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ORIGINAL ARTICLE

Stop-and-go cloth draping

Pascal Volino
Nadia Magnenat-Thalmann

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P. Volino (✉) · N. Magnenat-Thalmann
MIRALab, University of Geneva, Geneva, Switzerland
{pascal,thalmann}@miralab.unige.ch

Abstract The aim of cloth draping is to compute the rest state of a piece of cloth, possibly in contact with other solid objects, as quickly as possible. The context of free motion and very large deformations specific to cloth simulation makes the usual energy minimization schemes traditionally used in mechanical engineering inefficient. Therefore, most cloth draping applications only rely on dynamic simulation with ad hoc viscous damping or the dissipative behavior of numerical integration methods for obtaining convergence to the rest position of the cloth. We propose a "stop-and-go" technique which cuts out the velocity of the object at particular times for converging to the rest state, while taking advantage of the natural cloth motion toward equilibrium. This scheme can very easily complement any existing dynamical cloth simulation system, using either implicit or explicit numerical integration methods.

Keywords Cloth simulation · Draping · Relaxation

1 Introduction

The largest difficulties related to garment simulation result from the large computation times required for producing high-quality garment models, which often involve polygonal mesh surfaces made of several thousands polygons. Hence, any interactive garment CAD and prototyping system requires the simulation of numerous garment models (with different garment models and variation, different body sizes and postures) along the design process of garments [20], which have to be carried out as quickly as possible with acceptable accuracy (Fig. 1).

Although numerous mechanical models and simulation schemes are designed to handle virtual garments, there is little connection between these methods and those traditionally used for simulating deformable structures in mechanical engineering.

In the field of mechanical engineering, the simulation of elastic objects is, in most of the cases, within the context of small deformations [10]. Thanks to limited orientation changes, the rest position is fairly close to the initial position of the mechanical system, and any iterative relaxation scheme follows quite a "straight path" to the rest position. Hence, most finite-element methods compute the rest position by minimizing the energy of the mechanical system, through iterative methods. Among them, the Newton method is the most popular [16].

The context of cloth simulation is very particular, mostly because of the stiffness ratio between tensile and bending elasticity forces. While cloth materials are most of the time fairly inextensible, they can easily fold and buckle, and very small forces may indeed produce complete change in the fold patterns of the drape. Hence, an iterative relaxation process goes through a large varia-

Fig. 1. Design of high-quality garments (which typically exceed 10 000 polygons) require fast and efficient draping methods for computing the rest position of the garment on the body after each design or size change of the garment patterns

tion of object positions and shapes before reaching drape equilibrium. Though this specificity, ad hoc simulation systems were developed. Although some use models based on continuum mechanics [9], mostly use particle systems which trade accuracy for good computational speed along the versatility required for handling complex collisions [2–7, 14, 15, 17, 18]. More recent models achieve a good compromise between speed and accuracy by using particle-system representations of continuum models [11, 12, 20].

1.1 Dynamic simulation vs. draping

Cloth simulation systems have two main applications:

- *Dynamic simulation* aims at computing accurately the cloth motion along time, possibly on an animated character. Particle forces have to be computed precisely out of their positions and also their velocities.
- In contrast, *draping* only aims at computing the equilibrium position of the cloth. Velocity-dependent forces do not influence the final equilibrium position, and can therefore be ignored.

In practice, the main difference between these two systems lies in the numerical methods which are used for integrating the equations representing the mechanical system. While dynamic simulation requires the integration to preserve the dynamics of the system (through an explicit consideration of velocities and iterations along "real" time steps), draping only requires a numerical process that converges to equilibrium (minimum of mechanical energy or null forces) using as few iterations as possible through a numerical evolution of the position which is not necessarily consistent with dynamics.

