Methodology for Controlling Contact Forces in Interactive Grasping Simulation

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Abstract— **The paper proposes a new methodology to interactively simulate grasping of virtual product prototypes with the goal to evaluate the contact forces between the grasping hand and product as well as the load on the human arm. Interaction between product concepts and the users happens in a virtual environment, in which the user controls a virtual hand interactively. The contact between the virtual hand and the grasped product is simulated and visual feedback is provided to the user. Controlling the virtual hand interactively in real time holds many challenges. One of the challenges is mapping the motion of the user to contact forces, which then results in stable grasping of objects. In this paper we present a new methodology to convert and map the measured position of the real hand into contact forces so that the contact between the virtual hand and the object remains stable. Our approach applies a multi-objective optimization that takes into account the posture and anthropometric properties of grasping hand, as well as the penetration of the hand in the grasped virtual object in order to find the optimal arrangement of contact forces. The paper reports on the principle of our grasping control methodology as well as presents some test cases to show the advantages and disadvantages of the proposed approach.**

Index Terms— **Grasping force control, multi-objective optimization, kinematic hand model, virtual fingers**

I. INTRODUCTION

User evaluation of product concepts for haptic interaction plays an important role in the design of handheld devices, bottles of douche gels and shampoos, in which the phenomenon of grasping needs to be evaluated. It provides valuable information for the designers from ergonomics, user experience, and product behavior aspects. Though there are several methods available to conduct user evaluation, user studies, and/or use context exploration of handheld devices, most of them requires the existence of a real product or a physical prototype. User evaluation of products in virtual environments in the form of a human-in-the-loop assessment based on realistic computer simulation is still in its infancy. The existing approaches are mostly based on non-interactive techniques, in which a virtual avatar is controlled by prescribed motion or by predefined forces. On the other hand, some progress , have already been achieved with human-in-the-loop type of product

interaction and real time simulation of grasping based on measuring contact forces on the hand of the user when interacts the physical prototypes, and then the measured forces are applied in different virtual hand-virtual prototype interaction experiments [14，24]. In the case of a direct interaction with virtual prototypes, however, the above mentioned methods cannot be taken into account because it is impossible to establish physical contact between a physical object (i.e. the hand of the user) and a 3D virtual image (i.e. the virtual product). To make the direct interaction with virtual prototypes possible, control mechanisms should be developed, which enable the user to change the magnitude and location of contact forces, and to easily change grasping postures. One possible approach to control the grasping forces is to create a relationship between the penetration of the hand into the virtual object and the magnitude of grasping forces. This approach, however, has to take into account (i) that the user is not able to position his hands relative the grasped virtual object in a stable way, (ii) measurement errors of devices tracking the position of the user's hands and (iii) the distortion of the displayed 3D image which can negatively influence perception of virtual object. To achieve proper control of contact forces and to simulate the interaction with handheld products accurately these errors need to be compensated for.

There are two challenges in the case of performing interaction with virtual objects. The first challenge is to realize real time simulation of interaction and the second is to facilitate natural and realistic control of contact forces in grasping of the virtual product. A typical human-in-the-loop grasping simulation consists of the following steps: (a) capture and processing of the hand motion data, (b) measurement or computation of the grasping/contact forces, (c) simulation of interaction of a virtual hand with the grasped object, and (d) providing visual, tactile and haptic feedback.

Our implementation of grasping simulation captures hand motion data by optical tracking, which measures the position of various markers placed on the user's hand. The markers are tracked with the speed of 200 fps and their measured 3D positions are used to determine the posture of a virtual hand and its position in the 3D virtual space. In this paper we propose a new methodology, which measures the motion of the human hand, computes the intended contact forces based on the penetration of the hand into the virtual object, simulates the behavior of the virtual object, and provides visual feedback to the user. The proposed methodology takes into account the anatomy of the human hand at determining the grasping forces. In addition, it makes possible to control the grasping forces

based on the penetration of the human hand into the virtual product model and the posture of grasping. The use of anthropometrical data in the grasping control enabled us to achieve real time grasping simulation with reasonable accuracy. In this paper we report on the principle of controlling grasping forces that operates with mapping the penetration of the virtual hand into the grasped object onto grasping forces. This principle has been validated in various user studies.

II.   STATE OF THE ART

In various animation and simulation tasks, forward kinematics or inverse kinematics are used to reconstruct the motion of the hand based on measured data. When inverse kinematics is applied to determine the motion of the human hand, positions and angles of the joints should be computed based on the measured position of the finger tips and a set of constraints. However, this problem is inherently underdetermined in most cases. For example, for given positions of the hands, there are many possible hand poses that satisfy the constraints [10]. To reduce the number of possible solutions physiological constraints can be considered for the hand [23]. Based on Landsmeer's empirical studies of the physiology of the human hand Rijpkema incorporated the relationship between the joint angles of the fingers and the activation of the tendons into his human hand model [16]. In order to improve the realism hand motion calculated based on inverse kinematics, compliant joints have been used for capturing emotion or style of motion [20], for synthesizing motion [22], [26] and for reacting to impacts [31]. However, the compliance parameters of these solutions are either manually defined, or approximated through complex optimizations that must take into account the estimated contact forces. Kry et al. proposed a solution that can provide compliance estimates from captured data [14]. They modeled the finger as a kinematic chain of three revolute joints and described the joint angles as a vector. The compliance was represented as a collection of torsional springs that, when displaced from a reference configuration, produced joint torques by a relation.

