Simulation of Object and Human Skin Deformations in a Grasping Task

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ABSTRACT

This paper addresses the problem of simulating deformations between objects and the hand of a synthetic character during a grasping process. A numerical method based on finite element theory allows us to take into account the active forces of the fingers on the object and the reactive forces of the object on the fingers. The method improves control of synthetic human behavior in a task level animation system because it provides information about the environment of a synthetic human and so can be compared to the sense of touch. Finite element theory currently used in engineering seems one of the best approaches for modeling both elastic and plastic deformation of objects, as well as shocks with or without penetration between deformable objects. We show that intrinsic properties of the method based on composition/decomposition of elements have an impact in computer animation. We also state that the use of the same method for modeling both objects and human bodies improves the modeling of the contacts between them. Moreover, it allows a realistic envelope deformation of the human fingers comparable to existing methods. To show what we can expect from the method, we apply it to the grasping and pressing of a ball. Our solution to the grasping problem is based on displacement commands instead of force commands used in robotics and human behavior.

keywords: synthetic human animation, grasping task, tactile sensing modeling, simulation, contact, physical interaction, deformation

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INTRODUCTION

Along with walking and speaking, grasping is an important task to be included in a system for animating synthetic actors. In character animation, the notion of task planning is divided into three phases: world modeling, task specification and code generation. World modeling consists mainly of describing the geometry and the physical characteristics of the synthetic actors and the objects. Task specification and code generation are more language oriented; they are not treated in this paper.

World modeling for synthetic actors frequently uses skeletons made up of segments linked at joints. This is suitable for parametric key-frame animation, kinematic algorithmic animation or dynamic based techniques [23]. The skeleton is generally surrounded by surfaces or elementary volumes [3] [20] whose sole purpose is to give a realistic appearance to body.

The model developed by Komatsu [17] uses biquartic Bezier surfaces, and control points are assigned to the links. Magnenat-Thalmann et al. [24] used a technique based on Joint-Dependent Local Deformations (JLD) to tie skin points to joint points obtaining realistic stretching and inflation of flesh. Catmull used polygons [10], and Badler and Morris [2] used the combination of elementary spheres and B-splines to model the human fingers.

On the other hand, the environment of characters is made up of rigid objects, key-frame deformable objects, mathematically deformable objects [5], soft objects represented by scalar combinations of fields around key points [35] [7], or physically deformable objects based on elasticity theory [27] [30]. With physical models, the objects act as if they had a mind. They react to applied forces such as gravity, pressure and contact. Platt and Barr [27] used finite element software and discuss constraint methods in terms of animator tools for physical model control. The models developed by Terzopoulos et al. [30] are implemented using the Finite Difference Method. Collisions between elastic objects are simulated by creating potential energy around each object, i.e., intersections between deformable bodies are avoided by surrounding the object surfaces with a repulsive collision force. This approach is also developed by Luciani [19] who deals with 2D real time animation of objects and characters based on springs, dampers and masses, controlled by gestural transducers with mechanical feedback.

Moore and Wilhems [25] treat collision response, developing two methods based on springs and analytical solutions. They state that spring solutions are applicable to the surface shapes of flexible bodies but do not explain how the shapes are obtained before initiation of contact calculations nor how the shapes are modified as a result of a contact.

Our main objective is to model the world in a grasping task context by using a finite element theory. The method allows simulation of both motion and shape of objects in accordance with physical laws, as well as the deformations of human flesh due to contact forces between flesh and objects. The following two arguments support use of the same method for modeling deformation of objects and human flesh.

First, we want to develop a method which will deal with penetrating impacts and true contacts. For this reason, we prefer to consider true contact forces with possibilities of sliding and sticking rather than only repulsive forces. Our approach based on volume properties of bodies permits calculation of the shape of world constituents before contact, and to treat their shape during contact. When a contact is initiated we use a global resolution procedure which considers bodies in contact as an unique body. Simulation of impact with penetration can be used to model the grasping of ductile objects or to model ballistic problems. It requires decomposition of objects into small geometrically simple objects.

Second, all the advantages of the physical modeling of objects can be transferred to human flesh [13]. For example, we expect the hand grasping an object to lead to realistic flesh deformation as well as an exchange of information between the object and the hand which will not only be geometrical. When a deformable object is grasped, the contact forces on it and on the fingertips will lead to deformation of both the object and of the fingertips, giving rise to reactive forces which provide significant information about the object and more generally about the environment of the synthetic human body.