1.2 Dynamic simulation for relaxation

In most existing cloth simulation models, there is indeed confusion between draping and dynamic simulation, as the techniques of the latter are used to achieve the goal of the former: It is only a matter to wait that the simulation of the cloth reaches equilibrium. Using explicit numerical integration schemes [7, 17], this involves mechanical dissipative terms to be explicitly modeled, such as material viscosity and aerodynamic damping. However, since implicit integration methods started to be used [1, 8, 13, 19], this dissipation could be obtained through the sole "numerical damping" resulting from the inaccuracy of these methods when using large time steps. Among the simplest and most commonly used implicit integration methods used for dynamic simulation, the backward Euler step relates the evolutions of particle positions $\Delta \boldsymbol{P}$ and velocities $\Delta \boldsymbol{P}'$ to the particle forces $\boldsymbol{F}$ during a time step $\mathrm{d}t$ as follows, $\boldsymbol{M}$ being the mass matrix of the particles:

$$\Delta \boldsymbol{P} = \Delta \boldsymbol{P}' \, \mathrm{d}t$$
$$\Delta \boldsymbol{P}' = \left(\boldsymbol{M}^{-1} - \frac{\partial \boldsymbol{F}}{\partial \boldsymbol{P}'} \, \mathrm{d}t - \frac{\partial \boldsymbol{F}}{\partial \boldsymbol{P}} \, \mathrm{d}t^2 \right)^{-1} \left(\boldsymbol{F} \, \mathrm{d}t + \frac{\partial \boldsymbol{F}}{\partial \boldsymbol{P}} \boldsymbol{P}' \, \mathrm{d}t^2 \right) \tag{1}$$

The primary interest of using dynamic simulation is the mechanical consistency in the evolution of the mechanical system: The motion of the objects is smooth and in accordance of mechanical conservation laws. Although a mechanically realistic cloth motion is not our primary interest, this ensures a "no-surprise" convergence toward realistic equilibrium states. If multiple local minimums are possible, the process will converge to the most mechanically sound position in accordance to the initial state of the system. Furthermore, the dynamic computations do not exhibit singularities and artifacts resulting from the underconstrained nature of cloth objects.

Another major interest results from the second-order nature of dynamical simulation, which accumulates velocities along time for a faster evolution of the system along long minimum energy paths with low slopes. Unfortunately, this second-order nature also introduces oscillatory behaviors around the equilibrium state, which seriously limit the interest of dynamic simulation for draping applications, and which cannot be suppressed through dissipative effects without significantly slowing down convergence.

As the rest position of the cloth does not have any velocity, we could obtain simplified quasistatic iterations by

removing the particle velocities components from Eq. 1, obtaining a truly first-order system:

$$\Delta \boldsymbol{P} = \left(\boldsymbol{M}^{-1} - \frac{\partial \boldsymbol{F}}{\partial \boldsymbol{P}} \, \mathrm{d}t^2 \right)^{-1} (\boldsymbol{F} \, \mathrm{d}t^2). \tag{2}$$

A major benefit of quasistatic iterations is that no oscillations which are proper to second-order dynamic iterations are exhibited. Unfortunately, ignoring velocities produces a very slow convergence. Taking advantage of the stability of implicit integration, we could consider increasing the size of the "time step", but this would indeed lead to Newton's method as discussed below.

1.3 Newton relaxation

A more formal way to perform relaxation would be to use Newton's method to find the zero-force equilibrium using the Jacobian [16]. This is indeed the most common way of finding energy minimums in the traditional Finite Element methods using in mechanical engineering. Indeed, a single Newton iteration is enough for finding the solution if the problem is perfectly linear, which is a classic approximation when dealing with small deformations [12]. It is expressed as follows:

$$\Delta \boldsymbol{P} = - \left(\frac{\partial \boldsymbol{F}}{\partial \boldsymbol{P}} \right)^{-1} \boldsymbol{F}. \tag{3}$$

It can be noted that these Newton iterations are indeed analogous to the asymptotic behavior of the quasistatic implicit Euler integration iterations Eq. 2 as the "time steps" become infinite.

Unfortunately, the Newton relaxation method is quite inappropriate for the context of cloth simulation. This is mainly because the mechanical system representing cloth objects is rather underconstrained, as cloth is quite freely moving thanks to its very low bending stiffness. Through this, the Jacobian usually has a very poor condition number, or may even not be invertible at all. This may prevent Newton iterations to be computed, or otherwise produce animations with large artifacts which, in the context of cloth simulation, could be highly problematic for a correct handling of collisions (Fig. 2).

Fig. 3. More than thousand Newton iterations are required for this complex rearrangement of wrinkles during relaxation, whereas dynamic simulation only requires a fraction of that (but it won't converge because of oscillations)

Also, the nonlinear nature of cloth might also produce instability patterns. These issues might be addressed by performing drastic a linearization of the Jacobian [6], but the convergence speed will largely suffer from it. Another solution would be to rather use quasistatic iterations Eq. 2 with a well-chosen "time step", also at the expense of convergence speed.

