Proceedings of the ASME 2009 International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2009
August 30 - September 2, 2009, San Diego, California, USA

DETC2009-86520

COMPARING KINEMATIC AND DYNAMIC HAND MODELS FOR INTERACTIVE GRASPING SIMULATION

Zoltán Rusák
Faculty of Industrial Design Engineering
Delft University of Technology
Landbergstraat 15, 2628CE, Delft
The Netherlands
z.rusak@tudelft.nl

Csaba Antonya
Product Design and Robotics Department
Transilvania University of Brasov
Bdul Eroilor 29, 500036 Braşov
Romania
antonya@unitbv.ro

Imre Horváth
Faculty of Industrial Design Engineering
Delft University of Technology
Landbergstraat 15, 2628CE, Delft
The Netherlands
i.horvath@tudelft.nl

Doru Talaba
Product Design and Robotics Department
Transilvania University of Brasov
Bdul Eroilor 29, 500036 Braşov
Romania
talaba@unitbv.ro

ABSTRACT

This paper compares two approaches to controlling virtual hands in grasping simulation, and it investigates the ability of humans to control with their hands a virtual hand model in manipulative tasks. In our setup, the users are following their interaction in a desktop virtual reality environment, in order to determine the feasibility of user studies for 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, therefore accurate spatial position of the real hand and fingers are needed to be measured in real time. Our simulation program is using the Nvidia PhysX SDK. We have implemented two control mechanisms, which enables the users of the system to manipulate the virtual hand. The first mechanism controls the motion of the virtual hand and grasping forces based on the principles of kinematics and energy transfer by contact simulation. The second mechanism relies on the principles of multibody dynamics, controlling the motion of the hand by PD controllers, and applying joint torques to the hand in order to exert forces on the grasped object. In this paper, we compare how well these principles perform in (a) accurately moving the virtual hand in the simulation space, (b) accurately positioning the fingers on the grasped objects, and (c) controlling the grasping forces on the objects.

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 means to support and position products in their usage environments. Understanding the underlying physical and mental processes in these interactions requires an interdisciplinary research including various theories and principles 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. 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 [1]. From the software side, it needs more accurate contact models that consider changes of contact zone 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 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) minimizes latency caused by computation of the simulation 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. The second parameter is related to the grasping theory of stability. Grasping itself is an intensive 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.

This paper compares various control mechanism on their fitness for controlling (a) the motion of the hand, (b) the accuracy of positioning the fingers on the grasped object, and (c) stability of contact forces during grasping task. To compare kinematically and dynamically controlled hand models, we have done several experiments. This paper reports on the implementation of our control models for virtual hands as well as on the setup and results of our experiments.

APPROACHES TO GRASPING SIMULATION

To reconstruct the motion of the hand based on measured data forward or inverse kinematics is used in animation and simulation. When inverse kinematics of the human hand is simulated or animated, positions and angles of joints are to be determined based on measured position of the finger tips and from a set of constraints. However, in most cases this problem is inherently underdetermined. For example, for given positions of the hands, there are many possible hand poses that satisfy the constraints [2]. To reduce the number of possible solutions physiological constraints of the hand can be used [3]. Based on Landsmeer’s [4] empirical studies of the physiology of the human hand Rijpkema incorporated into his human hand model the relationship between the joint angles of the fingers and the activation of the tendons. In order to improve the realism of inverse kinematics based hand motion, compliant joints have been used in computer animation for capturing emotion or style [5], as part of controllers for synthesizing motion [6], [7], and for reacting to impacts [8]. However, the compliance (or stiffness) parameters of these solutions are either selected by hand, or approximated through complex optimizations that must simultaneously deal with estimated contact forces. Kry et al. proposed a solution that can provide compliance estimates from captured data [9]. They modeled the finger as a kinematic chain of three hinge (revolute) joints with joint angles collected in 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 joints are computed based on 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 [10]. 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 finger strength for the given joint configuration. Albrecht et al. developed a system around a reference hand model, which are animated using muscle contraction values [11]. They introduced a hybrid muscle model that comprises pseudo muscles and geometric muscles. While pseudo muscles control the rotation of bones based on anatomical data and mechanical laws, the deformation of 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 bone movements based on tendon movements, and collision detection among the parts of the hand.

Real time simulation of deformation of hands due to grasping has been realized based on particle systems model by Shieh et al. [12]. They proposed a unified mass-spring representation applied to the human hand and to the grasped object. However, there are some shortcomings to their current simulation system. First, the current simulation model only has limited response surfaces according to the movement of the virtual hand. Although the deformable model in their system is simulating based on physical rules, additional material properties has to be introduced into the deformable model, especially when the behavior of the human hand is considered.

