Vision, Modeling, and Visualization (2013)
Michael Bronstein, Jean Favre, and Kai Hormann (Eds.)

Cloth-Fluid Contact

M. Huber[1,2], B. Eberhardt[2] and D. Weiskopf[1]

[1]University of Stuttgart, Germany
[2]Stuttgart Media University, Germany

Abstract

We present a robust and efficient method for the two-way coupling between particle-based fluid simulations and infinitesimally thin solids represented by triangular meshes. Our approach is based on a hybrid method that combines a repulsion force approach with a continuous intersection handling to guarantee that no penetration occurs. Moreover, boundary conditions for the tangential component of the fluids velocity are implemented to model the no-slip boundary condition. The proposed method is particularly useful for dynamic surfaces, like cloth and thin shells. In addition, we demonstrate how standard fluid surface reconstruction algorithms can be modified to prevent the calculated surface from intersecting close objects. We have implemented our approach for the bidirectional interaction between liquid simulations based on Smoothed Particle Hydrodynamics (SPH) and standard mesh-based cloth simulation systems.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Animation

1. Introduction

Physics-based simulation methods for deformable solids and fluids have become indispensable in the creation of high quality animations. With these techniques, detailed behavior of cloth and complex fluid phenomena can be reproduced to generate physically plausible animations. Especially for VFX productions it is obvious that these objects have to interact with each other. In this work, we address the interaction and contact of fluids with infinitesimally thin deformable objects, like cloth or thin shells. We focus on state-of-the-art cloth simulation systems that use mesh representations of the cloth surfaces and on particle-based methods, such as SPH, to simulate fluid dynamics.

In this paper, we present an approach to overcome the difficulties of modeling the interaction and contact of the respective simulation approaches. Regarding the coupling of cloth and particle-based fluids, the special characteristic of cloth being represented as two-manifold surfaces that have no inside and outside, requires particular attention. During the interaction process, it is necessary to prevent the fluid particles to move from one side of the cloth surface to the other, often referred to as leaking. Once a particle has moved to the wrong side of the cloth mesh, it is very difficult to correct the situation even in postprocessing.

Having dealt with the interaction, another problem arises in the simulation pipeline: In many particle-based fluid systems, a marching cubes (MC) [LC87] based surface reconstruction pipeline is used to create a polygon mesh of the fluid surface. In the reconstruction process, the calculated surface mesh might intersect the surface mesh of close objects. While this is easily fixed with volumetric objects in postprocessing, difficulties occur with two-dimensional manifolds. Especially in case of highly flexible materials like cloth that result in folds and wrinkles during the simulation, extensive intersections with the generated fluid surface occur. These material intersections do not only produce implausible visual artifacts, but can also cause difficulties in rendering liquid materials, like water, when generating images with a raytrace-based renderer.

In this paper, we present an approach to treat these two main difficulties at contact between cloth and particle-based fluids. In Section 3, we demonstrate how particle-based fluids can be coupled with thin deformable surfaces using repulsion forces and a continuous intersection test that robustly prevents the fluid leaking through the surface. With the continuous intersection handling, two-way coupling is achieved preventing leaking that is not bound to small time steps. In addition to the separation in normal direction, we employ a boundary condition that affects the tangential component of

DOI: 10.2312/PE.VMV.VMV13.081-088

the velocities, thus modeling the no-slip boundary condition. The presented methods are designed to be independent of the internal specifics of the simulation systems so that they can be integrated in common simulation environments. Furthermore, we discuss the differences to previous approaches using boundary particles. In Section 4, we present a method to reconstruct the surface of the particle-based fluid at complex boundaries in an MC-based pipeline. With our proposed method, it is possible to extract an intersection-free surface mesh at cloth-fluid contact.

To cover the aspect of wetting at cloth-liquid contact, we additionally implemented the absorption and diffusion model of Huber et al. [HPS11] for the results section.

2. Related Work

For particle-based fluids, rigid-fluid coupling is often achieved by transforming the solid to a particle representation. Monaghan [Mon05] replaces boundaries with particles and avoids penetrations by applying a repulsion force between the particles. Becker et al. [BTT09] use direct forcing to achieve two-way rigid-fluid coupling with particle-sampled rigid bodies. This approach is extended by Ihmsen et al. [IAGT10] by including boundary particles in the fluids SPH computation. Recently, Akinci et al. [AIA*12] have presented a method for the two-way coupling of SPH-based fluids with rigid bodies represented with particles. They include the rigid body particles in the SPH computation to handle density discontinuities and their approach also considers one-layered particle objects.

To simplify the interaction of fluids and solids, Keiser et al. [KAG*05] present a unified particle model for the interaction and phase change of objects. Elastic forces are calculated using moving least squares (MLS). Solenthaler et al. [SSP07] extend this approach by developing a purely SPH-based particle model that also does not need an interface for coupling. This model is modified by Lenaerts and Dutré [LD08] to cope with thin objects like cloth. However, this approach is limited because it does not allow material stretching for cloth, just bending. Their work adds explicit collision handling to avoid leaking.