Another issue results from the large ratio between the stiffness of the tensile forces and the bending forces. Whereas tensile relaxation is obtained fairly quickly, relaxation has then to proceed through a long, narrow and complicated energy minimum path with very low slope corresponding to the evolution of the cloth bending toward equilibrium. The Conjugate Gradient process, which suffers from the significant nonlinearity of cloth models (mainly resulting from large orientation changes of the mechanical elements), is particularly inefficient for that. For instance, this situation occurs when simulating the formation and evolution of wrinkle patterns (Fig. 3).

Through this work, we show that combining dynamic simulation with a very simple "stop-and-go" scheme that globally cuts away velocity at well-defined moments is indeed a very good solution for fast convergence toward the rest state of cloth. In the following sections, we describe the method and demonstrate its performance in several contexts of cloth simulation.

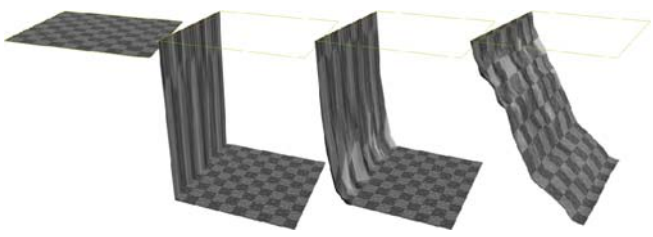

Fig. 2. Iterations 1, 2, 4, 8 of the Newton method on an initially flat cloth square hanging along one of its edge. The first iteration exhibits a huge overshooting because an almost singular Jacobian

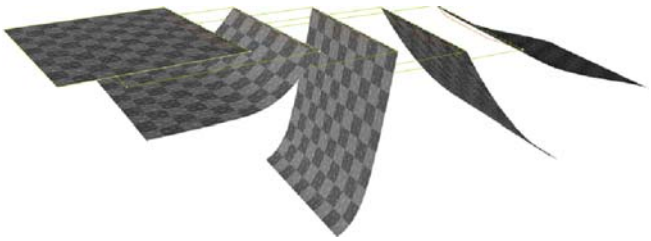

Fig. 4. The dynamic simulation of an initially flat 50 cm × 50 cm cloth square hanging along one of its edge, weight 0.1 kg/m^2, tensile elastic stiffness 10 N/m, simulated with backward Euler iterations Eq. 1, 20 ms time steps. Shown iterations: 0, 8, 16, 24, 32

2 Stop-and-go relaxation

During a dynamic mechanical simulation, there is a constant exchange between various forms of mechanical energies. Among them:

- The *potential energy of internal deformation* results from the elasticity forces of the material according to its deformation.
- The *potential energy of gravity* results from the gravity forces according to the altitude of the material.
- The *kinetic energy* results from the velocity of the material.

Energy is typically dissipated by mechanical forces opposing the velocities, or, during the simulation process, by the numerical errors resulting from the numerical integration of the mechanical equations. When dissipation is low enough, the energy exchange exhibits oscillation cycles between the kinetic energy and the potential energy represented by elasticity and gravity (Fig. 5). The mechanical object is at rest when the geometric position of the object corresponds to a local minimum of the potential energy with zero velocity.

While damping would help reduce the total energy of the system by reducing the velocity (and therefore the kinetic energy), this solution is in practice not quite appropriate, as low velocity also means slow position changes, and therefore slow convergence toward equilibrium (Fig. 6). Furthermore, it is not visible to devise a "critical viscosity" which would produce the fastest non-oscillatory convergence for all possible deformation modes of a complex object such as deformed cloth.