HAND MODELS FOR GRASPING SIMULATION

Conditions of stable grasping

Fearing in [13] defined the following three conditions of stable grasp in terms of resistance to slipping:

1. The grasped object must be in equilibrium so that the sum of all forces and torques acting on the object are zero formulated as follows:

$$\sum \mathbf{F}_i = 0 \tag{1}$$

$$\sum \mathbf{r_i} \times \mathbf{F_i} = 0 \tag{2}$$

In Equation (1) and (2), $\mathbf{F}_i$ are the force vectors acting on the grasped object, and $\mathbf{r}_i$ are the distance vectors from a point on the object to the location of force application.

2. The direction of contact forces of the hand should be within the friction cone, so that there is no slip at the fingers as expressed by Equation 3:

$$\mu \cdot \mathbf{F}_n > \mathbf{F}_s \tag{3}$$

, μ is the coefficient of friction expressing the relationship between the normal force $\mathbf{F}_n$ and the friction force $\mathbf{F}_s$. The coefficient of friction of grasping 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 the properties of the skin (e.g. conditions influencing sweating, wear and abrasion of the skin). Thus, the coefficient of friction for grasping, μ should be expressed by non linear models.

3. In response to any displacement due to an arbitrary applied force, it should be possible to increase the magnitude of grasping force. To present slipping, the magnitude of the grasping force should be increased when the external forces acting the grasped objects are increased.

In an interactive grasping simulation the user of the system must be able to control the contact forces on the finger tip in an intuitive and interactive manner in order to achieve stable grasping. Depending on the representation of the hand model (i.e. kinematic, dynamic, or hybrid), the system should be able to provide appropriate means to control the position of the hand, the forces exerted by the hand. In all cases, the relation between the contact forces and the joint torques are of interest for different reasons. In case of a kinematic hand model, the joint torques are needed to be derived from the applied contact force. In case of a dynamic hand model, the joint torques are directly controlled by the users and applied to the phalanges, which results in a contact force. In case of a hybrid model, the hand is represented by a kinematic model for the phase of approaching the grasped object and by a dynamic model for the phase of grasping. The transition between the phases requires controlled transition between the two models. In order to express 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 [15]: $\tau = \mathbf{J}^T \mathbf{F}$ and $\mathbf{F} = \tau \cdot \mathbf{J}$, where τ is the torques and forces to be applied at the joints, $\mathbf{J}$ is the Jacobian matrix composed of the individual finger Jacobians mapping the joint space (joint angles) to the Cartesian space (position and orientation of the contact points), and $\mathbf{F}$ are the generalized forces at the contact points.

Kinematic hand model

Controlling the motion of hand model

The spatial position and orientation of the hand can be obtained from the position of three markers (marker 1, 7 and 10, Figure. 1): 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) can be obtained by:

$$\begin{cases} (x_{Oh}, y_{Oh}, z_{Oh}) = (x_{M7}, y_{M7}, z_{M7}), \\ \bar{x}_h = \overline{M_7 M_{10}}, \\ \bar{z}_h = \overline{M_7 M_{10}} \times \overline{M_7 M_1}, \\ \bar{y}_h = \bar{z}_h \times \bar{x}_h. \end{cases} \tag{4}$$

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

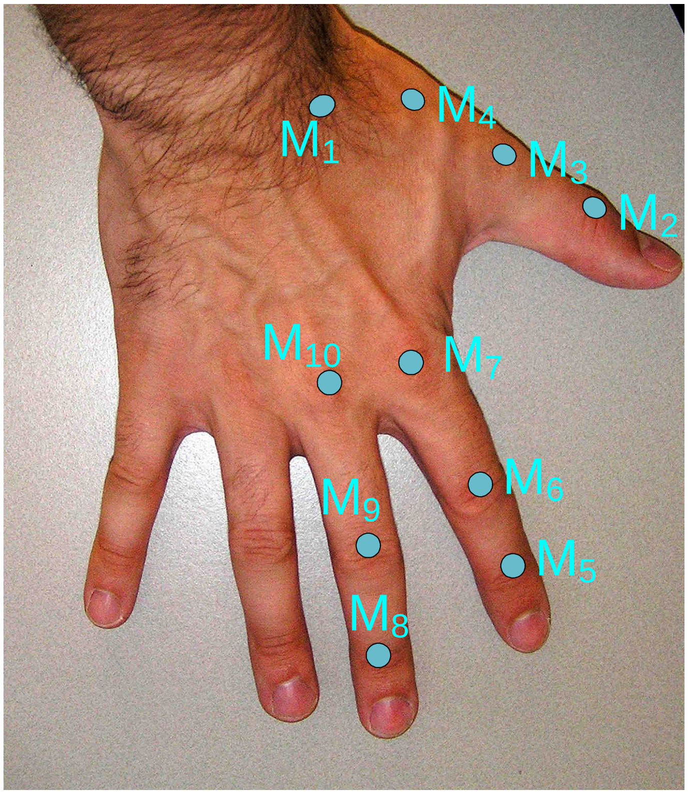

Figure 1: Marker positions on the hand

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 [8], 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, 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) origin is located on marker 10. The three markers (marker 8, 9 and 10, Figure 1) 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}) can be computed by:

$$\begin{cases} (x_{Of}, y_{Of}, z_{Of}) = (x_{M10}, y_{M10}, z_{M10}), \\ \bar{x}_f = \overline{M_8 M_{10}} \times \overline{M_9 M_{10}}, \\ \bar{y}_f = \bar{z}_h \times \bar{x}_f, \\ \bar{z}_f = \bar{x}_f \times \bar{y}_f. \end{cases} \tag{5}$$