In the case of forward dynamics, the position and angle of the joints are computed based on the torques and forces applied to the joints. For instance, a kinematic model for flexion and extension of the fingers has been developed by Lee and Kroemer [17]. Their model is based on the assumption that the moment arms of the tendons at the joints are constant. Considering external forces affecting the joints, they compute the forces in the tendons for the given joint configuration. Albrecht et al. developed a system based on a reference hand model, which is animated by taking into consideration of the muscle contraction values [1]. They introduced a hybrid muscle model that comprises pseudo-muscles and the geometric muscles. While pseudo-muscles control the rotation of bones based on anatomical data and mechanical laws, the deformation of the geometric muscles causes realistic bulging of the skin tissue. As a result, the created animations automatically exhibit anatomically and physically correct behavior. However, their model does not include movements of the bones due to tendon movements, and detection of collisions among the parts of the hand.

Real time simulation of deformation of grasping hands due to has been implemented based on a particle systems model developed by Shieh et al. [27]. They applied a unified mass-spring representation to the human hand and the grasped object. However, their current simulation system suffers from some shortcomings. This current simulation model has only limited response surfaces according to the movement of the virtual hand. Although a deformable model based on physical rules is simulated in their system, non-linear behavior of human tissue, stick slip effect of grasping contact and other advanced phenomena is not considered due to the low resolution of the hand model used for the sake of real-time ability.

Measurement of the grasping forces can be important in grasping simulator development in order to validate the simulated results. The maximal forces exerted by the fingers were measured using strain gauge transducers [7]. The developed model showed that, for simple tasks, the finger strength could be also predicted from measured contact forces. A finger device is presented in [15] to accurately assess the fingertip forces and torques on three fingers.

An automatic ergonomic assessment and ease of the finger motions in operating the user interface is presented in [8]. A digital hand model (called "Dhaiba-Hand") is created based on kinematic analysis of motion captured data and MRI scans. The minimum variance model was used in [28] for evaluating grasping motions and postures with a complete model of the hand and the arm.

The role of visual cues is very important in grasping simulation. Cuijpers et al. have investigated the role of haptic feedback when grasping (virtual) cylinders with an elliptical circumference [4]. They showed that both visual and haptic information are important for planning, reaching and grasping. Mason has assessed the role of graphical representation of the hand in reaching movements to acquire an object in virtual reality environment [18].

The interaction model of the multi-fingered hand is mapping the fingertip forces into a resultant wrench on the object with regard to the center of mass. A stable grasping maneuver is the movement of the fingers to form a grasping posture and to completely restrain an object against any disturbance wrench. In case of robotic hands a well-known grasp planning system is "GraspIt!" [19], which can perform grasping posture evaluation (force-closure and grasp quality).

Each of the investigated work proposed some sort of control mechanism that works based on the measured data of contact forces. However, when direct interaction of the (virtual) hand of the user with a virtual object is required, there are no contact forces to be measured. Our approach addresses this problem and proposes a possible solution, which converts the penetration of the hand to contact forces.

III.   STABILITY OF GRASPING

3.1. Conditions of stable grasping

Fearing defined the following three conditions of stable grasp in terms of resistance to slipping [9]. The grasped object must be in equilibrium so that the sum of all forces and torques acting

on the object is zero:

$$\sum \mathbf{F}_i = 0 \qquad (1)$$

$$\sum \mathbf{r_i} \times \mathbf{F_i} = 0 \qquad (2)$$

In Equation (1) and (2), $\mathbf{F}_i$ are the vectors of forces acting on the grasped object, and $\mathbf{r}_i$ is the vectors of distances from a given point on the object to the point of action of the force. The direction of the contact forces arising on the hand should be within the friction cone, so that there is no slip at the fingers. This condition is expressed by Equation 3:

$$\mu \cdot \mathbf{F}_n > \mathbf{F}_s \qquad (3)$$

where, is the friction coefficient representing the relationship between the normal force $\mathbf{F}_n$ and the friction force $\mathbf{F}_s$. The friction coefficient is influenced by the properties of surface of the grasped object (e.g. material properties, surface finish), conditions of grasping (e.g. temperature, humidity), as well as by the properties of the skin (e.g. sweating, wear and abrasion of the skin). Thus, the friction coefficient for grasping, should be described by non linear models.

In an interactive grasping simulation process the user of the system must be able to control the contact forces on the fingertip in an intuitive and interactive manner in order to achieve realistic scenario of grasping. Depending on the applied hand model (i.e. kinematic, dynamic, or hybrid), the system should be able to provide appropriate means to control the position of the hand, and the forces exerted by the hand. Our previous study compared different mechanisms to control the stability of grasping as well as the accuracy of positioning fingers on the grasped object [24] for kinematic, dynamic and hybrid hand models. In all cases, the relation between the contact forces and the joint torques are of interest in order to evaluate the stability of grasping. The relation between the contact force and the joint torque for a kinematic and for a dynamic hand model, respectively, we adopt the model of Salisbury [25]: $\tau = \mathbf{J}^T \mathbf{F}$ and $\mathbf{F} = \cdot \mathbf{J} \cdot \tau$, where is the torques and forces to be applied at the joints, J is the Jacobian matrix mapping the joint space (joint angles) to the Cartesian space (position and orientation of the contact points), and F are the generalized forces consisting of the normal forces, friction forces and soft finger moment at the contact points.