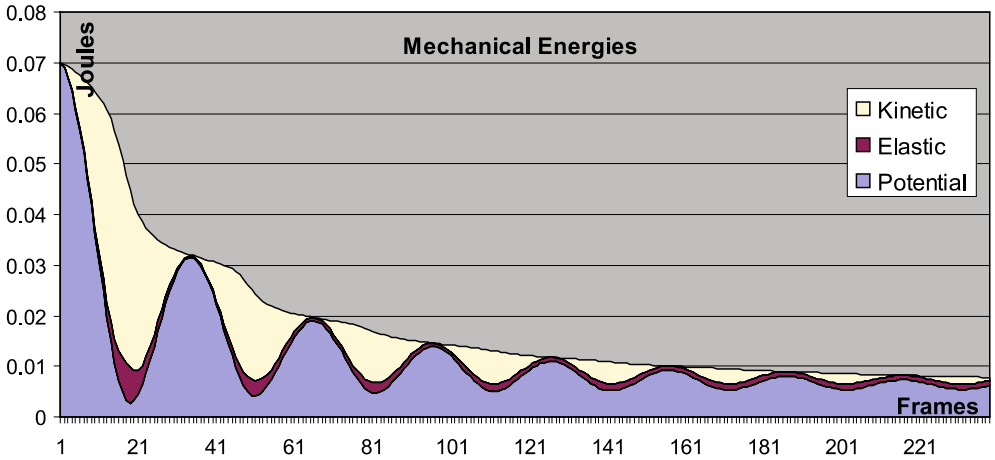

Fig. 5. Exchanges of mechanical energies during a dynamic simulation shown in Fig. 4, with low damping

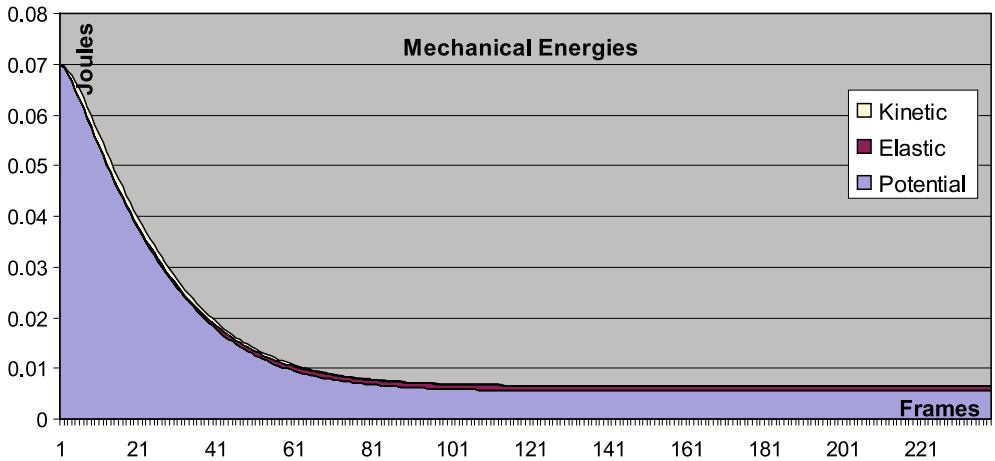

Fig. 6. Exchanges of mechanical energies during a dynamic simulation with high damping

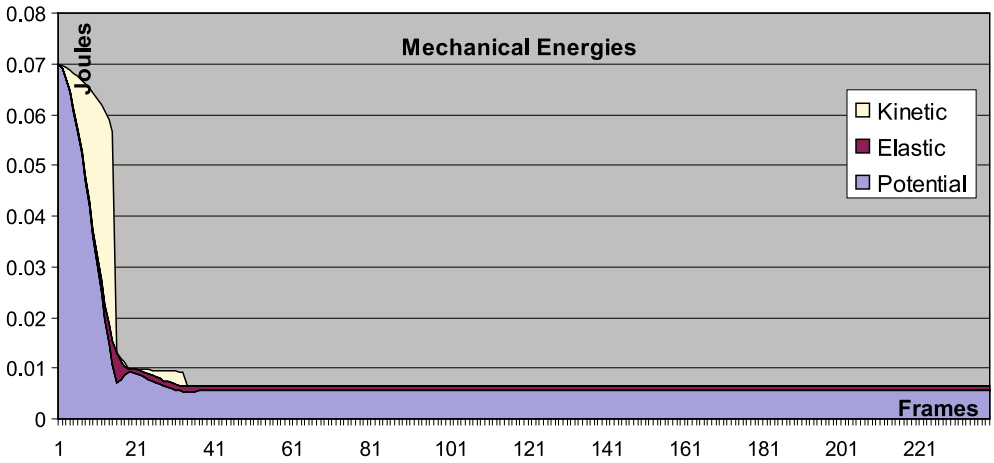

Fig. 7. Exchanges of mechanical energies during the stop-and-go dynamic simulation with low mechanical damping. Stops, where velocities are cut away, occurred at frames 16, 19, 34, 38, 45, 61, 68, 75

2.1 Description of dynamic stop-and-go

The basic idea of stop-and-go relaxation is very simple: Performing a dynamic simulation, we strip away mechanical energy from the system by removing velocity from the mechanical system at well-chosen moments (Fig. 7). The process goes as follows:

- Starting from the initial position, we perform a dynamic simulation of the system, ideally with as low damping as possible (without any viscous forces).
- As soon as the total potential energy resulting from conservative forces reaches a minimum, we set all velocities of the system to zero, and we resume the dynamic simulation.
- We stop the draping process through usual convergence criteria, such as using a residual force threshold.