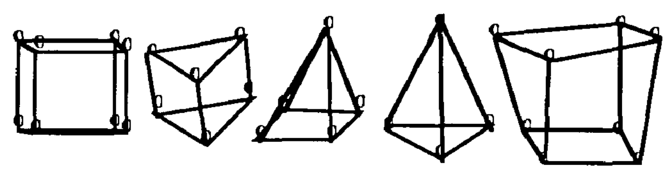
It is important to note that even if the deformations of the object and of the fingers are not visible, or if the object is rigid, the exchange of information will exist because the fingers are always deformable. This exchange of information using active and reactive forces is significant for a good and realistic grip and can influence the behavior of the hand and of the arm skeleton. For grip, interacting information is as important as that provided by tactile sensors in a robot manipulator. This is a well known problem of robotics called "compliant motion control". It consists of taking into account external forces and commanding the joints and links of the fingers using inverse kinematic or dynamic controls. In the past, authors dealing with kinematic and dynamic animation models oriented towards automatic animation control [1] [4] [9] [33], have often referred to works of roboticians [14] [18] [26]. In the same way, we believe that methods intensively used in CAD systems may improve the control of synthetic human animation. However, the method must be adapted to computer animation because the problems here are not the same as in CAD or robotics.

In robotics, it is impossible to expect a grip controller to perform a complete environmental finite element analysis in real time. Consequently, the adopted solution generally uses well-located fingertip sensors to measure the terms that are difficult to compute. In synthetic human modeling, complete computations are possible, though they represent a gigantic problem. To grasp an object, robots and humans apply a prescribed force to the object, whose intensity is related to environment knowledge. This process will not work in animation because force transducers are not yet used in computer animation systems. Hence, our grasping method for animation is based on prescribed displacements instead of prescribed forces.

In the next section, we emphasize the properties of the numerical method developed for computer animation purposes. In the second part, we show how a global approach can contribute to animation of synthetic actors in their environment, using the same method for modeling deformation of objects and human bodies. We describe in detail the grasping and pressing of a ball, and show envelope deformation during finger flexing. In the last section, we discuss how our numerical approach enhances the HUMAN FACTORY system [23].

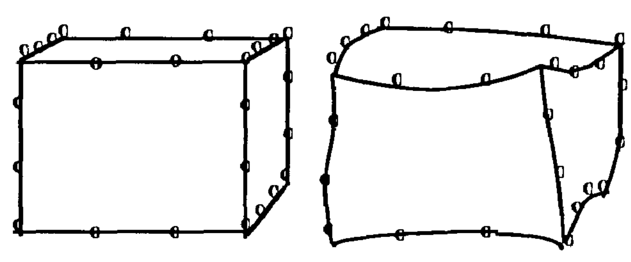
NUMERICAL METHOD FOR COMPUTER ANIMATION

This section does not describe the finite element theory in detail, but rather introduces those concepts used for computer animation purposes. A comprehensive study of the finite element theory is given in Bathe [6] and Zienkiewicz [36]. A summary of the theory of elasticity can be found in Timoshenko and Goodier [32].



cube (8 pts) | prism (6 pts) | pyramid (5 pts) | tetrahedron (4pts)

a. linear elements with zero order continu



b. cubic element with zero order continu

Figure 1 - elements and their deformations

Solid three-dimensional objects and human flesh are discretized using simple or complex volume elements, depending on the choice of the interpolation function. Zero order simple linear elements and complex cubic elements with their deformations are shown in Figure 1. The finite element approach is compatible with requirements of visual realism because a body surface corresponds to an element face that lies on the body boundary. As with surface patches, it is possible to ensure high order of continuity between elements. However, this procedure is expensive in terms of memory space and CPU time. For this reason, our calculations are based on linear elements with zero order continuity. Nevertheless, the use of complex elements and high order continuity allows us to obtain the same visual effects as with surface patches. Indeed, elements are parametric volumes and the boundary object surface is a parametric surface.

Once the various kinds of elements are defined, the modeled shape is obtained by composition. Each element is linked to other elements at nodal points. In continuum mechanics, the equilibrium of a body presenting a shape can be expressed by using the stationary principle of the total potential or the principle of virtual displacements:

$$wR = wB + wS + wF \qquad (1)$$

where wB represents the virtual work due to the body forces such as gravity, centrifugal loading, inertia and damping, wS represents virtual work of distributed surface forces such as pressure, wF represents the virtual work of concentrated forces and wR represents the internal virtual work due to internal stresses.

In the finite element method, the equilibrium relation (1) is applied to each element e

$$w_{Re} = w_{Be} + w_{Se} + w_{Fe} \qquad (2)$$

and the whole body is obtained by composing all elements

$$\sum_{element=1}^{NBEL} W_{Re} = \sum_{element=1}^{NBEL} W_{Be} + \sum_{element=1}^{NBEL} W_{Se} + \sum_{node=1}^{NBP} W_{Fe} \qquad (3)$$

Our three-dimensional model uses elements with eight nodes and NBDOF = 3 degrees of freedom per node. These elements are easily modified to prismatic or tetrahedral elements to approximate most existing 3D shapes. The composition of NBEL elements with 8 points give NBP points and NB = NBP*NBDOF equations. From the relation (3) we can write the following matrix equation between vectors of size [NB*1] as follows:

$$R + RI = RB + RS + RF \qquad (4)$$

where RB is the composition of body forces, RS is the composition of surface forces and RF represents the concentrated forces acting on the nodes. R + RI is the composition of internal forces due to internal stresses. These stresses are initial stresses which give the RI term, and reactions to deformations created by RB, RS and RF which give the R term.