3.2. Controlling the magnitude of grasping forces

Although much advancement has been achieved in the development of tactile and haptics technologies for the last two decades, the application of tactile/haptics feedback to virtual grasping tasks is still limited. Haptic technologies working with mechanical principles (such as breaks, wires, pneumatic pistons) are limited in their usability for grasping simulation. Even the most advanced haptic gloves are limited in creating accurate contact on the proximal, metacarpal joints and on the palm, which limits their application to precision grasping. Power grasping tasks require proper haptic feedback not only on the

fingertips, but also on the palm as well as on the proximal and metacarpal phalanges. Other types of haptic technologies work with a force field effect but they are typically facing occlusion problems. The generated force field can be obstructed by the hand itself or by other physical objects in the modelling space. In addition to these limitations, haptic devices have to cope with errors of measurements of the hand positions and errors coming from shaky hands. It is rather challenging for the users to position the hand around a virtual object and keep it stable. For this reason, control mechanisms are required, which provides the user an intuitive means to control the grasping (or contact) forces in the full range of anthropometric possibilities and able to compensate unintended movements of the hand and measurement errors of the tracking devices.

As discussed in section 3.1, stable grasping requires that the sum of contact forces and moments acting on the grasped object should be zero. In grasping virtual objects, it is practically impossible to place the hand around the virtual object in such a way that the contact and penetration of the hand in the opposite sides of the virtual object are the same. If the penetration is used as input to compute the contact forces, the virtual object always oscillates between the opposition spaces, since the computational simulation of grasping is done in discrete time steps and the object cannot some to a rest in the hand. It is typical that the hand penetrates on one side of the object more than on the other side, which repulses the object and forces it to move towards the other opposition space. In the following time step, the penetration will be larger on the other side of the opposition space depending on the rate of sampling, and it pushes the object towards its original position. We have experienced that even a small amount of oscillation largely influences not only the stability of grasping but also the increases probability of slipping. These issues can be addressed by overriding the penetration or the magnitude of contact forces and thereby reducing the oscillating motion of grasped object.

IV. METHODOLOGY FOR GRASPING CONTROL

To address the above problems, we propose a new force control methodology in simulating grasping. Fig. 1 shows the reasoning model of our approach. When contact is detected between the virtual hand and the grasped object, the simulation uses our grasping force control methodology, which specifies the intended contact forces between the object and the hand as follows. As the first step an algorithm sorts the contact points and penetrations into six clusters one for each finger and one for the palm. Each phalange of the hand contains one cluster of contact points, which may belong to a single or to multiple contact patches.

In order to determine the grasping posture the distribution of contact points on the hand is taken into account. The evaluation procedure is based on seven rules that are mapped onto the taxonomy. Section 4.2 presents the rules for defining the grasping postures. Based on the grasping posture and the distribution of the contact points, virtual fingers are defined with the goal to ease the determination of the stability of grasping. For each virtual finger the contact forces are calculated based on the penetrations of the fingers, thumb, and
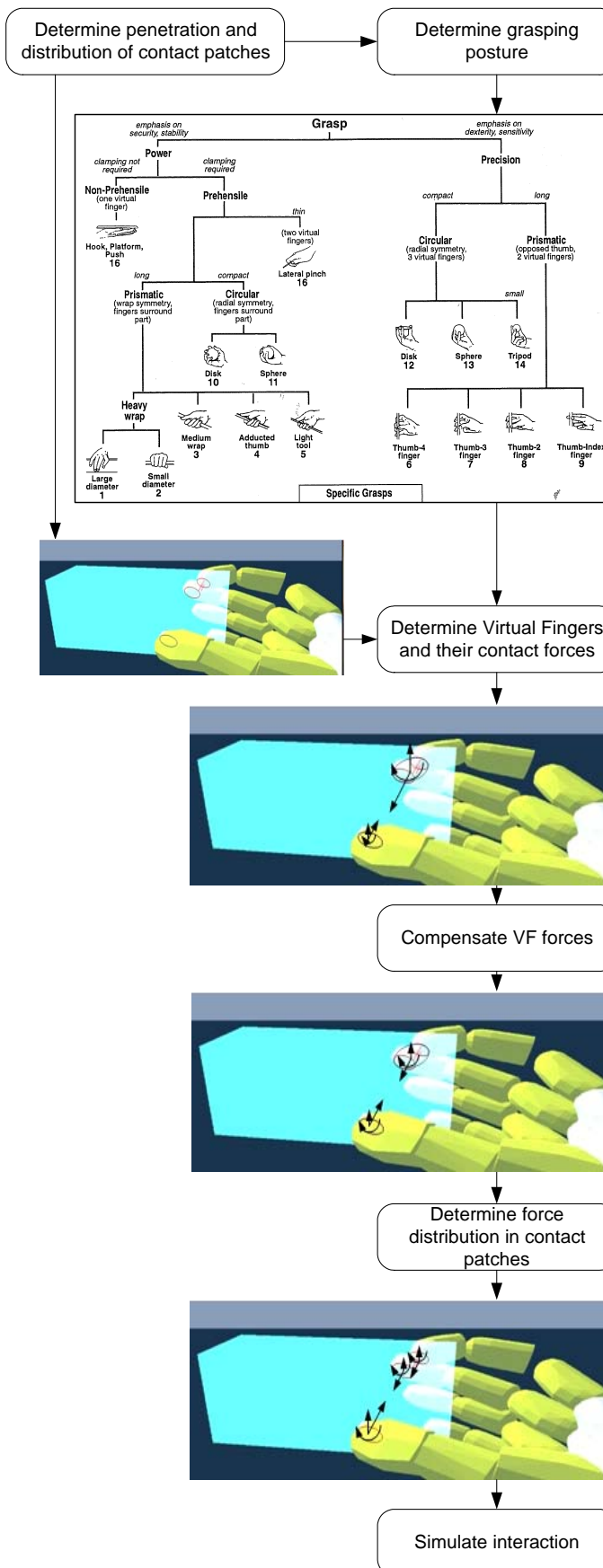
Fig. 1. The framework of grasping force control