In the case of deformable objects, Müller et al. [MST*04] place virtual boundary particles on the surface of the deformable object and use a Lennard-Jones like force to model repulsion and adhesion. However, their approach requires small time steps to ensure that particles do not penetrate the solid. To overcome leaking issues with boundary particles, Akinci et al. [ACAT13] extend the rigid-fluid coupling approach of [AIA*12] for elastic objects and introduce an adaptive boundary sampling scheme to avoid over- and undersampling of meshes at deformation. Yang et al. [YLHQ12] generate proxy-particles during runtime at contact points and apply coupling forces with the direct forcing approach of [BTT09]. Like all methods that rely on inter-particle interaction, the contact distance depends on the particle radii.

Recently, Du et al. [DTM*12] have presented an approach for the bidirectional interaction of cloth and fluids without boundary particles similar to ours. They also use a continuous intersection test to ensure that fluid particles do not penetrate the cloth, however they use elastic impulses to separate the objects and they do not consider tangential boundary conditions (e.g. no-slip).

Collision handling methods are related to our approach. We refer the reader to the state-of-the-art report [TKH*05] for a comprehensive overview.

There are several approaches for the surface reconstruction for particle-based fluids. The main challenge in the development of these techniques is to overcome the bumps of classical blobbies and to generate a smooth surface that represents the fluid in a visually plausible and appealing manner, despite irregular particle distributions. Müller et al. [MCG03] represent the surface as the isosurface of a density field of the particles. Although this approach results in fewer bumps on the surface, they are still clearly visible. The approach of Yu and Turk [YT10] is also based on a density field. They overcome the problem of irregular particle distribution and use an anisotropic kernel to capture the smooth shape of the free surface more accurately. Zhu and Bridson [ZB05] achieve smooth surfaces based on a distance field over the particles. This approach is improved by Adams et al. [APKG07] by tracking the particle to surface distance over time. Both of these methods suffer from artifacts in concavities and between particles with a certain distance. Solutions to this problem are proposed by Solenthaler et al. [SSP07] and Onderik et al. [OCD11]. None of these methods considers areas of contact with other, not to mention thin, deformable objects in a scene.

The interaction of cloth and fluids is not only limited to boundary handling, as most fabrics absorb fluid upon contact that is complementary to our work. Lenaerts et al. [LAD08] apply their porous flow model to a simple particle-based cloth model. In the work of Chen et al. [CMTA12], wet cloth is modeled with measured data for friction and wrinkling based on the imperfection sensivity theory. In particular, we use liquid transport in cloth based on a diffusion model and absorption that is introduced by Huber et al. [HPS11].

For the simulation of fluids with the Eulerian approach, coupling to thin deformable objects is covered by Guendelman et al. [GSLF05]. Fully two-way coupling is achieved by Robinson-Mosher et al. [RMSG*08] and later extended with the accurate handling of tangential velocities [RMEF09].

3. Two-way Coupling

To achieve a plausible motion upon contact, it is necessary that the fluid affects the cloth object and vice versa. In this context, cloth is considered as impenetrable and therefore, it is crucial to prevent particles from intersecting the cloth mesh. We model the bidirectional interaction between the cloth and the fluid particles with repulsion forces. Our approach is based on the point-triangle collision handling of Bridson et al. [BFA02] for cloth.

3.1. Interaction Detection

Similar to their approach, we model the cloth of thickness h. If the distance of a particle's center and the cloth mesh is within this threshold, a repulsion force is applied to prevent a possible intersection and to make the particle move smoothly along the cloth surface. Therefore, it is necessary to test if a particle is located within the defined threshold in the first place. We follow the notation of [BFA02] with a mesh triangle represented by its corner vertices $\mathbf{x}_1\mathbf{x}_2\mathbf{x}_3$ and $\mathbf{x}_{ij}$ to represent $(\mathbf{x}_i - \mathbf{x}_j)$. A particle's center is defined as $\mathbf{x}_p$. The proximity test consists of two parts. At first, the distance between the particles center and the plane containing the triangle is calculated and checked against the thickness with

$$|\mathbf{x}_{p3} \cdot \mathbf{n}| < h, \tag{1}$$

where $\mathbf{n}$ is the normal of the triangle $\mathbf{x}_1\mathbf{x}_2\mathbf{x}_3$ and $\mathbf{x}_{p3}$ the vector from the particle to $\mathbf{x}_3$. If the particle is close, the particle's position is projected onto the plane in order to evaluate if the position lies within the edges of the triangle. This is done by calculating the barycentric coordinates of the projected position on the triangle. This process results in a set of particles and triangles that are possibly in contact.

3.2. Impulse Coupling

To prevent a particle from intersecting the cloth surface, we add a repulsion force to particle-triangle pairs to keep the particle and triangle apart.