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

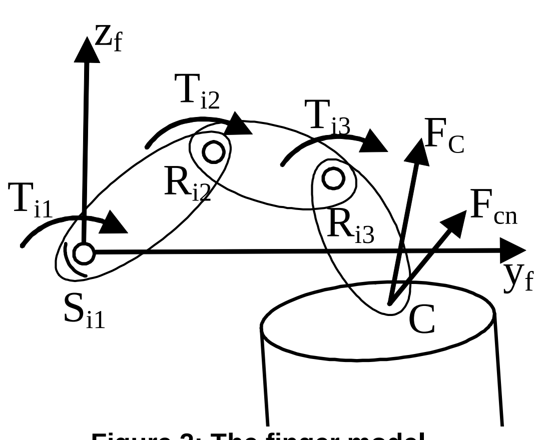

Figure 2: The finger model

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 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).

Dynamic hand model

For the mechanical systems dynamic simulation and control various theories and computer technologies are known and still are the subject of intensive studies. A popular technology for this purpose is usually referred in the technical literature as "multi-body system simulation technology" [14]. In recent years, multi-body systems (MBS) technology evolved in powerful computer analysis and control software, which became widely used in industry, research and development areas and also for real time simulations. The MBS commercially available codes include nowadays a wide range of facilities allowing simulation of sophisticated experiments with virtual prototypes of various systems with rigid and elastic elements.

The motion equations in most usual representation, in which the mechanical system is consider as a collection of interconnected rigid bodies, can be formulated as

$$\begin{cases} [J][\ddot{q}] = [\psi], \\ [m][\ddot{q}] - [J]^T[\lambda] = [Q_{ex}], \end{cases} \tag{6}$$

In (6) the kinematic constraints corresponding to the joints are represented by the algebraic equations of the generalized accelerations $[\ddot{q}]$ and the external forces are included in the generalized forces vector, $[Q_{ex}]$. In (6) J represents the Jacobian matrix, λ the Lagrange multiplier and m the generalized mass.

In the case of contact between the virtual hand and virtual product it is generated a contact force (as previously shown) acting on the finger (F_C). This force can be decomposed to a component (F_{cn}) which is in the yz plane of the finger (Figure 1). This force is the actual grasping force, so in the three phalangeal joints has to supply the amount of torque to generate the necessary grasping force. This can be formulated as:

$$T_{i1} + T_{i2} + T_{i3} = \bar{F}_{cn} \times \overline{CS_i}. \tag{7}$$

where CS_i is the distance between the contact point and center of the proximal phalangeal joint measured in the yz plane of each finger (Figure 2).

Because the joint torques in the fingers are not measured, they has to be computed only from the position data of the fingers. The adopted solution was that the joint torques can be found using a PD controller – so the joint torques will assure the required contact force (4) and the measured position of the real hand and virtual hand will be the same:

$$T_i = P_i(\alpha_{i\_desired} - \alpha_i) + D_i(\dot{\alpha}_{i\_desired} - \dot{\alpha}_i) \tag{8}$$

The torques are not distributed randomly in the interphalangeal joints, we adopted the following distribution of the torques in the three joints of each finger [4]:

$$T_{i1} = 2T_{i2} = 3T_{i3} \tag{9}$$

This dynamic hand model is following the movement of the real hand, it has contact forces applied on it which are always equaled with the joint torques of the fingers. This hand model is valid only if the torque from the wrist is not participating in grasping process (the palm is considered in a fix position).

RESEARCH SETUP

In order to validate and compare our models, we have setup an experiment. In the first test we have compared how well dynamic and kinematic hand models are able to follow the motion of the real hand. We have measured the time lag and the error of the angular position of the virtual hand model compared to the angular position of the measured hand. We defined time lag as the time that is needed for the motion control of virtual hand model to set the angular position of a joint to the measured data with a given error. The error of the angular position is defined as the difference of desired joint angle (i.e. computed angle from measured hand landmarks) and current joint angle of the virtual hand model. We have measured the fidelity of control of motion for two setups. In the first setup, the hand was not moving, only the angles of the fingers were changed. In the second setup, the hand of the user was moving with an average speed to pick up an object on the table. In both setups the palm and the middle finger of the virtual hand was controlled kinematically, while the ring finger was controlled dynamically. The control mechanism of both fingers used the same measured data (i.e. landmark position of the middle finger) to compute the desired angle of joints. Computed angles of the measured middle finger were used to control the middle finger dynamically, and the ring finger kinematically.