In the following sections we will use the equilibrium relation (4) under the form (5)

$$K.U = R \qquad (5)$$

where K is the [NB*NB] stiffness matrix, a function of material and flesh constitution, R is the [NB*1] load vector including the effects of the body forces, surface tractions and initial stresses, and U is the [NB*1] displacement vector from the unloaded configuration.

Relation (5) is valid in static equilibrium and also in pseudo-static equilibrium at instant t_i. Instants t_i are considered as variables which represent different load intensities. In this paper, we do not deal with dynamics when loads are applied rapidly. In this case, true time inertia and damping, displacement velocity and acceleration must be added to (5).

Under this form, the body can be viewed as a huge three-dimensional spring of stiffness K and return force R. The equilibrium relation (3) is a function of volume properties because each component is obtained by the summation of integrations over the volume and the area of each element (see [36] for more details).

Since the process used consists of the composition of elements to create a global deformable object, we believe that this property and its inverse, i.e. the decomposition of a global deformable object into two or multiple sub-objects, should be used in computer animation.

The decomposition is very easy to implement because the constitutive properties of each element as well as inter-element forces are memorized and are taken into account during numerical calculations. It is possible for example to create a global object made of different sub-objects; each sub-object would have its own constitutive properties and be composed of one or more elements.

There are several ways to exploit the intrinsic properties of this method:

- The decomposition approach can be exploited to model penetrating shocks between two or more deformable objects. Each object is subdivided into many deformable sub-objects which are able themselves to interact with each other because each inherits its own properties. The decomposition approach may also be used in contact problems when contact is released.

- The composition approach can be used for modeling contacts without penetration between two or more objects. In this case, objects can be considered as sub-objects evolve independently until contact is detected and a global object is composed following contact. In practice this means that relations $K_n.U_n = R_n$ are resolved independently before contact and a unique relation K.U = R is resolved after contact of n bodies. This process works if we take into account the contact forces that prevent overlapping in equation (5). We use the composition approach for the grasping and pressing of a ball described in the following section. A survey of contact problems is given by Bohm [8]. Example of 3D treatments can be found in Chaudary and Bathe [11].

BALL GRASPING AND PRESSING

To show how the physical modeling of deformable objects can contribute to human animation, we present an example of a contact problem dealing with the grasping and pressing of a ball. Starting with the facet-based envelopes of ball and hand obtained from our image synthesis system SABRINA [22], we mesh the volume of the objects to create full 3D bodies or shell bodies depending on the application. After calculations of the deformations using our method based on finite element theory, the facet-based deformed envelopes are extracted from the data base used in our calculations and restored to SABRINA for visualization. In this way, visual realism is always ensured by the image synthesis system. The ball can be modeled by a shell with internal pressure, or can be fully meshed in its volume.

Figure 2 shows the hand and bones used in our calculations. The hand tissue is meshed in a volume around the bones. According to Cutkosky [12], sensory information probes, strategically located on the fingertips and palm seem to provide adequate information on the whole. For example, the fingertip palmar is about ten times more sensitive than the fingertip dorsal. For this reason, the volume mesh may be very loose in poorly sensitive areas and tight in sensitive areas which require accurate calculations. Bones are connected to the segment and joint skeleton animated by the HUMAN FACTORY system. The hand envelope and segment-joint skeleton are sufficient for realistic hand animation without contact but are not able to reproduce skin deformations due to a contact. A mere bone segment is not sufficient to give realistic large deformation of skin under contact forces because, as in human fingers, skin deformations are restricted because of bones. For this reason, we use the realistic bones shown in Figure 2. This has an impact on visual realism and behavior of the hand during grasping, because bone parts are flush against the skin in some regions and are more distant in others. Moreover, in the future, more complex modeling will probably take into account nerves and muscles tied to bones [31].

Consider the equilibrium of the ball and finger shown in Figure 3b, the external forces acting on the ball and finger are surface tractions (such as internal pressure, and external loads representing force contact between ball and support table) and body forces (such as gravity and muscular forces).