To prevent an impending intersection, a stopping impulse is applied if the particle and triangle approach each other. This is the case if the relative velocity $\mathbf{v}_r$ of a particle and a triangle is negative, where $\mathbf{v}_r = \mathbf{v}_p - \mathbf{v}_T$ and $\mathbf{v}_p$ and $\mathbf{v}_T$ are the particle's and triangle's velocity. The impending intersection is stopped by adding an inelastic impulse to the repulsion force to keep the particles and the cloth mesh separated. Thus, we avoid adding stiffness to the system at this point and the fluid can move smoothly along the cloth surface. Following the approach of [BFA02], the impulse

$$\mathbf{I}_c = m\mathbf{v}_n \tag{2}$$

is applied to the triangle and the particle in normal direction. To apply the impulse to the cloth triangle, it is directly distributed to its nodes weighted with the barycentric coordinates w_i to ensure appropriate torsional moments. The impulse is adjusted with the appropriate masses to excert on the particles and the respective nodes of the cloth.

As stated in Section 3.1, a thin region around the cloth mesh is defined to model the thickness of the cloth. To ensure that this particle-triangle distance is kept, an elastic impulse is applied over multiple time steps once an intersection is prevented. The impulse is proportional to the distance so that it is maximal when the particle touches the mesh triangle. The overlap beyond the cloth thickness h is calculated by

$$d = h - (\mathbf{x}_p - w_1\mathbf{x}_1 - w_2\mathbf{x}_2 - w_3\mathbf{x}_3) \cdot \mathbf{n}. \tag{3}$$

The impulse is then calculated by

$$\mathbf{I}_s = -kd\Delta t. \tag{4}$$

We apply the impulse sequentially in a Gauss-Seidel style iteration.

Using the above mentioned repulsions, most of the possible intersections can be successfully handled in an efficient manner and the fluid moves smoothly along the cloth surface. In contrast to coupling techniques that use particle-sampled solids or introduce proxy-particles (e.g. [YLHQ12]), our approach provides full control over the distance between particles and the cloth mesh.

However, it is not possible to prevent all the fluid particles from penetrating the cloth mesh because repulsion forces are only applied at discrete times. Especially in the case of large time steps, particles can change sides of the surface unnoticed. At this point, if a particle has leaked through the surface, the intersection cannot be detected because cloth is represented as an infinitesimally thin surface with no inside or outside. In the subsequent steps, repulsions will keep leaked particles on the wrong side of the cloth. Therefore, intersections in-between a time step have to be detected.

3.3. Geometric Intersection Handling

To this end, we extend our approach considering the path of the moving particle-triangle pairs in between a time step. Since in the first phase, the intersection detection can fail to detect penetrations, we employ this second phase with continuous intersection handling. The goal of this step is to detect the intersection between time steps and calculate the time and positions of the features at impact to prevent the intersection.

This step of our approach is based on the work of Provot [Pro97]. As shown in Figure 1, a particle can move through a triangle of the cloth mesh in-between a time step Δt, especially when using large time steps. To prevent the intersection, the time t_c at which the three nodes of the moving triangle and the moving particle are coplanar has to be determined (see Figure 1). Similar to [Pro97], we assume constant velocity for both the triangle and the particle over the time step:

$$\begin{aligned} \mathbf{x}_1(t) &= \mathbf{x}_1 + t\mathbf{v}_1 \\ \mathbf{x}_2(t) &= \mathbf{x}_2 + t\mathbf{v}_2 \\ \mathbf{x}_3(t) &= \mathbf{x}_3 + t\mathbf{v}_3 \\ \mathbf{x}_p(t) &= \mathbf{x}_p + t\mathbf{v}_p. \end{aligned} \tag{5}$$

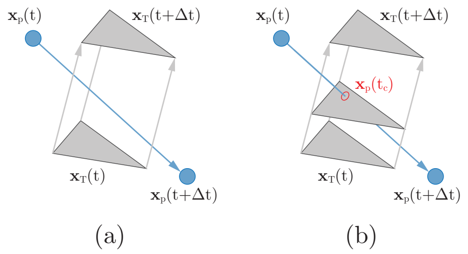

Figure 1: *Intersection in-between a time step: (a) A particle is intersecting a moving triangle without being detected. (b) With the continuous intersection test, the particles position at contact $x_p(t_c)$ is detected.*

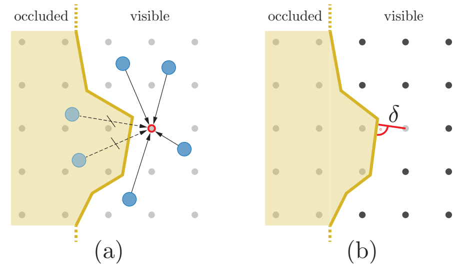

Figure 2: *2D view of the MC grid at a contact area: (a) For the calculation of the scalar values on MC grid nodes, only particles in the visible region contribute. (b) Grid nodes are skipped if the distance δ to the closest face of the cloth mesh is smaller than a certain threshold.*

With this, the unknown time t_c is obtained by finding the roots of the cubic equation

$$((\mathbf{x}_{21}+t_c\mathbf{v}_{21})\times(\mathbf{x}_{31}+t_c\mathbf{v}_{31}))\cdot(\mathbf{x}_{p1}+t_c\mathbf{v}_{p1})=0. \quad (6)$$

For roots in $[0,\Delta t]$, a proximity test is performed. As proposed by Bridson et al. [BFA02], we use a rounding error tolerance in the root finding process and check for collisions at the end of the time step.