the palm into the grasped objects. The contact forces are then

compensated based on multi-objective optimization method, in order to keep the grasped object in a stable position in the hand. Then the adjusted contact forces of the virtual fingers are redistributed on the initial contact patches and the simulation is executed with the compensated input.

4.1. Classification of grasping tasks

The literature presents many different types of taxonomies for classifying grasping tasks in manipulative interaction. We have adopted the most comprehensive taxonomy of grasping from Cutkosky [5], which distinguishes 16 different prehensile and power grasping postures. We have defined a rule-based method, which takes into account the distribution of contact points on the hand. Table 1 shows the mapping of our seven rules onto the particular grasping postures. Existence of contact points on the fingertips, thumb, palm, and multiple contacts on a single finger, as well as the orientation of a contact for multiple fingers enables us to determine the grasping posture with high accuracy. In the first branching point of the taxonomy, power and precision grasps are distinguished, which can be recognized by checking if there are contact points on the palm (RULE 1). In the group of power grasps, nonprehensile grasps are defined as single opposition spaces expressed as hook, platform and push grasping tasks.

Prehensile grasps are further classified as prismatic and circular types of grasping. We can distinguish prismatic and circular grasp by testing if the orientation of the contact normal forces on different fingers are in an angle that is greater than a given value (RULE 2). This condition is valid for both precision and power grasping. RULE 3, which is defined as having an opposition space on the same finger, has been introduced to separate power grasping of small objects from large objects. RULE 4 is used to distinguish compact disk and sphere grip by investigating if all parts of the hand has a contact point or not. The role of the thumb in grasping is taken into account in RULE 5, which investigates if the thumb is creating part of the same opposition space as the fingers or it defines a separate opposition space. RULE 6 simply expresses if the contact patches are located on the thumb and the index finger only. Finally, RULE 7 enumerates the number of fingers in contact.

The advantage of this method is its expandability both in terms of the taxonomy of grasping and in terms of the rules. In addition, the implementation of the rules is rather simple and can be connected to any contact simulation approach. The only condition is that the hand model should represent the phalanges and the palm as separate bodies, which facilitates deriving the list of contact point separately for each part of the hand.

4.2. Defining virtual fingers

As discussed above, penetration of the hand has to be transformed to contact forces in such manner that the contact forces are distributed among the contact patches in a realistic way and errors from placing the hand around the objects are eliminated. To achieve this, we have defined a mapping method that takes into account the anthropometric grasping force data and the grasping posture in the computation of the grasping force distribution over the contact patches. A contact patch on a virtual object, C_o, is defined as a set of connected triangles $C_o = \{t_1, \ldots, t_n\}$, so that for $\forall t_i$, $t_i \in C_o$, $\exists t_k$, $t_k \in C_h$, for which it is true

TABLE 1: VALUES OF RULE BASED POSTURE RECOGNITION METHOD

	Finger Tip Contact	Opposing Forces On Fingers	Opposing Force On One Finger	Sphere Contact	Thumb Opposition	Only Index And Thumb	number of fingers in contact
LargeHeavyWrap=1,				Y	Y		5
SmallHeavyWrap=2,			Y	Y/N			5
MediumWrap=3,				Y/N	Y/N		5
AdductedThumb=4,			Y	Y			5
LightTool=5,			Y	Y			5
Thumb4Fingers=6,	Y				Y		5
Thumb3Fingers=7,	Y				Y		4
Thumb2Fingers=8,	Y				Y		3
ThumbIndexFinger=9,	Y				Y	Y	2
CompactGripDisk=10,		Y		N	Y		5
CompactGripSphere=11,		Y		Y	Y		5
DiskPinch=12,	Y	Y					5
SpherePinch=13,	Y	Y					5
Tripod=14,	Y	Y					3
LateralPinch=15						Y	2
Hookplatform=16		N	N	N	N	N	5

that t_i and t_k are intersecting, where $C_h=\{t_1, …, t_m\}$ is a contact patch on the hand model. Intersection of a pair of triangles t_1 and t_2 is defined as a pair of 3D points $I_{t1t2}=\{\mathbf{p}_{t1}, \mathbf{p}_{t2}\}$ representing the distance of the penetrating edges in the faces of triangles. To determine the list of colliding triangles we are using the collision detection algorithm implemented in the PhysX engine. Representative penetration of two contact patches C_o and C_h is defined as:

$$P_C = \sum_{j=1}^{N} | \mathbf{p}_{t1} \text{-} \mathbf{p}_{t2} |, \qquad (4)$$

where N is the number of intersecting pair of triangles between contact patches C_o and C_h.