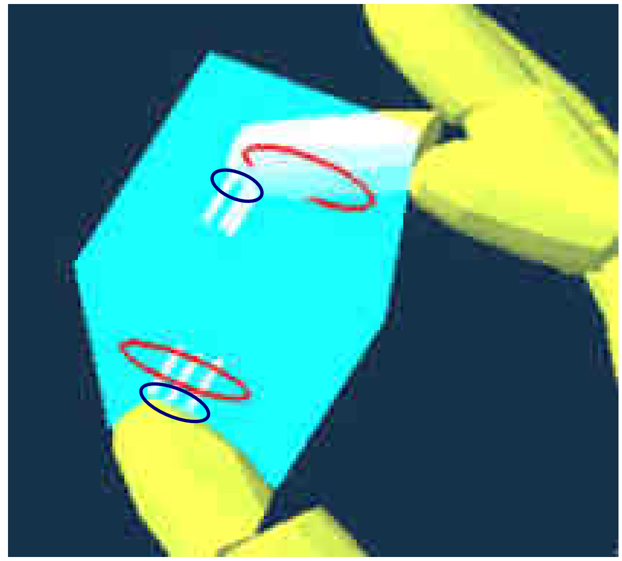

Figure 3: Accuracy of contact area positioning

This way we made sure that the control mechanisms for kinematic and dynamic finger motion control were compared under the same conditions and circumstances.

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

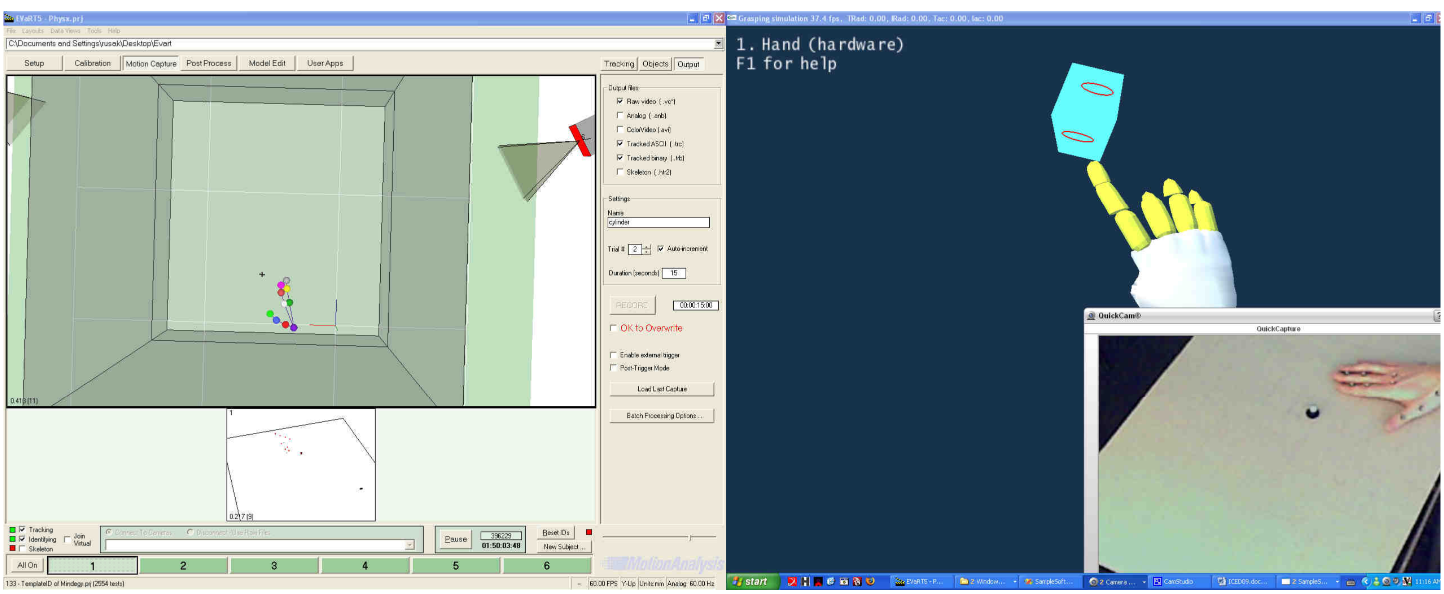

Figure 4: Experiment setup: motion tracking feedback (left), virtual scene (right), and physical environment (bottom-right)

$$\sigma_{[t_1..t_2]} = V_t(\max_k(d_k(P_k))) \quad (10)$$

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, $C_a(r_a, \mathbf{p}_a)$ 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 $[t_1..t_2]$.

$$A_{[t_1..t_2]} = \left|\mathbf{p_a} - \mathbf{p_i}\right|_{t_1}^{t_2} \quad (9)$$

RESULTS OF HAND MODEL COMPARISON

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.