3.4. Tangential Boundary Conditions

In Section 3.2, we demonstrated how to prevent the fluid from intersecting a surface by correcting the components of the velocities in the normal direction. However, there are additional boundary conditions regarding the tangential component of the velocity that have to be considered. As stated in fluid simulation literature, e.g. [BMF07], letting the tangential component of the fluids velocity untouched is only valid for an inviscid fluid. We model the no-slip boundary condition where the fluid has zero velocity relative to the boundary. In our case, it means that the fluid does not have any velocity in the tangential component relative to the cloth at the contact surface:

$$\mathbf{v}_t^{triangle}\times\mathbf{n}=\mathbf{v}_t^{particle}\times\mathbf{n}. \quad (7)$$

We achieve the no-slip boundary condition by setting the tangential component of the velocity to

$$\mathbf{v}_t=\max\left(1-\frac{\Delta\mathbf{v}_N}{|\mathbf{v}_t^{pre}|},0\right)\mathbf{v}_t^{pre}, \quad (8)$$

where $\mathbf{v}_t^{pre}$ is the tangential component of the relative velocity at the beginning of the time step.

3.5. Differences to Boundary Sampling Approaches

With the approach of coupling fluids and solids using boundary particles, it is possible to model the coupling effects and different boundary conditions by the interaction of pairwise particles. The generated boundary particles on the interacting object can be incorporated into the SPH computation of the fluid. The main challenge there is to sample the deformable mesh consistently, adjusted to the size of the fluid particles. In this paper, we follow a different approach: Coupling is achieved with the exchange of impulses between the fluid particles and the simulation mesh directly. Thus, boundary conditions can be calculated in the quality given by the simulation mesh. By avoiding any sampling of the cloth and the consequential need for resampling if deformations occur, temporal coherence of the treatment of the boundary is guaranteed and all cloth details, such as folds and wrinkles, are considered. In contrast, with boundary sampling, the resolution of the boundary conditions calculation is bound to the particle size of the SPH simulation. This also does not allow one to model an arbitrary thickness of the cloth that can be used to control the distance between the fluid particles and the cloth mesh.

In our approach, the interaction and calculation of boundary conditions is implemented as a module that couples the simulation engines in a separate process. No additional particles have to be integrated in the SPH computation loop and different simulation engines can be coupled without altering their internal systems.

4. Surface Reconstruction at Contact

As mentioned in Section 2, there are several methods for the reconstruction of surfaces for particle-based fluids. With most of the popular MC-based surface reconstruction methods, the resulting surface mesh has a certain offset to the fluid particles. Therefore, when using small contact distances between particles and moving objects, the reconstructed surface mesh of the fluid will intersect the mesh of objects in contact. To resolve these intersections, snapping the vertices of the surface mesh to the boundary, as proposed for example by Harada et al. [HKK07], is one possible approach. Snapping surface vertices, however, can result in (self-) intersections of the meshes. While this could work satisfactorily in case of large area boundaries, e.g. con-

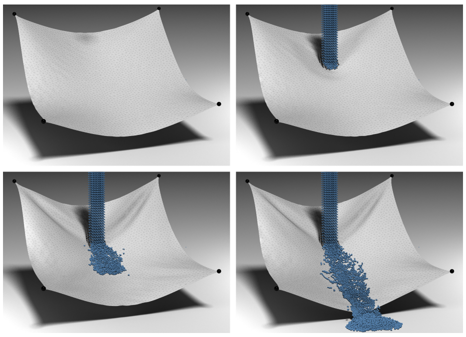

Figure 3: *A jet of water hits a piece of cloth that is pinned at its corners without leaking.*

tainer walls, it would lead to defective meshes with complex boundaries. Another possibility is to solve these intersections manually in a postprocessing step. This however, is a time consuming task and in some cases, it is very hard or even impossible to eliminate all the intersections.

Therefore, we modify the surface reconstruction algorithm to eliminate possible intersections. In common surface reconstruction algorithms, the scalar values ϕ on the marching cube grid are calculated based on contributions of nearby particles. This holds for both mentioned approaches in Section 2: the density field approach as well as the distance field approach. When iterating over the neighboring particles, we use a visibility criterion to determine if the particle contributes to the current scalar value. From the perspective of any grid node, we divide the domain in a visible and occluded region. A point in space is visible if the line segment from the reference point to the point does not intersect the cloth mesh (see Figure 2 (a)). If a particle is located in the occluded region in the perspective of a grid point, it does not contribute to the scalar value computation. With this step, we prevent particles located in the occluded region to contribute to the surface computation.