The geometry of the virtual hand is defined as a set of rigid bodies represented by as a triangulated model. Taking into account its anatomy, the hand is decomposed into 15 phalanges and the palm. As a result, our virtual hand consists of 16 rigid bodies, denoted by $B_1..B_{16}$. Each rigid body can have a set of contact patches $C_B=\{C_{h1}, ..., C_{hN}\}$, which can transfer contact forces and moments to the grasped object. The relation between the penetration and the normal force, friction force and friction moment of a contact patch is given as follows:

$$\mathbf{F}_N=f(P_C) \qquad (5)$$

$$\mathbf{F}_F< \; \mathbf{F}_N \qquad (6)$$

$$\mathbf{M}_F=g(F_F, e(C_{hi})) \qquad (7)$$

where $f(P_C)$ is a mapping function that establishes a relation between the penetration and normal force on the patch, $\mathbf{F}_F$ is the resultant friction force vector, and $\mathbf{M}_F$ is the resultant friction moment acting on a patch. This friction moment is limited by the size of the contact patch and the magnitude of resultant friction force.

By using the concept of virtual fingers we can investigate the stability of grasping for given postures. Arbib et al. suggested that each of the functions of supporting grasping can be substituted by virtual fingers as a method of applying forces and moments [2]. He defined a virtual finger as an abstract representation and a functional unit of a collection of individual fingers and hand surfaces applying an oppositional force. Real fingers are grouped together into a virtual finger to apply a force or torque opposing other virtual fingers.

A state variable model for virtual fingers was defined by Iberal et al. [13] by five variables: (a) the length of the virtual finger (VF) (from the centre of the contact surface patch to the joint where it connects to the palm), (b) orientation of VF relative to the palm, (c) the width of VF (the number of real fingers mapped into the VF), (d) orientation of the applied force, (e) amount of force available from the VF (mean, maximum and minimum), and (f) amount of sensory information available at grasping surface patch. Our approach extends this modelling of virtual finger with a friction torque. This extension is necessary to be able to address grasping situations presented in Fig. 2.As illustrated in this figure, the contact patches of the index finger and the thumb are exerting not only a friction force but also a friction moment in order to compensate for the rotation due to gravity.

We defined a virtual finger as VF=$\{F_N; F_S; M_S, p_m, p_a, P\}$, where $F_N=\{min, actual, penetration, max\}$ is the normal force that can be exerted by the virtual finger, F_S is a friction function having values in the range of friction force, $F_S=\{0…\mu F_N\}$, M_S is the sum of moments that can be exerted by the configuration of contact patches $M_S=\{min, mean, max\}$, p_p is the resultant point of action of $F_N=\{penetration\}$, p_a is the resultant point of action of $F_N=\{actual\}$, and P is the sum of actual penetration of all contact patches.

4.3. Determining stability of grasping

The resultant normal forces are determined from the penetration and the change in the location and amount of penetration of the hand into the virtual object. We distinguish three cases:

1) *The penetrations increased in all contact patches belonging to a virtual finger.*

2) *The penetrations decreased in all contact patches belonging to a virtual finger.*

3) *The penetrations increased in some contact patches and decreased or remained the same in others.*

The goal with distinguishing these three cases is to separate the intended and unintended grasping actions of the user. Case 1 and Case 2 represents when the user closes or opens his hands, which can be reliably determined as an intended action. Case 3
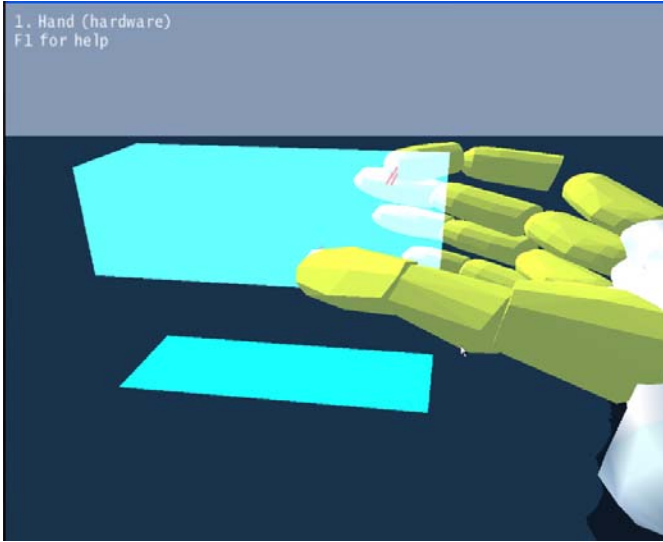

Fig. 2. Pinching situation with friction moments (Color Plate 1)

usually occurs when multiple fingers are represented by one virtual finger and there is a change in the distribution of forces. This change can be either intended or unintended. An example for intended change is when the user changes grasping posture, for instance, changing from 2 finger pinching to 3 fingers pinching. Unintended changes typically occur when the relative position of the hand changes compared to the simulated object. In these cases the user is not changing the arrangement of the fingers, but tries to control the relative position of the hand by applying balancing and extra forces. What we observed was in these situations the arrangement of contact points is frequently changing. In some cases the penetration on the same finger increases for some contact patches, while it decreases for others.