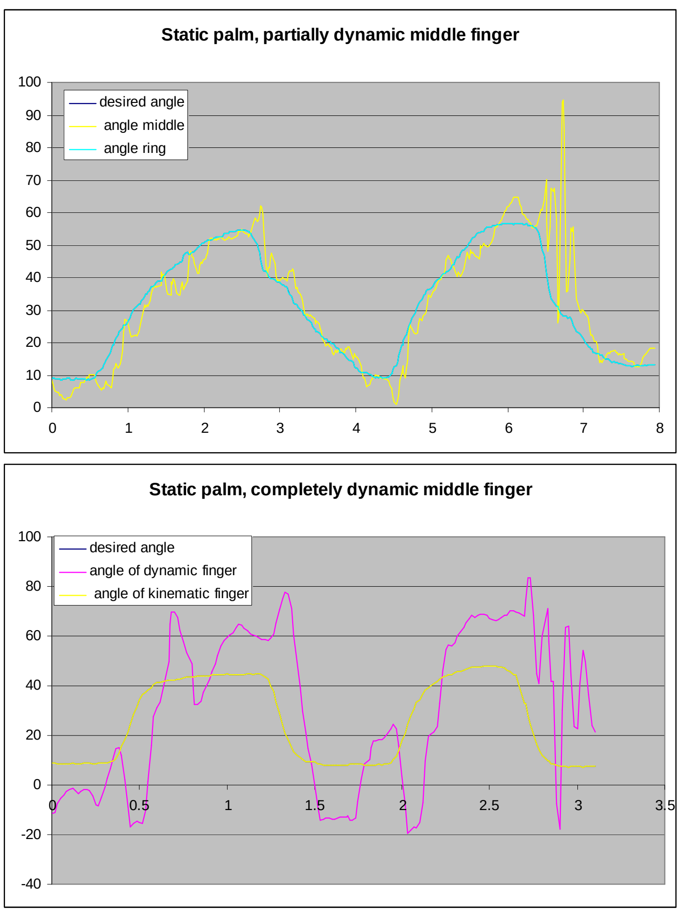

Figure 5: Motion following with static palm

Control of hand motion for approaching objects

Figure 5 and 6 shows the results of the motion simulation tests. This data represents only the simulation lag, we did not take into account the lag that is coming from the measurements, since this depends on the motion capture system used to measure the position of the hand of the user. The frame rate of the simulation was 60fps in all measurements. The desired angle and the angle of the kinematically represented ring finger are in all cases coincide. Therefore only the graph of the angle of middle finger is illustrated in all figures.

When the palm was static, so that it was making no significant motion, the control mechanism of the dynamically represented finger could better follow the desired angle than in the case of a moving palm. The time lag created by PD controller of the dynamic finger was in the range of 0.1-0.2 seconds. For the kinematic model we did not measure any time lag in the simulation. The errors of the dynamically represented finger were influenced by the angular velocity of the finger in motion. As it can be seen on Figure 5a, around the sixth second of the measurements, when the angular velocity is higher (more than 30 degrees/sec), the motion of the middle finger becomes instable. We have also found that controlling a completely dynamic finger with PD controllers makes the hand model more instable than the model with partially dynamic fingers.