At this point, it is still possible that the resulting surface mesh intersects the cloth mesh. Therefore, we additionally iterate over the grid nodes after the scalar value computation to identify close faces of the cloth mesh. If the distance of a face of the cloth mesh to a grid node is smaller than a threshold δ, the scalar value of the grid node is reset and does not contribute to the surface generation in the marching cubes algorithm (see Figure 2 (b)).

With these proposed techniques, we prevent costly and error-prone repositioning of surface mesh vertices. In combination with the cloth thickness value h as mentioned in Section 3.2 that models the interaction distance in the cloth-fluid coupling process, it is possible to control the location of the fluid surface at contact which helps eliminate unwanted reflection and refraction occurences when rendering transparent surfaces.

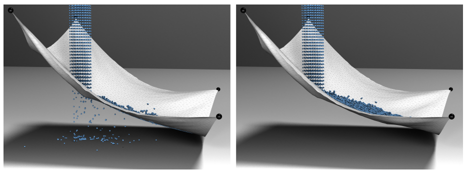

Figure 4: *Side view of the first scene. Left: With penalty forces only, fluid particles can leak through the cloth surface. Right: With our continuous intersection handling, leaking is prevented.*

5. Implementation

Our approach for the interaction between the fluid and the cloth simulation of Section 3 is independent of the particular choice of the simulation engine. Any of the well-established particle-based fluid simulation systems can be coupled with state-of-the-art cloth models as long as the cloth is based on a triangle mesh. As input to our system, only the positions of the current and the previous time step of the particles and the mesh nodes are needed. This is an important property of our approach since existing simulation systems can be extended with our technique without altering the existing system.

We conducted our experiments with cloth simulators based on the continuum mechanics derived cloth models of Volino et al. [VMTF09] and Etzmuss et al. [EKS03], combined with the simple linear bending approach of [VMT06]. However, methods based on the mass-spring model are also possible. For the simulation of fluids, we employ a standard SPH-based model [MCG03]. Since our method is able to prevent leaking even at large time steps, the predictive-corrective incompressible SPH (PCISPH) method [SP09] is particularly suitable.

To speed up the detection of possible close particle-triangle pairs of the presented two-way coupling technique in Section 3, we employ a spatial hashing technique [THM*03].

For the surface reconstruction, the scalar value computation is based on the method of Zhu and Bridson [ZB05]. We added the modifications of Onderik et al. [OCD11] to avoid the artifacts resulting from uneven particle distributions. Our method to reconstruct the fluid surface at complex boundaries, however, is not limited to a certain method to calculate the scalar values. It can be employed in any MC-based surface reconstruction pipeline that uses one of the surface reconstruction methods mentioned in Section 2.

6. Results

We have implemented our proposed methods in C++ and all the following test scenes have been performed on an Intel Core i7-2600 processor at 3.4 GHz. For all scenes, the given length unit is m and the time unit is s. The simulations and

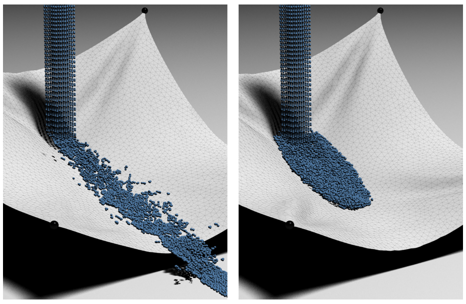

Figure 5: *Tangential boundary conditions. Left: Free slip at cloth-fluid contact. Right: No-slip at the cloth-fluid boundary.*

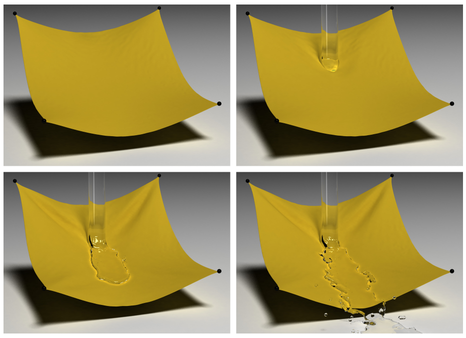

Figure 7: *Transparent rendered surface of the scene in Figure 3.*

the intersection handling are calculated with a constant time step of $\Delta t = 0.001$. The resting distance for the SPH simulation is 0.005 for all scenes.

As shown in Figure 3, the water flows off the cloth that stretches under the weight of the jet producing wrinkles. Our two-way coupling system reliably prevents fluid particles from leaking through the cloth mesh. In our first experiment, a jet of water hits a pinned piece of fabric. The cloth mesh consists of about 6300 faces and there are up to 15K fluid particles in the scene. In Figure 4 (left), we demonstrate that penalty forces are not sufficient to prevent fluid particles from intersecting the object in contact using a small h (0.001) and a time step of 0.001. With the proposed continuous intersection handling, robust two-way coupling without leaks even with large time steps (Figure 4, right) is achieved.