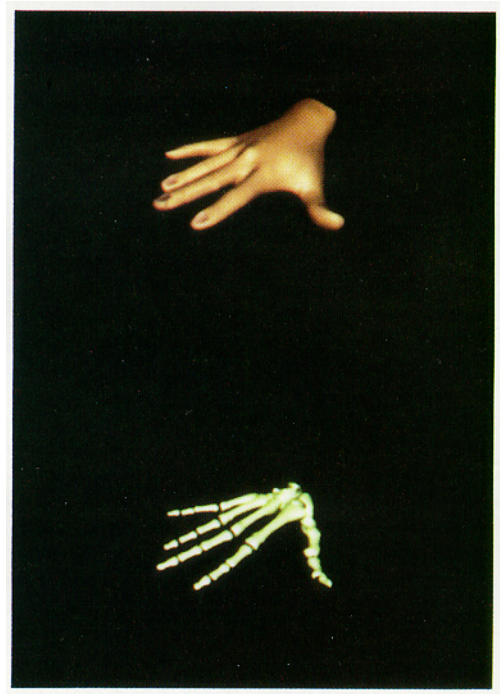


Figure 2 - Hand and bones at rest

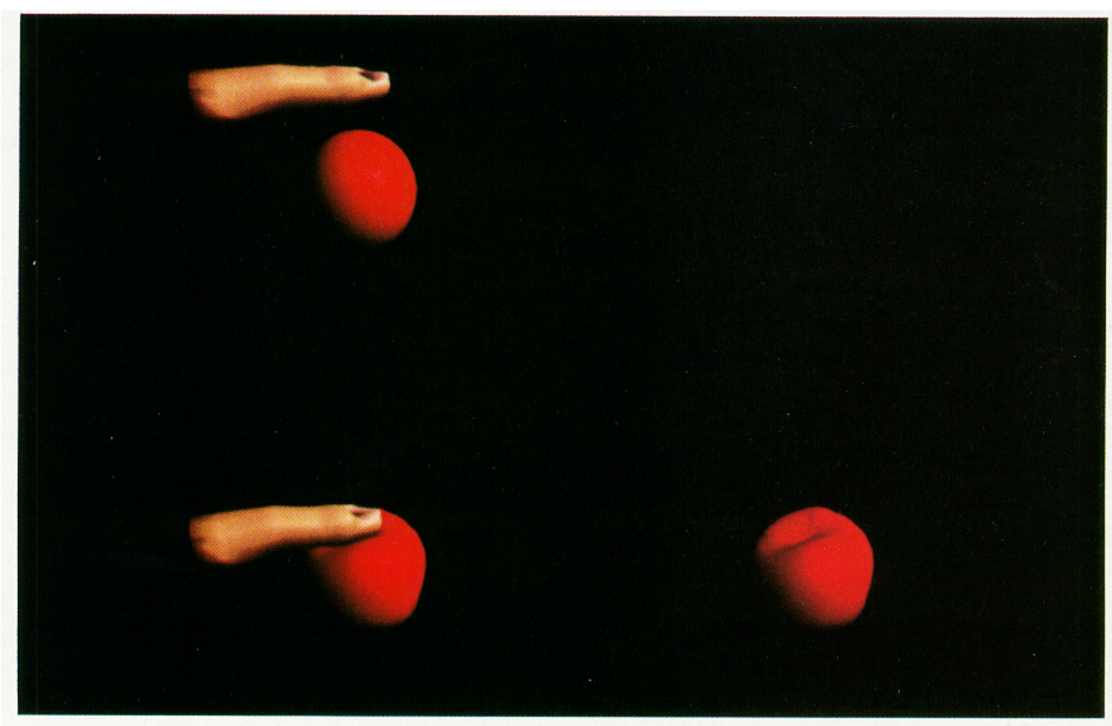


Figure 3 - (a) ball and finger before contact (b) ball and finger after contact (c) deformed ball; this picture presents deformations and fingermarks created by the finger in picture b. It is obviously not a realistic situation because the ball, submitted to internal pressure, will in reality return to its initial shape when the action of the finger is released

We use a composition approach based on the resolution of relation (5) including contact forces between ball and finger. This relation works perfectly in a grasping problem because loads are applied slowly.

However, contact modeling is not easy because the equilibrium equation (5) is obtained on the assumption that the boundary conditions remain unchanged during each time t_i. Two kinds of boundary conditions exist: geometric boundary conditions corresponding to prescribed displacements, and force boundary conditions corresponding to prescribed boundary tractions. We cannot control a single degree of freedom in both position and force; consequently, the unknown displacement will correspond to known prescribed force and conversely known prescribed displacement will correspond to unknown force.

In matrix notation, the problem can be stated in the following way: U_k are known prescribed displacements, U_u are unknown displacements, R_k are known prescribed forces and R_u are unknown forces. In this way, relationship (5) can be written

$$\begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \cdot \begin{bmatrix} U_u \\ U_k \end{bmatrix} = \begin{bmatrix} R_k \\ R_u \end{bmatrix} \qquad (6)$$

If NP degrees of freedom are displacement prescribed, NBEQ=NB-NP equations are necessary to find the U_u unknown displacements. Matrix dimensions are [NBEQ*NBEQ] for K_{11}, [NBEQ*NP] for K_{12}, [NP*NBEQ] for K_{21} and [NP*NP] for K_{22}.

Equations for solving U_u are

$$K_{11}.U_u = R_k - K_{12}.U_k \qquad (7)$$

Hence, in this solution for U_u, only the [NBEQ*NBEQ] stiffness matrix K_{11} corresponding to the unknown degrees of freedom U_u need to be assembled. Once U_u is evaluated from (7) the nodal point forces corresponding to U_k can be obtained from (8)

$$R_u = K_{21}.U_u + K_{22}.U_k \qquad (8)$$

Boundary conditions can change during grasping and pressing when prescribed forces or displacements are sufficient to strongly deform the ball and hand skin. This situation creates other contact points between ball and table, and between ball and fingers. Consequently the calculations are more complicated because the number of unknown displacements U_u, and reactive forces R_u, will vary depending upon the number of contact points which prescribe R_k and/or U_k.