Motion of the palm increased the time lag compared to a

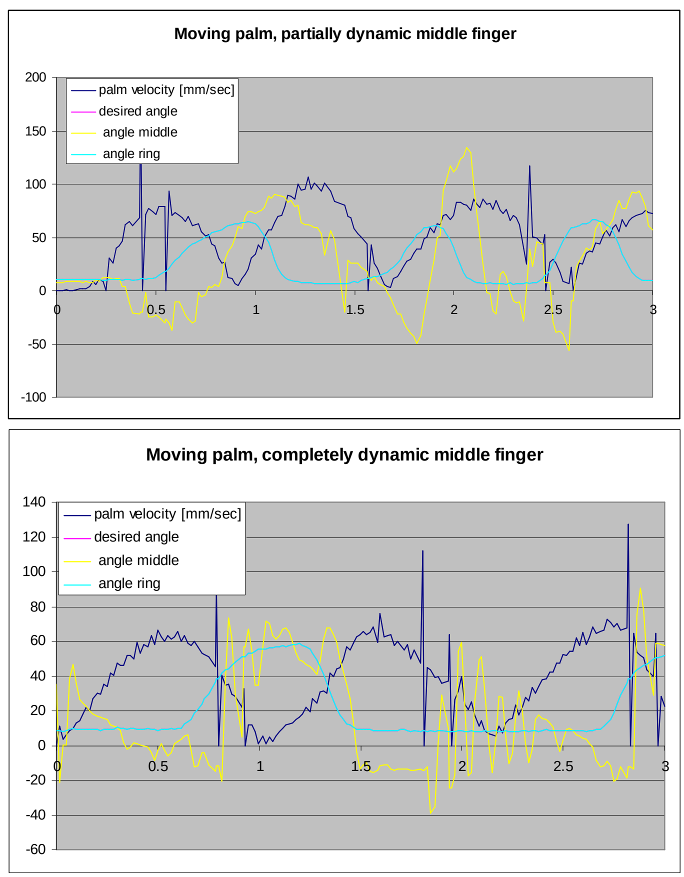

Figure 6: Motion following with dynamic palm

resting palm. In fact the acceleration of the palm forces the finger to move in the opposite direction, resulting in a higher error of the angular position at first. To compensate this error the PD controller applies higher torques at the joints of the finger, which makes the virtual finger overshoot the designer angle. Figure 6a and 6b illustrates the problem well. The angle of the middle finger has higher values in the negative domain as a result of overshooting. Fast motion of the palm introduced high instability both for the partially and completely dynamic fingers, but had no influence on the kinematic finger.

Accuracy of positioning finger tips

In this experiment, the users were asked to position the virtual hand so that the index finger and the thumb are in contact with two predefined areas illustrated by Figure 7. They were asked to place their hand into a pinching position on a static and dynamic behaving object with kinematic control and with dynamic control of the virtual hand. The results did not show significant differences between positioning the hand with kinematic or dynamic control. However, in all cases, the accuracy of positioning the thumb seemed to be more difficult than positioning of the index finger. We have observed that the visibility of the intended contact area had an influence on the accuracy of positioning. In fact in all setups the thumb occluded the intended contact area, while the contact area of the index finger remained visible as the object was rendered with half transparency. For this reason, in most cases the thumb has been positioned outside the intended contact area, while the index finger was kept inside the contact area.

We also found that dynamic objects (i.e. objects that can move in response to the contact with the hand) did not make the task more challenging for the users. In fact, the results are somewhat better than with static objects. As it can be seen on

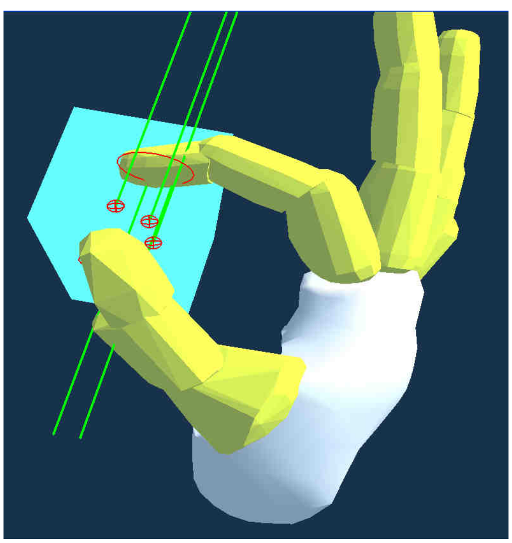

Figure 7: Positioning and controlling virtual hand with visual feedback of grasping force and contact points