The normal force on virtual fingers is determined based on the change of penetration compared to the penetration in the previous frame. Fig. 3 presents the mapping function between the gradient of penetration and the gradient of normal force. The normal force acting on a virtual finger is given by Equation (8):

$$\mathbf{F}_{VF,n}^{Np} = \mathbf{F}_{VF,n-1}^{Np} + f(\frac{P_{VF,n} - P_{VF,n-1}}{\Delta t}) \qquad (8)$$

, where $\mathbf{F}_{VF,n}^{Np}$ is the normal force in the current frame, $\mathbf{F}_{VF,n}^{Np}$ is the normal force in the previous frame, $P_{VF,n}$ is the penetration in the current frame, $P_{VF,n-1}$ is the penetration in the previous frame, Δt is the elapsed time between frame n and n-1, and f() is the function describing the relationship between finger penetration and the change of normal force. Once the normal forces are determined for the virtual fingers, they need

to be adjusted in order to compensate for the measurement errors and unintended changes in the force magnitude and point of action. A stable configuration of grasping forces is computed by a multi-objective optimization function:

$$\min_x [f_1(x), f_2(x)...f_n(x)]^T$$

where

$$f_1(x) = \min \sum \left| \mathbf{F}_{VF}^{Na} \right| - \left| \mathbf{F}_{VF}^{Np} \right|;$$
$$f_2(x) = \min \sum \left| \mathbf{p}_{VF}^{Na} \right| - \left| \mathbf{p}_{VF}^{Np} \right|; \qquad (9)$$
$$f_3(x) = \max \sum \mu \cdot \mathbf{F}_{Ci}^{Na}$$
$$f_4(x) = \max \sum \mu \cdot \mathbf{F}_{Ci}^{Na} \times \mathbf{r}_{ci}$$
$$x = \{VF_1; VF_2; VF_3\}$$

This multi-objective optimization function expresses by $f_1(x)$ that the magnitude of adjusted normal force of the virtual fingers should approximately be the same as normal force computed from the penetration, $f_2(x)$ that the point of action of the computed normal forces should be as close as possible to the point of action of normal force computed from the penetration, $f_3(x)$ and $f_4(x)$ expresses maximization of the friction forces and friction moments in order to compensate slipping, if necessary. With these, the equality conditions of stable grasping are defined as:

$$\sum \mathbf{F}_{VFi} + \sum \mathbf{F}_{Cj} + \mathbf{F}_G = 0 \qquad (10)$$

$$\sum \mathbf{F}_{VFi} \times \mathbf{r}_{VFi} + \sum \mathbf{M}_{VFSi} + \sum \mathbf{F}_{Cj} \times \mathbf{r}_{VF} = 0 \qquad (11)$$

In Equation (10), $\sum \mathbf{F}_{VFi}$ is the sum of forces acting on the virtual finger, $\sum \mathbf{F}_{Cj}$ is the sum of forces with other objects (e.g. if the object is placed on a table and is in the process of lifting up), and $\mathbf{F}_G$ is the force of gravity. By Equation (11) the balance of moments is expressed around the centre of gravity of the object. The inequality conditions are defined as follows:
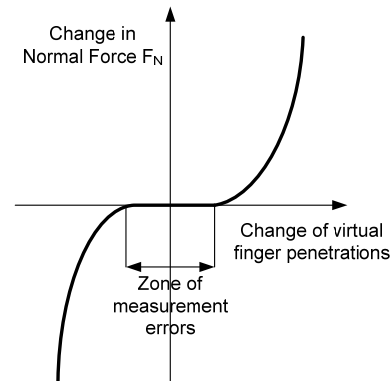

Fig. 3. Assumed relation between the gradient of finger penetration and gradient of normal forces

$$\left|\mathbf{p}_{VF}^{a}\right| - \left|\mathbf{p}_{VF}^{n}\right| < V(C_i) \qquad (12)$$

$$\mathbf{F}_{VF}^{Na} < \mathbf{F}_{VF\,\max}^{N}(P,A) \qquad (13)$$

$$\mathbf{M}_{VF}^{Na} < \left|\mathbf{M}_{VF\,\max}^{NP}\right| - \left|\mu \cdot \mathbf{F}_{VF}^{Na} \times \mathbf{r}_C\right| \qquad (14)$$

Equation (12) states that point of action of the optimized normal forces of virtual fingers should be in the possible range that can be expressed by the actual contact patch configuration. The Equation (13) aims to maintain the magnitude of computed normal forces in a range that corresponds to the values that can be exerted by the particular user (A) in the identified grasping posture (P). The third inequality expresses in an indirect manner that friction forces first compensate linear motion of the grasped object and then they can form pairs of forces in order to create friction moments.

V.   EXPERIMENTS

Research instrument

The experiments were conducted in a hardware setup that contains a motion tracking system, a high-end computer, and a 3D display. Fig. 4 shows the configuration of the hardware tools. For the purpose of hand motion and position measurements, a passive optical tracking system was used, which is able to measure the 3D position of retro-reflective markers placed at specific landmarks of the user's hand. Our six camera based system enables us recognize complex hand postures and motions with an accuracy of 0.1 mm. The position data measured by the tracking device are used as the input for controlling the virtual hand in simulation and for recognizing grasping postures.