When the hand grasps a ball or when a finger presses a ball, the senses of sight and of touch are generally used consecutively.

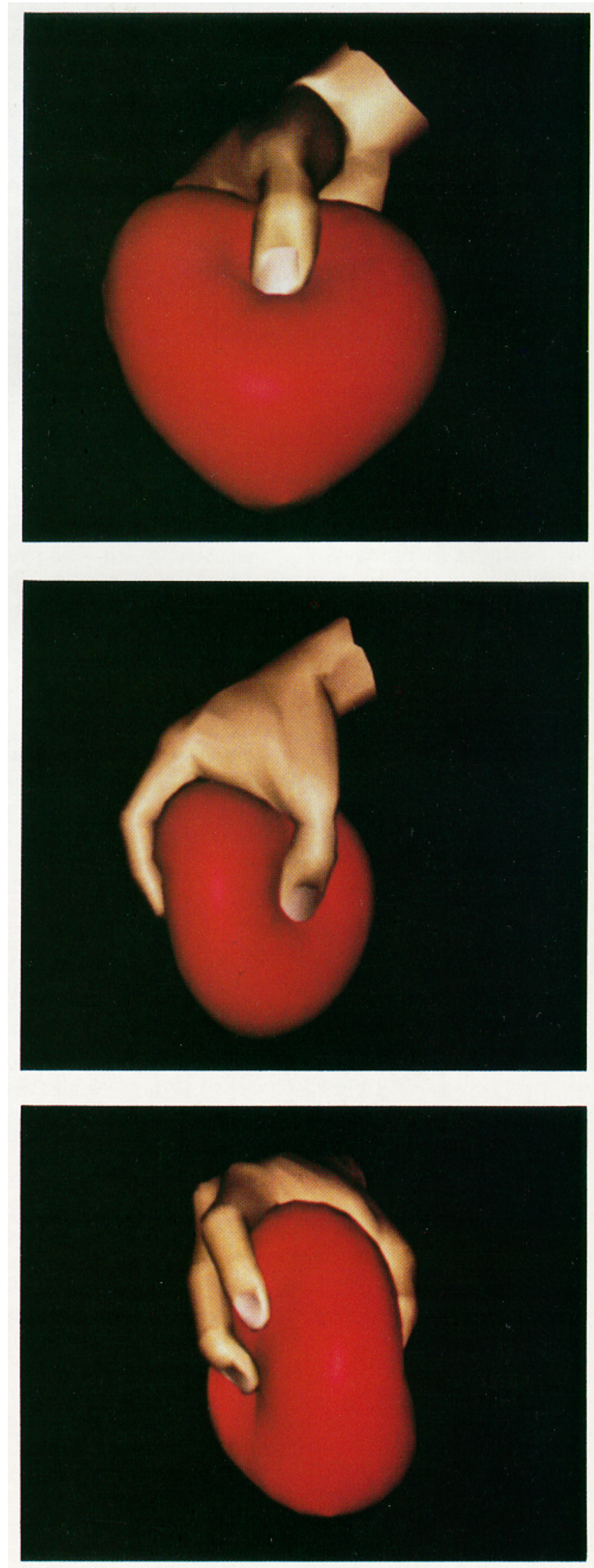


Figure 4 - Grasping of a ball submitted to internal pressure, seen from various viewpoints

In a first step, sight allows us to evaluate certain dimensions, mass, roughness, elasticity etc. i.e. to imagine our position in relation to the ball. In the domain of animation, this information is contained in the ball data base (e.g. volume point coordinates, and physical characteristics such as constitutive law, mass density, and texture which can be related to roughness). The hand grasps or presses the ball applying a prescribed force, whose intensity is dictated by the knowledge acquired by the sense of sight. The prescribed contact force is created by muscular forces acting on bones and using flesh as an intermediary. Generally, the grip is as gentle as possible without letting go of the ball. This can be viewed as a "minimization of the power due to the muscles", as pointed out by Witkin and Kass [34]. A gentle grip not only prevents damage to a fragile object, but also results in a grip that is more stable [12] [29]. In a second step, the sense of touch allows an exchange of information between the ball and the fingers, implying contact forces, sliding contacts, deformations, and internal stresses in the fingers. In computer animation the first step is difficult to implement because the animator does not dispose of force transducers for forces applied directly to the bones. Consequently the first step based on given prescribed forces R_k on bones is not presently possible. For this reason our solution for the grasping problem is different from the robot or human solution. It is displacement-driven rather than force-driven.