If dissipation is low enough for having approximate total energy conservation during the simulation, it is also possible to cut the velocities rather when kinetic energy reaches a maximum. The evaluation of kinetic energy is most of the time far less computation-consuming than the evaluation of the potential energy resulting from gravity and internal elasticity.

It is interesting to observe that the successive stops of the process cut away, one by one, the main oscillation modes of the mechanical system. Hence, in the cloth draping of Fig. 4, the first stop cuts away the main fall, the second cuts away tensile elongation, the third cuts away horizontal bending, then higher mode deformations . . . . The "global" nature of the stop-and-go process seems to take advantage of some kind of orthogonality between the different oscillation modes.

Since cutting velocities away strips away mechanical energy (by removing all kinetic energy) without altering the position of the object (and therefore its potential energy), we ensure that the process will effectively converge to an energy minimum.

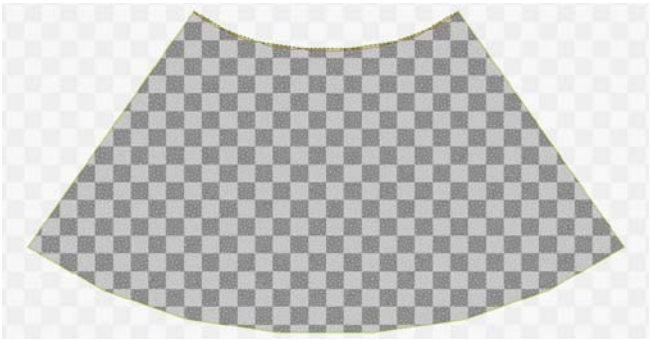

Fig. 8. The initial geometry of the cloth, initially horizontal, attached along the upper arc. A square is 5 cm × 5 cm. The surface is discretized into approximately 19 000 triangles. Weight 0.1 kg/m^2, tensile elastic stiffness 10 N/m

2.2 Performance

We have implemented the stop-and-go relaxation scheme in a cloth simulation system that uses Inverse Euler numerical integration as used in [1, 19, 21], along other integration schemes, explicit (Runge–Kutta [7, 17]) or implicit (BDF-2 [13]).

Our first test was performed on the high-resolution cloth shown in Fig. 8 and draped as in Fig. 3. The initial configuration was obtained by performing a drape with a fairly high elastic bending elastic stiffness of 0.001 Nm. Reducing this stiffness by a factor 100, we compute the evolution of the wrinkles toward the new drape.

The convergence rate is quantitatively evaluated by measuring the evolution of the elastic and gravity potential energies toward the rest state.