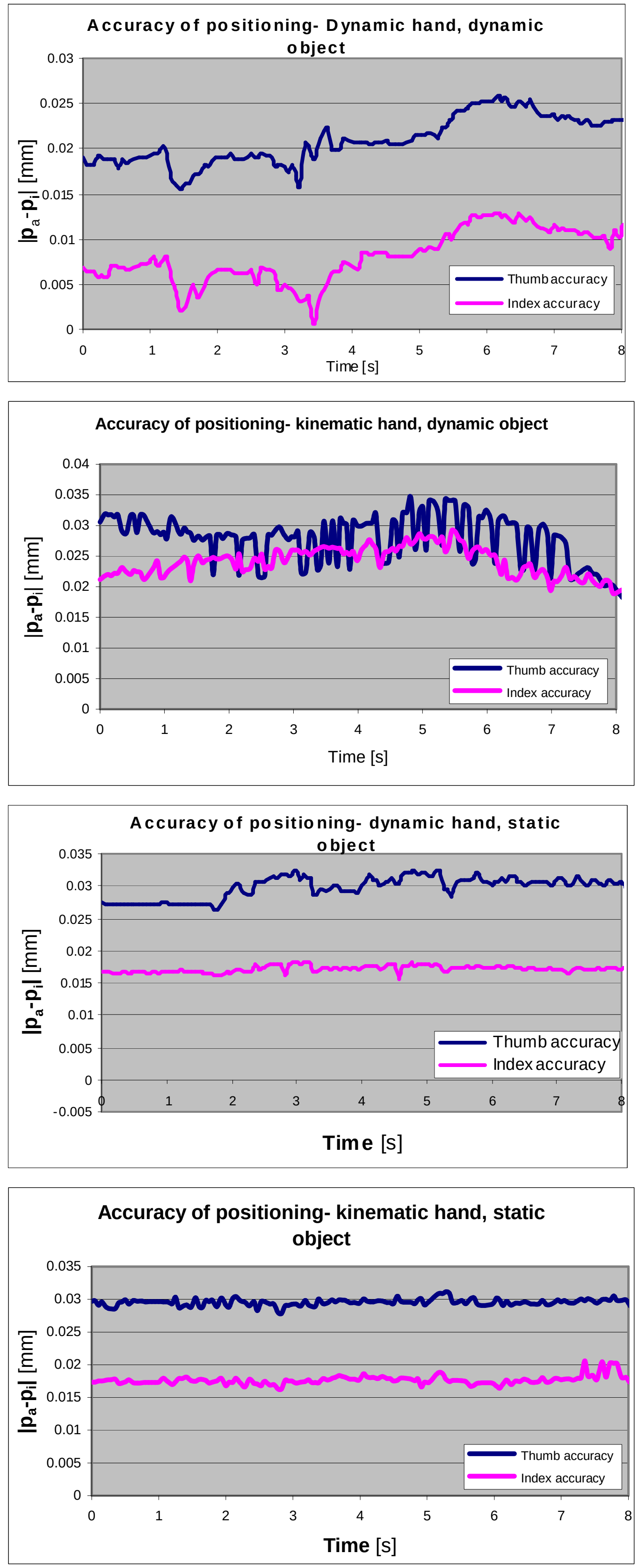

Figure 8: Positioning and controlling virtual hand

the diagrams, the values for the accuracy are in the same range for all cases, but in the case of dynamic hand and dynamic objects they are somewhat better.

Stability of controlling magnitude of grasping force

On the aspect of controlling the stability of contact forces, the followings have been found. Kinematic control of the hand showed higher fluctuation of the penetration in case of dynamic objects. In this situation, we have observed a wiggling effect has been observed in all cases. As shown in figure 9c, the fluctuation of stability was 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 has changed due to the wiggling motion of the grasped object.

In case of static object, the users were able to keep the penetration in the range of 1-2mm. This means, that when the objects are relatively stable or it is moving slowly, controlling the contact forces can be kept on a stable value with kinematic controls.

In case of dynamic control of the hand, we have observed the opposite effect. Controlling the penetration on a static object was in the range of 3-5 mm, while for dynamic objects it was in the range of 1-3 mm. However, it was more difficult for the user to control the thumb. On the other hand, we did not observe wiggling effect in these cases. Interaction with dynamic objects with dynamically controlled hand was definitely better for controlling the stability of the forces compared to kinematically controller hand.

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 principles of controlling virtual hands on the accuracy and stability of grasping. For this purpose a set of experiments has been conceived and conducted allowing us to draw important conclusions that could be summarized as follows:

Firstly, 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. Secondly, motion of the