In this way, the animator is not concerned with forces but with the hand key position required by the script. For ball grasping, shown in figure 4, the ball is made up of a rubber envelope and is submitted to internal pressure. The animator imposes prescribed displacements U_k on the hand bones using a "classical" method (parametric, kinematic or dynamic) and places the ball between the fingers. During this process the animator can ignore the material of which the ball is built. It can be a very soft ball or a very stiff bowl. The animator positions the fingers (skin and eventually bones) inside the ball. The purpose of calculations is to decide if the chosen finger position is or is not a realistic one and its consequences on skin and ball shapes. This is the reaction of the ball on the fingers which will decide the validity of grasping. Since finger position is prescribed by the animator, the ball must be repelled to prevent overlaps, ignoring, as a first approximation, whether it is stiff or soft. The computational geometry procedure used for determination of repelling points is beyond the scope of this paper.

We show in figure 5 an example of overlap. When a ball node B penetrates the finger and/or palm, it is repelled over the skin surface (point C) in the direction of polygon normal n_F. Ball and hand surface patches are polygon faces of finite elements. With linear elements of zero order continuity, patches are triangular or quadrilateral. The normal direction n_F of each polygon face is calculated at the polygon center. It is a true normal if the patch is triangular and an approximated normal if the patch is quadrilateral because the four surface points are generally not in the same plane. For this reason we use triangular polygons for fingers in our contact calculations.

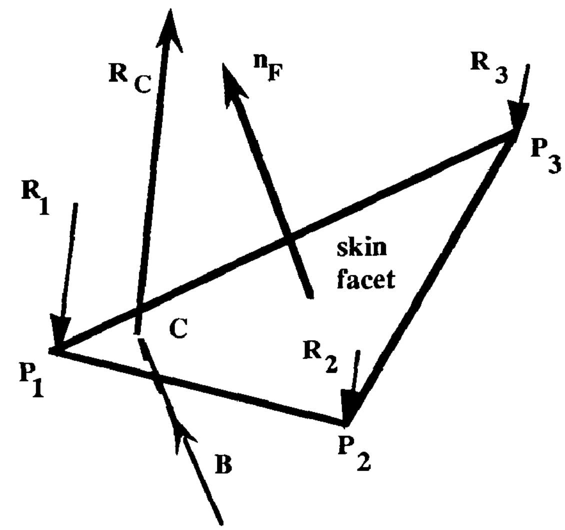


Figure 5 - Overlapping of a ball node. The ball node B is repelled over point C of the skin facet P_1, P_2, P_3 in direction of normal n_F to the facet. The reactive force created by overlapping suppression is shared out among R_1, R_2 and R_3. $R_i=h_i.R_c$ (i=1, 2, 3) where h_i is the interpolation function corresponding to node i, evaluated at point c. Value of h_i is unity at node i and zero at all other nodes.

The overlap suppression creates reactive forces on the ball surface, which are applied to the skin. At equilibrium, these forces maintain compatible surface displacements between the two deformable bodies.

The following is an iterative procedure for obtaining both the contact forces and the displacements under contact:

1 -	move links and joints using some "classical" method (parametric, kinematic or dynamic) and calculate new prescribed bone displacements U_k.	
	While equilibrium between ball and hand is not reached or reactive force on bones has not overrun a threshold force, do:	
	begin	
	2 -	prescribe displacements U_k of skin; repel ball nodes to prevent overlapping; prescribe displacements U_k of repelled ball nodes;
	3 -	resolve (7) and (8) to obtain displacements U_u on ball and reactive forces R_u on contact points of the ball;
	4 -	affect equal and opposite reactive forces R_u on contact points of the skin;
	5 -	assume the contact forces R_u are prescribed forces R_k, i.e. release all degrees of freedom of ball and skin;
	6 -	resolve (7) and (8) to obtain displacements U_u of ball and skin, and reactive forces R_u on bones;
end;		

Relation (7) is solved using a direct solution (Gauss method). Convergence occurs when for all points the variation between two successive iterations is less than some fixed threshold. In this procedure, relations (7) and (8) represent the global system made up of ball and hand. The first step requires animator manipulation and has been described previously. In the second step all skin displacements, and those ball displacements resulting from overlap suppression are prescribed. In this way, resolution of (7) and (8) in step 3 will give displacements U_u on ball and reacting forces on repelled ball nodes. Step 4 ensures that at equilibrium, contact forces between ball and skin will be equal and opposite to maintain compatible surface displacements. Because ball nodes are not repelled in coincidence with skin nodes, but on skin polygon surfaces, the reacting force calculated in step 4 is distributed among the three nodes constituting the skin facet (Figure 5), with weights depending on the position of the ball node on the facet. In steps 5 and 6, reacting forces are assumed to be known and all degrees of freedom of ball and skin are released. In other words, we rearrange matrix relation (6) because the number of equations is modified in comparison with step 3. The method can be interpreted as a Lagrangian multiplier method that forces the non-penetration condition between the ball and the hand with additional equations. Steps 2 to 6 are repeated until convergence is reached. Otherwise they are stopped when the evaluation of the reacting force on bones overruns a force threshold allowable by the human musculature. Indeed, assume that animator places finger skin and bones into a very stiff bowl. The reacting force R_k on bones obtained in step 6 can then be gigantic and overrun the threshold force attributed to the muscular command of this bone.

In a parametric computer animation system, the reacting force on bones can be used to suggest solutions to the animator as in an expert system.