In the second scenario, different boundary conditions for the tangential component of the velocity at cloth-fluid contact are used. As shown on the left side of Figure 5, the tangential component of the boundary handling is unchanged and the effect of inviscid flow at contact can be observed. In Figure 5 (right), the no-slip boundary condition as presented in Section 3.4 is shown. A full animation can be found in the accompanying video. The velocity of the particles at contact matches the velocity of the respective cloth triangle. If the resolution of the fluid is chosen high enough (millions of particles), the effect of a thin film of water on the cloth is achieved and the rest of the water flows off the cloth.

Figure 6 shows an opaque surface rendering of the first scene using a cell size of the MC grid of 0.004. The frontal view (left) does not reveal any intersections. However, if the camera position changes as shown in Figure 6 (middle), intersections between the cloth mesh and the surface mesh are observed at the bottom side of the cloth despite a certain thickness of the cloth. With our modified surface reconstruction algorithm (Figure 6, right), there are no intersections visible and the camera can be moved freely in the scene. Figure 7 and the accompanying video show a transparent surface rendering of the same scene. Our modified surface reconstruction algorithm produces visually clean results and as noted in Section 4, there are no rendering artifacts due to unwanted reflection or refraction events resulting from mesh intersections.

In the next example, we demonstrate our surface reconstruction algorithm at a sharp corner. Again, a cell size of 0.004 is used for the MC grid. A jet of water is placed over a V-shaped rigid plane as shown in Figure 8. This synthetic example is chosen to analyze the behavior of the surface reconstruction algorithm at a sharp bend that is common in many cloth scenarios with folds and wrinkles. In Figure 8 (bottom), cross sections of the respective frame of the animation are shown. On the left side, the object in contact is not considered in the surface reconstruction and the result-

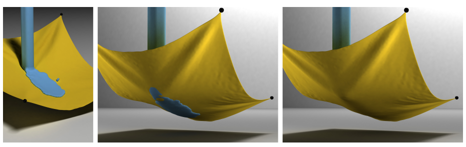

Figure 6: *Standard surface reconstruction methods can lead to visible intersections (middle). With our modified surface reconstruction algorithm (right), no intersections occur and there are no restrictions to the viewpoint.*

Table 1: *Computation times (in seconds) of the simulations and two-way coupling for a time span of* 0.5 *for the scene in Figure 3.*

h	No-slip	Cloth	Fluid	Coupling
0.0005	no	26.83	2.97	29.32
0.001	no	26.34	2.95	25.30
0.001	yes	27.04	3.21	21.37
0.005	no	27.73	3.66	7.21

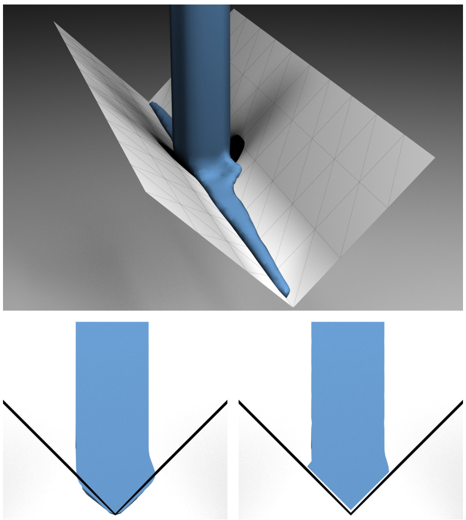

Figure 8: *Top: A jet of water hits a V-shaped static surface. Cross Section (bottom): With standard surface reconstruction algorithms, the surface mesh intersects the rigid plane at contact (left). With our contact aware reconstruction algorithm, an intersection free state is maintained (right).*

ing mesh overlaps the interacting object. With our method, an intersection-free state is maintained during the animation (Figure 8, bottom right) and the scene can be rendered artifact-free from any perspective.

Table 1 provides computation times of the simulations and the two-way coupling for the first scene as shown in Figure 3. Decreasing the cloth thickness results in higher costs for the continuous intersection handling. Using a broader region around the triangles of the cloth mesh for the interaction, the continuous intersection handling is not needed to prevent leaking in this scene, which explains the difference of the performance for the coupling in the last row. Table 2 shows the fractions of the computation times of the coupling for the same scene, broken down into the repulsion step and the continuous intersection handling. As expected, the continuous intersection handling accounts for the major part of the coupling.

Finally, we integrated the absorption and diffusion model

Table 2: *Fractions of the computation times (in seconds) of repulsions and the continuous intersection handling for a simulated time span of* 0.5 *for the scene in Figure 3.*

h	Repulsions	Geometric Intersections
0.0005	2.85	19.53
0.001	2.70	16.31
0.005	1.83	-

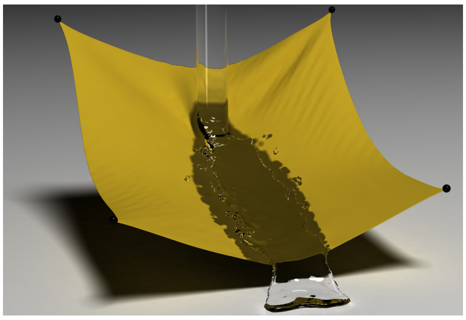

Figure 9: *Our contact algorithms combined with the absorption and diffusion model of [HPS11].*

of [HPS11] to cover the aspect of wetting at cloth-fluid contact. As shown in Figure 9, the cloth absorbs liquid and it is spreading inside the cloth. Due to the mass gained, the cloth behaves differently than in the above experiments.