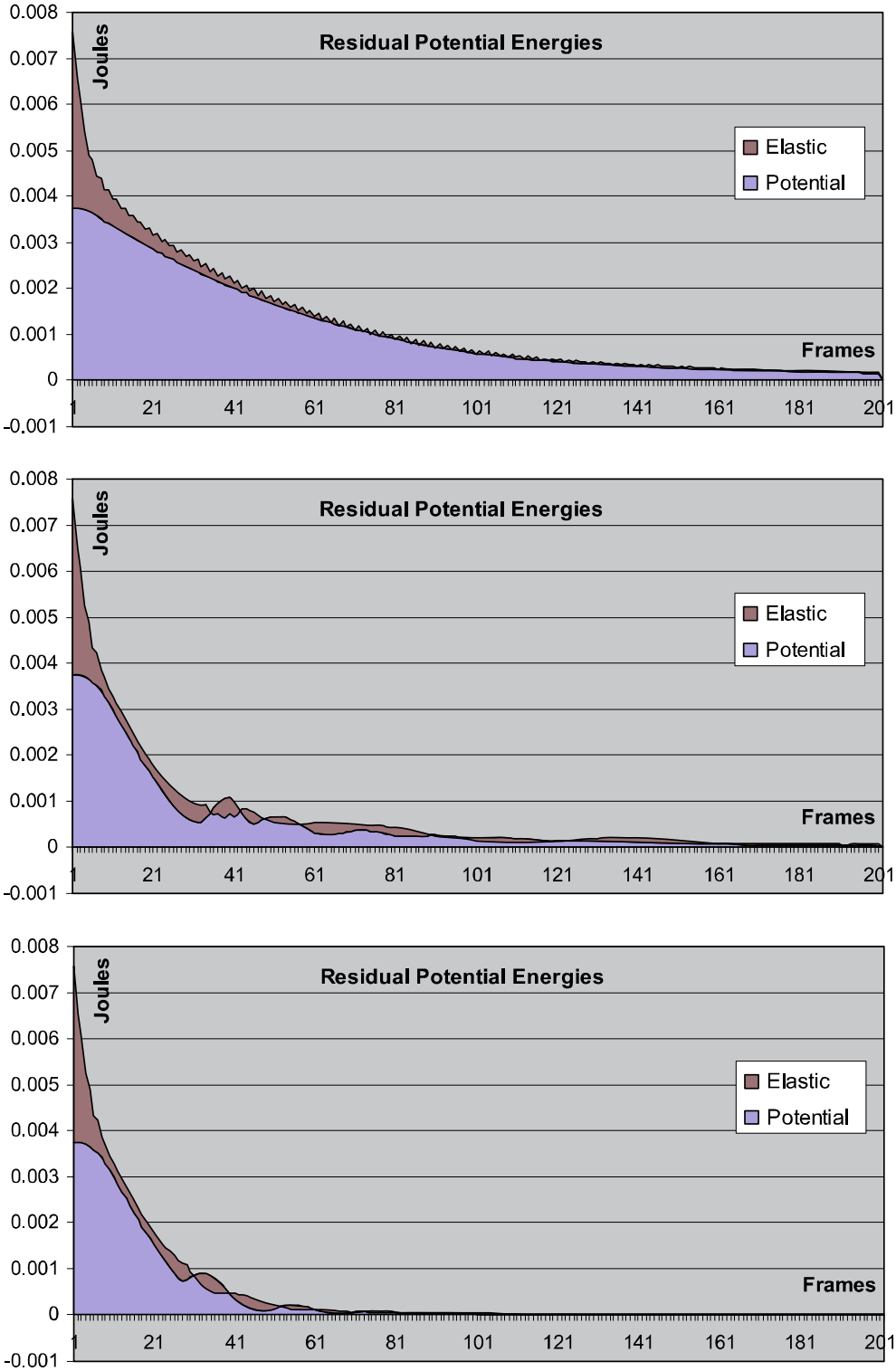

Fig. 9. Residual potential energy values along the iterations for the wrinkle relaxation using Newton's method (*top*), regular dynamic simulation (*middle*) and dynamic stop-and-go simulation (*bottom*)

Whereas initial wrinkles appear quite quickly during the first iterations, the Newton relaxation method then struggles to rearrange them into a configuration that fulfills a better global equilibrium. Meanwhile, dynamic simulation is more prone to make them evolve, as velocity accumulates for displacing them significantly along very small energy gradients. Furthermore, the stop-and-go scheme prevents the oscillations of dy-

Fig. 10. Starting from the initial fold pattern (*center*), after 100 iterations, the dynamic Stop-and-Go drape process (*left*) exhibits even wrinkles close to the rest state, whereas the Newton relaxation drape process (*right*) is still far

Fig. 11. From an initial design position (*left*), the garment is first draped on the character (*center*), then redraped after resizing (*right*)

namic simulation, leading to an even faster convergence.

In this test, the Newton relaxation scheme requires more than 1500 iterations for reaching the residual potential energy level obtained through dynamic stop-and-go with 100 iterations. Because of the oscillations, usual dynamic simulation still requires about 400 iterations.

Our other test considers the dressed character of Fig. 1. The high-resolution garment surface contains around 30 000 polygons, and the mechanical behavior is modeled using a highly accurate nonlinear representation of the strain-stress curves of fabric materials [20]. Starting from an initial undraped position, we drape it to the rest position on the character and then redrape it after changing the pattern sizes (Fig. 11).

We have compared the efficiency of stop-and-go dynamic simulation against regular simulation for performing these tasks. It was not possible to use Newton relaxation in this context, mainly because of computational problems resulting from the collisions against significantly extended cloth on the upper body.