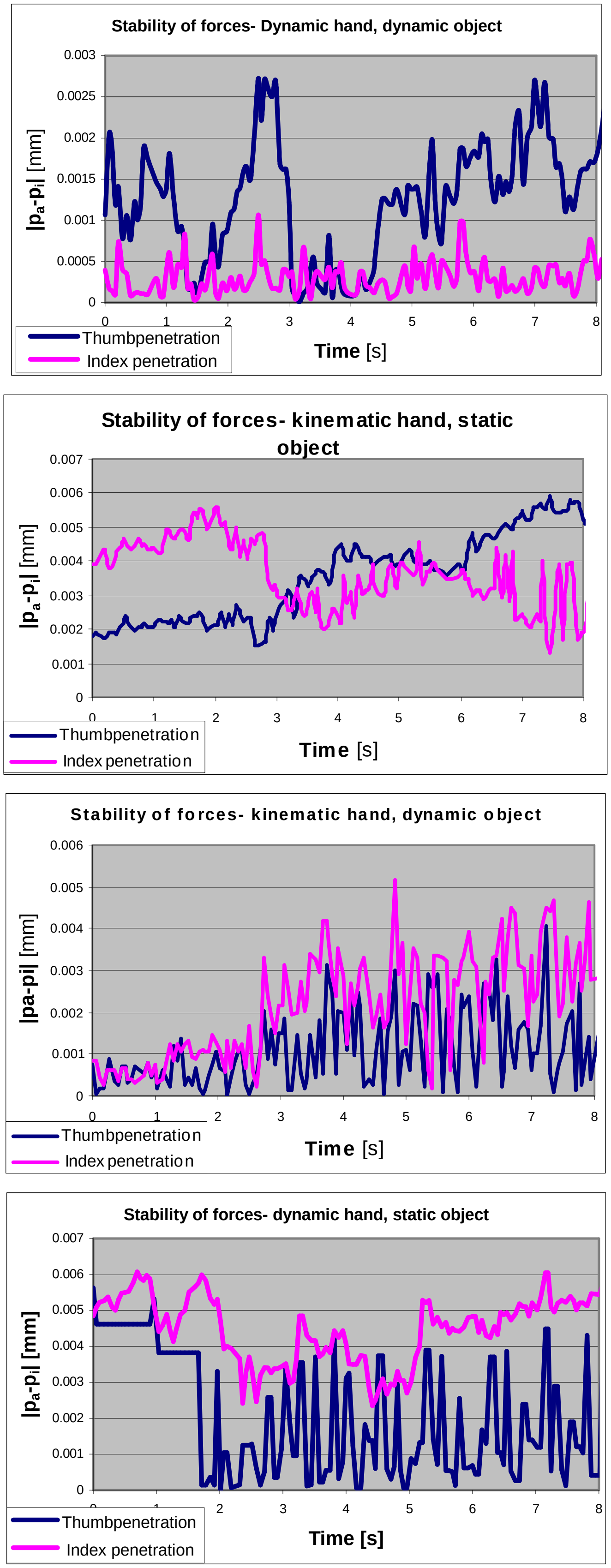

Figure 9: Results of force stability tests

hand in the virtual scene can be better controlled by kinematic principles than by dynamic principles. Testing of the accuracy of positioning the fingers on the grasped objects did not show significant difference when static or dynamic objects were manipulated with either kinematic or dynamic hand. On the other hand, tests of controlling the stability of contact forces proved that dynamic hands are more appropriate for handling objects with dynamic behavior and kinematic hands are better for static or slowly moving objects. In conclusions, we believe that a hybrid control of the hand will be the most suitable solution for a comprehensive solution.

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.

REFERENCES

[1] Doug L. J. and Dinesh, K. P., 2001. “A Unified Treatment of Elastostatic Contact Simulation for Real Time Haptics, Haptics-e”, September 27, Vol. 2, Number 1, pp. 1-13, http://www.haptics-e.org

[2] Grochow K., Martin S.L., Hertzmann A. and Popovi Z., 2004. “Style-based inverse kinematics”, ACM Trans.Graph., Vol. 23-3, pp. 522-531.

[3] Rijpkema, H. and Girard, M., 1991. “Computer animation of knowledge-based human grasping”, in Proceedings of SIGGRAPH 91 ACM Press, pp. 339-348.

[4] Landsmeer J.M.F., 1955. “Anatomical and fictional investigations on the articulations of the human fingers”, Acta Anat. Suppl. 25 (24), pp. 1-69.

[5] Neff, M., And Fiume, E., 2002. “Modeling tension and relaxation for computer animation”, In SCA ’02: Proceedings of the 2002 ACM SIGGRAPH/Eurographics symposium on Computer animation, pp. 81–88.

[6] Popovic, Z., And Witkin, A., 1999. “Physically based motion transformation”, In SIGGRAPH ’99: Proceedings of the 26th annual conference on Computer graphics and interactive techniques, ACM Press/Addison-Wesley Publishing Co., pp. 11–20.

[7] Shapiro, A., Pighin, F., and Faloutsos, P., 2003. “Hybrid control for interactive character animation”. In PG ’03: Proceedings of the 11th Pacific Conference on Computer Graphics and Applications, IEEE Computer Society, p. 455.

[8] Yin, K., Cline, M. B., and Pai, D. K., 2003. “Motion perturbation based on simple neuromotor control models”, In Proceedings of the 11th Pacific Conference on Computer Graphics and Applications, pp. 445–449.

[9] Kry P. G. and Dinesh, K. P., 2006. “Interaction capture and synthesis”, ACM Trans. Graph., Vol. 25-3, pp. 872-880.

[10] Lee K.-H. and Kroemer K. 1993. “A Finger Model with Constant Tendon Moment Arms”. In *Proc. Human Factors and Ergonomics Society 37th Annual Meeting*, pages 710–714,

[11] Albrecht I., Haber J. and Seidel H.P., 2003. “Construction and animation of anatomically based human hand models”. in Proceedings of the 2003 ACM SIGGRAPH/Eurographics symposium on Computer animation, , ed. by Eurographics Association, San Diego, California, pp. 98-109.

[12] Shieh M.-D. and Yang C.-C. 2006. “Designing Product Forms Using A Virtual Hand And Deformable Models”, ASME 2006 International Design Engineering Technical Conferences and Computers and Information In Engineering Conference, pp. 1-8.

[13] Fearing R. S., 1986. “Simplified grasping and manipulation with dexterous robot hands”, IEEE Journal of Robotics and Automation, RA2(4), pp 188-195.

[14] Coutinho M. G.., 2001. Dynamic Simulations of Multibody Systems, Springer-Verlag, New York.

[15] Salisbury J. K. and Craig J. J., 1982. “Articulated Hands: Force control and kinematic issues”. International Journal of Robotics Research, 1 (1), pp. 4-17.