We have developed and implemented a virtual model of a right hand in PhysX SDK. The markers placed on the joints of the user's hand were measured by the motion tracking system and their position used to calculate angles of the finger joints of the virtual hand. With a frame-rate of 72 fps, the virtual hand model is able to follow the motion of the user's hands. We have used 10 markers as illustrated on Fig. 5. With these ten markers, the users were able to control the thumb, index and middle finger accurately, and the ring finger and pinky were following the motion of the middle finger. This simplification helped us to improve the reliability of marker identification of the motion tracking approach without significantly influencing the distinguishable grasping postures.

Procedure and results

To test our grasping force control methodology, we have conducted a user experiment, in which 6 people took part. They were asked to position a virtual hand around a virtual object so that the index finger and the thumb were in contact with a virtual object. This is shown in Fig. 6. The participants were asked to grab a virtual object, a rectangular block, with their hand and to lift it up with some 10 cm and hold it in this position for 10 seconds. The computed contact forces were recorded in a logfile during the simulation with the frame rate

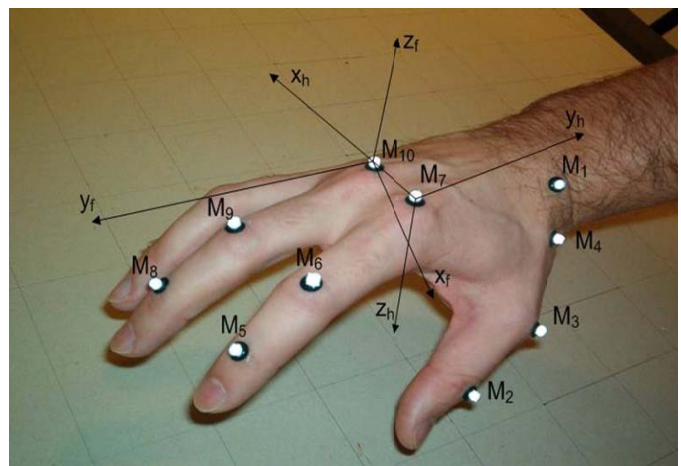
Fig. 4. Hardware setup of the experiments

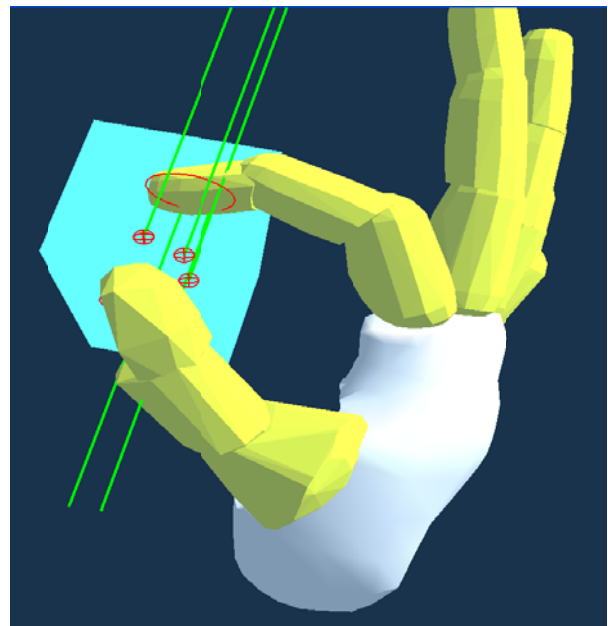Fig. 5. Markers measured on the user's hand

Fig. 6. Positioning and controlling virtual hand with visual feedback of grasping force and contact points (Color Plate 2)

of 72 fps. Fig. 7 shows an example of the contact forces computed for the index finger and the thumb. The diagram on top of Fig. 7 shows a sample data of the normal forces without multi-objective optimization. In this case, the normal force was computed by using Equation (8). The fluctuation of the force magnitude indicated that the grasped object wobbled in the hand of the user, which was the results of fluctuation of penetration and therefore also in fluctuation of the computed normal force. As in the bottom of Fig. 7, application of multi-objective optimization reduced this fluctuation of the normal force from standard deviation of 4N to a standard deviation of 0.3N for the index finger and from 6N to 0.5N for the thumb. Although in this case the magnitude of the measured forces was not equal to each other, the object was in balanced position. We have observed that all users were holding the object in a tilted position, which resulted in a difference in the magnitude of forces on index finger and on the thumb as it is shown in Fig. 5.

Measurement results of all 6 subjects have been analyzed by using descriptive statistics, in order to identify tendencies in the measured data. Fig. 8 shows the results of the six subjects in the form of a box diagram. The mean value of the measured results is represented by small black rectangles, the yellow rectangles show the standard deviation of the measured data, and the blue lines show the full range of the captured data. To give an example, the top diagram of Fig. 8 shows that for subject 1 the average contact forces were 3N and 6.5N, the standard deviation was in the range 1-5N and 3-9N, and range of measured values are in the ranges of 0-12N and 1-15N for the index finger and for the thumb, respectively. The variation of

these values has been significantly reduced by applying the multi objective optimization approach proposed earlier. As it is shown on the bottom diagram of Fig. 8, the standard deviation have been reduced to a range of 4.4-4.6N and 5.1-5.5N, and the total range of measured values to 4.2-4.8N and 4.6-6.2N respectively for the index finger and the thumb of subject 1.