7. Conclusion

We have presented an approach to model fluids and cloth at contact. With the proposed method for the two-way coupling, we achieve robust and efficient bidirectional interaction between particle-based fluids and cloth. Our system combines repulsion forces with a geometric intersection test to ensure that particles do not leak through the cloth surface. In our experiments, we have shown that our system can handle cloth-fluid interaction even at large time steps without using substeps. Our approach for the two-way coupling is designed to be independent from the underlying simulation systems and can easily be employed in existing simulation pipelines.

Furthermore, we have presented a novel method for the surface reconstruction of particle-based fluids at complex shapes. This method can be used for common MC-based surface reconstruction algorithms to generate intersection free surface meshes at contact. The shape of the resulting surface mesh at contact with complex shaped cloth meshes depends on the resolutions of the cloth mesh and the MC grid. The common MC grid resolutions that produce a smooth surface mesh are usually small enough to adjust to a buckled mesh. If, however, the surface mesh should align with a very high resolution cloth mesh with fine wrinkles, a very small cell size of the MC grid is needed. In this case, an adaptive MC grid could be used to avoid extensive computation times.

As future work, we would like to explore methods to control the reconstructed fluid surface at contact. For example, the possibility to adjust the distance between the surfaces in the reconstruction process would be desirable. Furthermore, we would like to incorporate methods to model surface effects like surface tension and adhesion. Finally, we did not perform optimizations for the modified surface reconstruction. In scenarios with large contact areas of the fluid and cloth, the overhead for our modified surface reconstruction results in high computation times. Standard accelerations strategies and a GPU implementation should considerably increase the performance of our algorithm.

Acknowledgments

This work was partly supported by "Kooperatives Promotionskolleg Digital Media" at Stuttgart Media University and the University of Stuttgart.

References

[ACAT13] AKINCI N., CORNELIS J., AKINCI G., TESCHNER M.: Coupling elastic solids with smoothed particle hydrodynamics fluids. *Comput. Anim. Virt. Worlds 24* (2013), 195–203. 2

[AIA*12] AKINCI N., IHMSEN M., AKINCI G., SOLENTHALER B., TESCHNER M.: Versatile rigid-fluid coupling for incompressible SPH. *ACM Trans. Graph. 31*, 4 (2012), 62:1–62:8. 2

[APKG07] ADAMS B., PAULY M., KEISER R., GUIBAS L. J.: Adaptively sampled particle fluids. *ACM Trans. Graph. 26*, 3 (2007), 48:1–48:7. 2

[BFA02] BRIDSON R., FEDKIW R., ANDERSON J.: Robust treatment of collisions, contact and friction for cloth animation. *ACM Trans. Graph. 21*, 3 (2002), 594–603. 3, 4

[BMF07] BRIDSON R., MÜLLER-FISCHER M.: Fluid simulation: SIGGRAPH 2007 course notes. In *ACM SIGGRAPH 2007 Courses* (2007), pp. 1–81. 4

[BTT09] BECKER M., TESSENDORF H., TESCHNER M.: Direct forcing for Lagrangian rigid-fluid coupling. *IEEE Trans. Vis. Comput. Graph. 15*, 3 (2009), 493 –503. 2

[CMTA12] CHEN Y., MAGNENAT-THALMANN N., ALLEN B. F.: Physical simulation of wet clothing for virtual humans. *The Visual Comput. 28* (2012), 765–774. 2

[DTM*12] DU P., TANG M., MENG C., TONG R., LIN L.: A fluid/cloth coupling method for high velocity collision simulation. In *Proc. ACM SIGGRAPH Int'l Conf. Virtual-Reality Continuum and its App. Industry* (2012), pp. 309–314. 2

[EKS03] ETZMUSS O., KECKEISEN M., STRASSER W.: A fast finite element solution for cloth modelling. In *Proc. Pacific Graph.* (2003), pp. 244–251. 5

[GSLF05] GUENDELMAN E., SELLE A., LOSASSO F., FEDKIW R.: Coupling water and smoke to thin deformable and rigid shells. *ACM Trans. Graph. 24*, 3 (2005), 973–981. 2

[HKK07] HARADA T., KOSHIZUKA S., KAWAGUCHI Y.: Smoothed particle hydrodynamics in complex shapes. In *Proc. Spring Conf. Comput. Graph.* (2007), pp. 235–241. 4

[HPS11] HUBER M., PABST S., STRASSER W.: Wet cloth simulation: A fast simulation framework for liquid diffusion in porous textiles. In *Proc. Comput. Graph. Int'l* (2011). 2, 7