In a system with inverse dynamics, the position of bones is modified automatically using calculated reacting force.

Calculation of finger deformations are necessary even if fingers and palm deformations are not visible. An exchange of information will take place since the fingers are always deformed. It is finger flexibility and frictional resistance which permit human grasp of rigid objects. This is the reason why actual robot hands are made up of elastic extremities equipped with tactile sensors [16] [28]. Our actual simulation is based on prescribing and releasing the displacement of contact points during each iteration. This allows us to release dynamically the parts of the two bodies. A more sophisticated model, now being developed, must include an evaluation of frictional resistance. For example a Coulomb friction law may be used to simulate the adhesion of papillary ridges. In this law, a coefficient of friction u relates the normal force F_n to the tangential force F_t at contact points. Force $u.F_n$ represents the frictional resistance during contact, and sliding contact is initiated when $F_t \geq u.F_n$.

During the second step of grasping, if the initial prescribed force R_k has been poorly evaluated by the sense of sight, the ball and finger(s) will slide. This information can then be used to increase the prescribed force, or to modify the position of fingers on the ball. The evaluation of sliding and the increase in the prescribed force must be repeated until an equilibrium or an unstable condition is obtained.

Both the tactile sensor model and the command model must be included in a complete automatic motion control, because the stiffness of grip is a function of the stiffness of finger tissue and of the disposition of fingers around the ball. This compliant motion control scheme, which is made to sustain the environmental factors, might be made easier by the fact that kinematic and dynamic models dealing with articulated bodies can be looked upon as a displacement based finite element method applied on trusses and bars.

The global treatment of contact presented here can be applied to inter-deformation of fingers, deformation between fingers and palm, or, more generally, between two synthetic human parts following a compression or a stretching of skin. For this purpose, each part of the body must be considered as an entity able to interact with each other part. An entity cannot interpenetrate itself and some entities cannot reach all others because of joint angle limits imposed on the skeleton [15]. For example, during finger flexing, we consider the third phalanx unable to interpenetrate the second and first phalanges. In the same way we also consider that a foot cannot reach the face unless we are simulating a chubby baby.

FINGER FLEXION WITHOUT CONTACT

The problem of 3D modeling of human skin deformations, during the process of joint flexing, has many different solutions that give a realistic visual appearance to the human body. The skeleton can be surrounded by surfaces of planar or curved patches, or the skin can be modeled by elementary volumes. All the methods have been created to give a realistic appearance to hands and bodies with no concern for the force information exchanged during contact.

In Figure 6, we show the successive steps of finger flexing whose last position can be compared with a JLD result. The starting position was the neutral rest position and the following procedure was applied:

For each time t_i corresponding to link displacement angle less than 10 degrees, do:
begin
1 Move links and joints using some "classical" method (parametric, kinematic or dynamic), and calculate new position of prescribed DOF on bones, 2 from preceding position at time t_{i-1} calculate prescribed DOF displacement U_k on bones 3 calculate stiffness K, erase R_k and solve relation (5) to obtain tissue displacements U_u, 4 update position of tissue points
end

In our calculations, an updated Lagrangian formulation in small strains [32] was used. We also used a classical engineering stress measure (Cauchy stress) and a linear constitutive law for flesh tissue. This formulation is simple, but it gives good visual results, without requiring long calculations. For the displacement of finger links, a variation angle of 10 degrees seems to be a maximum to ensure a small displacement and rotation condition.

Therefore, 30 degrees displacement of the first phalanx and 50 degrees of the second phalanx as shown in Figure 6, needs at least height position calculations corresponding to displacements of 10, 20 and 30 degrees for the first phalanx and displacement of 10, 20, 30, 40 and 50 degrees for the second phalanx; or any combination of these displacements.

