability. The research presented in this paper investigated the influence of the most important human sensory channel on the accuracy and stability of grasping: visual feedback. For this purpose a set of experiments has been conceived and conducted allowing us the draw important conclusions that could be summarized as follows:

We found that the optical measurements contains 0.05-0.15 measurements errors in our calibration setup, which is amplified to a range of 0.15-0.2 mm due to the discrete representation of the virtual hand. We believe that this amplification can be reduced by refining the discrete representation of the triangular mesh of the virtual hand. Secondly, we found that the visibility of the intended contact area has a positive influence on the accuracy of positioning the fingers, however there is no influence on the stability of controlling the penetration of fingers. Our experiments showed that the orientation of grasping position influences both the stability and the accuracy of contact control. Especially, the control of the thumb with tilted wrist was difficult for the participants of our experiments. We found no significant effect of the size of the grasped blocks neither on stability nor on the accuracy of contact control.

In the current setup the users were asked to manipulate the position and posture of a virtual hand and interpret the visual feedback provided on the interaction between the virtual hand and the virtual object. In the future, we would like to use a holographic display for visualizing the virtual object and calibrate the scene in a way that the real hand of the user and the virtual hand completely coincide in the 3D space. This would enable the user to directly manipulate the virtual objects with his own hand. From this new setup we expect that the accuracy and stability control of the interaction will significantly improve.

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