[IAGT10] IHMSEN M., AKINCI N., GISSLER M., TESCHNER M.: Boundary handling and adaptive time-stepping for PCISPH. In *Proc. VRIPHYS* (2010), pp. 79–88. 2

[KAG*05] KEISER R., ADAMS B., GASSER D., BAZZI P., DUTRÉ P., GROSS M.: A unified Lagrangian approach to solid-fluid animation. In *Proc. IEEE/Eurographics Symp. on Point-Based Graph.* (2005), pp. 125–133. 2

[LAD08] LENAERTS T., ADAMS B., DUTRÉ P.: Porous flow in particle-based fluid simulations. *ACM Trans. Graph. 27*, 3 (2008), 49:1–49:8. 2

[LC87] LORENSEN W. E., CLINE H. E.: Marching cubes: A high resolution 3d surface construction algorithm. *Computer Graphics (Proceedings of SIGGRAPH '87) 21*, 4 (1987), 163–169. 1

[LD08] LENAERTS T., DUTRÉ P.: *Unified SPH model for fluid-shell simulations*. Tech. rep., K. U. Leuven, 2008. 2

[MCG03] MÜLLER M., CHARYPAR D., GROSS M.: Particle-based fluid simulation for interactive applications. In *Proc. ACM SIGGRAPH/Eurographics Symp. Comput. Anim.* (2003), pp. 154–159. 2, 5

[Mon05] MONAGHAN J. J.: Smoothed particle hydrodynamics. *Reports on Progress in Physics 68*, 8 (2005), 1703–1759. 2

[MST*04] MÜLLER M., SCHIRM S., TESCHNER M., HEIDELBERGER B., GROSS M.: Interaction of fluids with deformable solids. *Comput. Anim. Virt. Worlds 15*, 3-4 (2004), 159–171. 2

[OCD11] ONDERIK J., CHLÁDEK M., DURIKOVIC R.: SPH with small scale details and improved surface reconstruction. In *Proc. Spring Conf. Comput. Graph.* (2011), pp. 29–36. 2, 5

[Pro97] PROVOT X.: Collision and self-collision handling in cloth model dedicated to design garments. In *Proc. Graphics Interface* (1997), pp. 177–189. 3

[RMEF09] ROBINSON-MOSHER A., ENGLISH R. E., FEDKIW R.: Accurate tangential velocities for solid fluid coupling. In *Proc. 2009 ACM SIGGRAPH/Eurographics Symp. Comput. Anim.* (2009), pp. 227–236. 2

[RMSG*08] ROBINSON-MOSHER A., SHINAR T., GRETARSSON J., SU J., FEDKIW R.: Two-way coupling of fluids to rigid and deformable solids and shells. *ACM Trans. Graph. 27*, 3 (2008), 46:1–46:9. 2

[SP09] SOLENTHALER B., PAJAROLA R.: Predictive-corrective incompressible SPH. *ACM Trans. Graph. 28*, 3 (2009), 40:1–40:6. 5

[SSP07] SOLENTHALER B., SCHLÄFLI J., PAJAROLA R.: A unified particle model for fluid-solid interactions. *Comput. Anim. Virt. Worlds 18*, 1 (2007), 69–82. 2

[THM*03] TESCHNER M., HEIDELBERGER B., MÜLLER M., POMERANETS D., GROSS M.: Optimized spatial hashing for collision detection of deformable objects. In *Proc. Vision, Modeling, and Visual. Conf.* (2003), pp. 47–54. 5

[TKH*05] TESCHNER M., KIMMERLE S., HEIDELBERGER B., ZACHMANN G., RAGHUPATHI L., FUHRMANN A., CANI M.-P., FAURE F., MAGNENAT-THALMANN N., STRASSER W., VOLINO P.: Collision detection for deformable objects. *Comput. Graph. Forum 24*, 1 (2005), 61–81. 2

[VMT06] VOLINO P., MAGNENAT-THALMANN N.: Simple linear bending stiffness in particle systems. In *Proc. 2006 ACM SIGGRAPH/Eurographics Symp. Comput. Anim.* (2006), pp. 101–105. 5

[VMTF09] VOLINO P., MAGNENAT-THALMANN N., FAURE F.: A simple approach to nonlinear tensile stiffness for accurate cloth simulation. *ACM Trans. Graph. 28*, 4 (2009), 105:1–105:16. 5

[YLHQ12] YANG L., LI S., HAO A., QIN H.: Realtime two-way coupling of meshless fluids and nonlinear FEM. *Comput. Graph. Forum 31*, 7 (2012), 2037–2046. 2, 3

[YT10] YU J., TURK G.: Reconstructing surfaces of particle-based fluids using anisotropic kernels. In *Proc. 2010 ACM SIGGRAPH/Eurographics Symp. Comput. Anim.* (2010), pp. 217–225. 2

[ZB05] ZHU Y., BRIDSON R.: Animating sand as a fluid. *ACM Trans. Graph. 24*, 3 (2005), 965–972. 2, 5