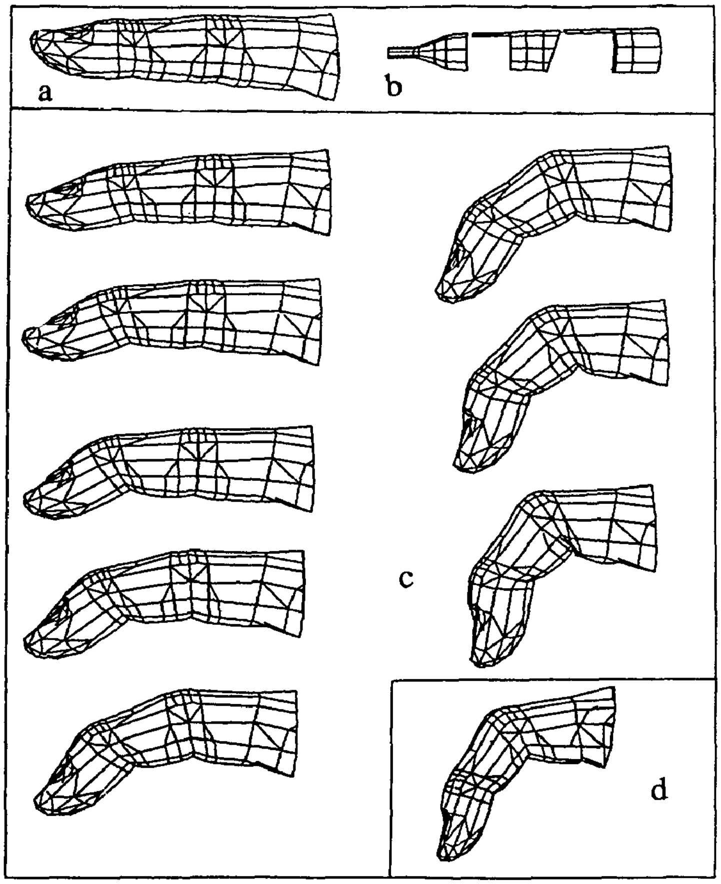


Figure 6 - Successive steps of finger flexing without contact; a. rest position; b. particular bones; c. finger flexing based on FEM deformation d. finger flexing based on Joint-dependent Local deformation (JLD)

It must be noted, however that the final position could be obtained directly from rest position using another formulation which takes into account large displacements and rotations in small strains. In this case, the formulation would be based on the use of a Piola-Kirchhoff stress instead of Cauchy stress, and would require an iterative computation. However, this scheme does not seem very interesting in hand animation because inbetween positions are indispensable for realistic movement decomposition. If more realism, or incompressible material modeling, are desired, increased computation time will be required for material non-linear calculations. When material non-linearities exist, a Newton-Raphson iterative method must be added in step 3 of the procedure for each time t_i. The use of a linear material allows us to obtain inflation of flesh without an iterative calculation and requires less than 1 minute per frame on a VAX 780. But this procedure works only with the particular shape of bones shown in Figure 6. More realistic bones require incompressible material and this increases the computation time.

Although we proved that the calculations described here give realistic deformations of fingers during flexion, in the HUMAN FACTORY system we use a hybrid formulation based on JLD operators when there is no contact, and on FEM calculation when a contact is detected. In a complete grasping task, this method saves CPU time during the reach phase of the task when the hand comes closer to the object.

ANIMATION CONTROL

In this section, we briefly discuss how animation of deformable objects and human bodies has been introduced into the HUMAN FACTORY system. For animation of rigid objects, the HUMAN FACTORY system already contains animation procedures for simple physical movements applied to material points. Examples are movement of pendula, circular movement with acceleration, projectile with initial velocity and so on. It also contains basic animation laws like the Catmull laws (see [20], p.49). These physical or empirical laws are applied to animated variables or state variables. In this way, during the specified interval, state variables are automatically updated to the next value according to the law [21]. Moreover these state variables drive actor transformations. Combining state variables and actor transformations allows a complex animation of actors.

Animation of a physically deformable object can be simply supported in the HUMAN FACTORY system by defining prescribed displacements called U_k in the preceding sections as new state variables. When the three degrees of freedom of some point are prescribed, state variables of VECTOR type are sufficient for defining the movement of prescribed points. When less than three degrees of freedom are displacement prescribed, a new type of state variable has been defined. With this approach deformable bodies are processed as actors. Object points are not only submitted to translations and rotations, but automatically follow the prescribed degrees of freedom according to constitutive laws and other potential constraints such as body forces and surface forces. It should be noted that the use of state variables is not always required and can often be omitted. For example the problem of free fall of a deformable object is implicitly defined and does not require an extra physical law and prescribed degrees of freedom.

We have already discussed the problem of hand animation in the preceding sections. In the system, skeleton animation is based on joint angle definition. A realistic skeleton is linked to animated skeleton segments, and prescribed displacements are fixed on bones surfaces.

We use displacement-based degrees of freedom because displacement transducers (such as mouse, rolling bowl and so on) are more common in computer animation than force transducers (such as remote manipulators in robotics). The procedure based on prescribed displacements is easy to implement in parametric animation systems and can pass information to dynamic animation systems.

Force prescribed systems will be effective when forces transducers are intensively introduced in computer animation. In this case, the animator will be fully engaged in the scene during creation and it will be possible to define a new TYPE OF ACTOR called animator.

CONCLUSION

In this paper we have simulated objects and skin hand deformations in a grasping task. To this end, a finite element module has been developed for modelling both object and synthetic human flesh deformations and their contacts. The method gives information about the synthetic environment of the human. It may be compared to the robot *tactile sensor or to the human sense of touch.* This information provides a significant contribution to automatic motion control in 3D character animation. We believe that it can be used to improve the behavior of synthetic human grasp and more generally to improve the synthetic human behavior in the synthetic environment. These problems cannot be solved using only geometric solutions, or only force solutions implying gravity and muscular forces based on a single point of contact. In an artist oriented system, the finite element model can be used to define objects in the same way as a sculptor molds his shapes.

The object and human data base contain not only envelope coordinates but also volume point coordinates and information about physical material, tissue characteristics and force threshold. In this way, we take advantage of the intrinsic properties of the numerical method, based on composition-decomposition of elements, for computer animation purposes.

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