In the experiment the users have been provided with visual feedback only on a 2D display. We expect that the variation in the measured data can be further reduced by applying truly 3D visual feedback as well as providing haptic feedback on the fingertips. Future research aims to investigate the combination of the proposed approach with deformable model of the hand and its effect on the stability of grasping and real time simulation. In addition, further studies will be conducted to validate the methodology for the complete set of grasping postures.
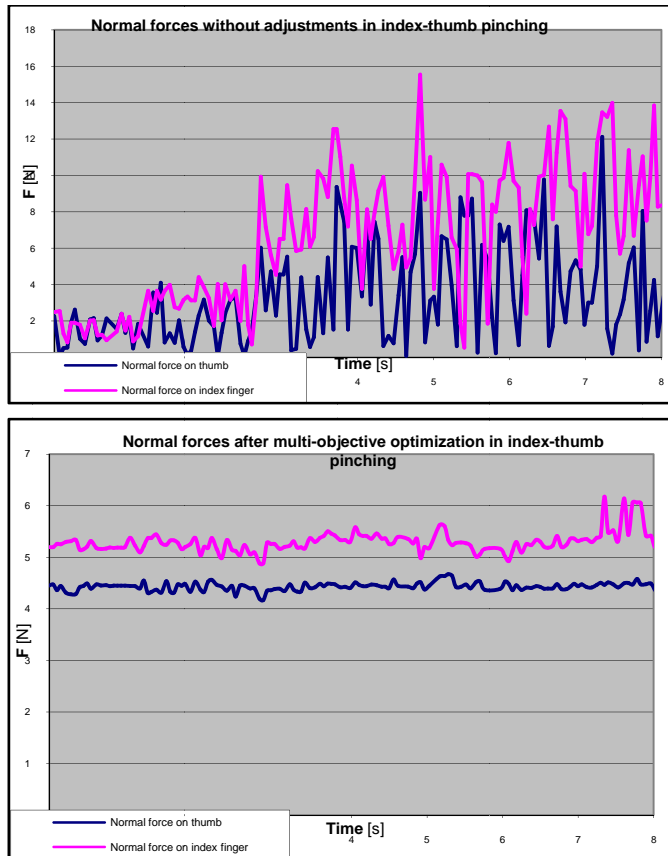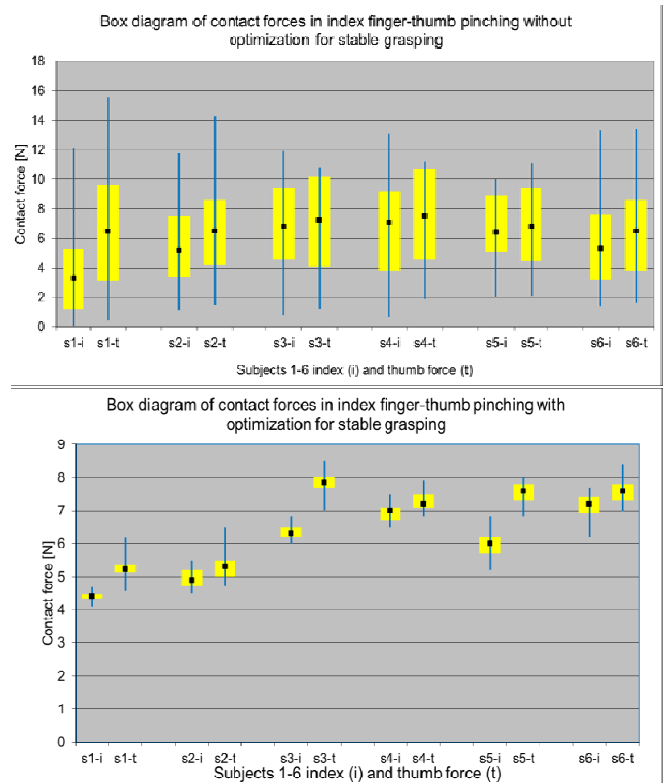

Fig. 8. Box diagrams of contact forces for six subjects

VI. CONCLUSIONS

Realistic and accurate simulation of grasping of virtual products is of importance to evaluate comfort of handheld product during usage. The research presented in this paper resulted in a new methodology for interactively controlling grasping forces in a virtual reality environment. The proposed methodology detects the motion of the hand of the user and determines the intersection of the hand and the grasped object. It converts the penetration of the hand into the virtual object to contact forces. In addition to penetration, our method takes into account the grasping posture and the anthropometric data of the hands of the users. Then the contact forces are applied on the grasped object, and the motion of the object is computed.

Fig. 7. Sample data of normal forces in index-thumb pinching

However, in this setup, the stability of grasping is influenced by the ability of the user to hold his/her hand steady relative to the virtual object and by the measurement errors of the motion tracking device. To compensate for these errors, we have applied the concept of virtual fingers to investigate and improve the results of stability of grasping computation and multi objective optimization approach to adjust the forces and moments according to certain anthropometric rules.

Our concept of grasping computation has been tested in user experiments. The users were asked to lift a virtual object while pinching it with thumb and index finger and hold it in the air for 10 seconds. The results showed that the new methodology helped reducing the wobbling problem of grasping to approximately 10 percent of the original oscillation.

ACKNOWLEDGEMENT

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