Fig. 12. High-quality drape of complex garments on arbitrary body postures

As a result, we have observed that while regular dynamic simulation requires more than 650 iterations for reaching visible stability of the cloth, this is obtained with stop-and-go with only 150 iterations. Meanwhile, garment resizing requires more than 400 iterations with regular dynamic simulation, and only 80 with stop-and-go. Using our C++ implementation on a 3 GHz PC, we find that both methods require roughly 0.6 seconds per iteration.

We have attempted to speed up convergence of regular dynamic simulation through the addition of various mechanical damping, either external (air viscosity) or internal (material viscosity), without any significant success, as any value preventing oscillations would excessively slow down speed toward equilibrium.

In the meantime, we have also attempted several local correction schemes on the particle velocities relatively to the particle forces (such as locally removing velocity components moving against the force), but these approaches have not shown any convincing benefits compared to the global stop-and-go scheme that we propose. The problem with these local schemes seems to result from the

inconsistent mechanical motion they induce on the global dynamic behavior of the object.

Our draping method has been successfully integrated in a high-quality garment simulation system which is able to simulate simultaneously several complex multi-layer garments on virtual characters (Fig. 12). While the cloth motion toward the desired body posture is obtained through regular dynamic simulation, stop-and-go dynamic simulation offers quick oscillation-free convergence of the garment drape on the final posture.

3 Conclusion

We have demonstrated the efficiency of the very simple stop-and-go scheme for draping cloth complementing a standard dynamic cloth simulation system. Compared to cloth simulation alone, several times less computational iterations are required to reach equilibrium, whereas other mathematical minimization techniques, such as Newton iterations, are not adapted at all for the context of cloth simulation. This efficiency is used for speeding up the draping process of high-quality garments.

Stop-and-go relaxation requires that all forces involved in the mechanical model to be either conservative (they derive from a potential energy) or dissipative (they dissipate mechanical energy). Collision contact forces are acceptable as long as the collision objects are all part of the simulated mechanical system, or non-moving. Performance is best when dissipative forces are as low as possible. In the context of garment simulation, stop-and-go can be used for draping garments over a non-moving virtual character (Fig. 11). Ideally, the model should take into account only the internal elasticity of the cloth material, gravity forces and collision forces.

Another major interest is that stop-and-go relaxation can be implemented with any kind of dynamic simulation, and the numerical integration method does not need to be implicit. While implicit methods have a major interest in draping applications through the use of large time steps as motion accuracy is not expected, simple explicit methods such as Runge–Kutta may also be used, without the need of computing the Jacobian of the forces and solving any linear system. In the context of garment simulation, we have observed best performance when using the backward Euler numerical integration method with fairly large time steps, but small enough for preserving approximately the dynamic motion behavior of the garment without introducing the artifacts typical of Newton iterations in the context of highly nonlinear and underconstrained models.

While a major feature of the presented stop-and-go relaxation scheme is its simplicity and generality, there are still numerous possibilities of improvements for this method. Although we have shown the practical efficiency of this very simple method, it would be worth carrying out the theoretical mathematical study a bit further, which could lead to variants with better efficiency, possibly through adapted velocity corrections of the mechanical system over given surface regions.

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DR. PASCAL VOLINO is a computer scientist and researcher. He studied engineering sciences in Lyon, France and graduated in 1992. He then joined MIRALab, University of Geneva, and has since then been working on various topics, including techniques for collision detection, mechanical simulation and user interaction. He obtained his Ph.D. in 1998 on the topic of garment simulation. He is currently involved into several European projects involving accurate or real-time cloth simulation, virtual garments and hair animation.

PROF. NADIA MAGNENAT-THALMANN has pioneered research into virtual humans over the last 25 years. She obtained her Ph.D. in quantum physics from the University of Geneva. From 1977 to 1989, she was a professor at the University of Montreal, where she founded the research lab MIRALab . She was elected 'Woman of the Year in the Grand Montreal for her pioneering work on virtual humans and presented the Virtual Marilyn at the Modern Art Museum of New York in 1988.
Since 1989, she has been a professor at the University of Geneva, where she recreated the interdisciplinary MIRALab laboratory. With her 30 Ph.D. students, she has authored and coauthored more than 300 research papers and books in the field of modeling virtual humans. She is presently coordinating three European Research Projects (INTERMEDIA, HAPTEX and 3DANATOMICAL HUMANS).