Blurring the Line Between Real and Digital Water in Avatar: Fire and Ash

Sam Cole
Weta FX
Wellington, New Zealand
scole@wetafx.co.nz

Nicholas Illingworth
Weta FX
Wellington, New Zealand
nillingworth@wetafx.co.nz

Alexey Stomakhin
Weta FX
Mililani, USA
st.alexey@gmail.com

Sean Flynn
Weta FX
Salt Lake City, USA
sflynn@wetafx.co.nz

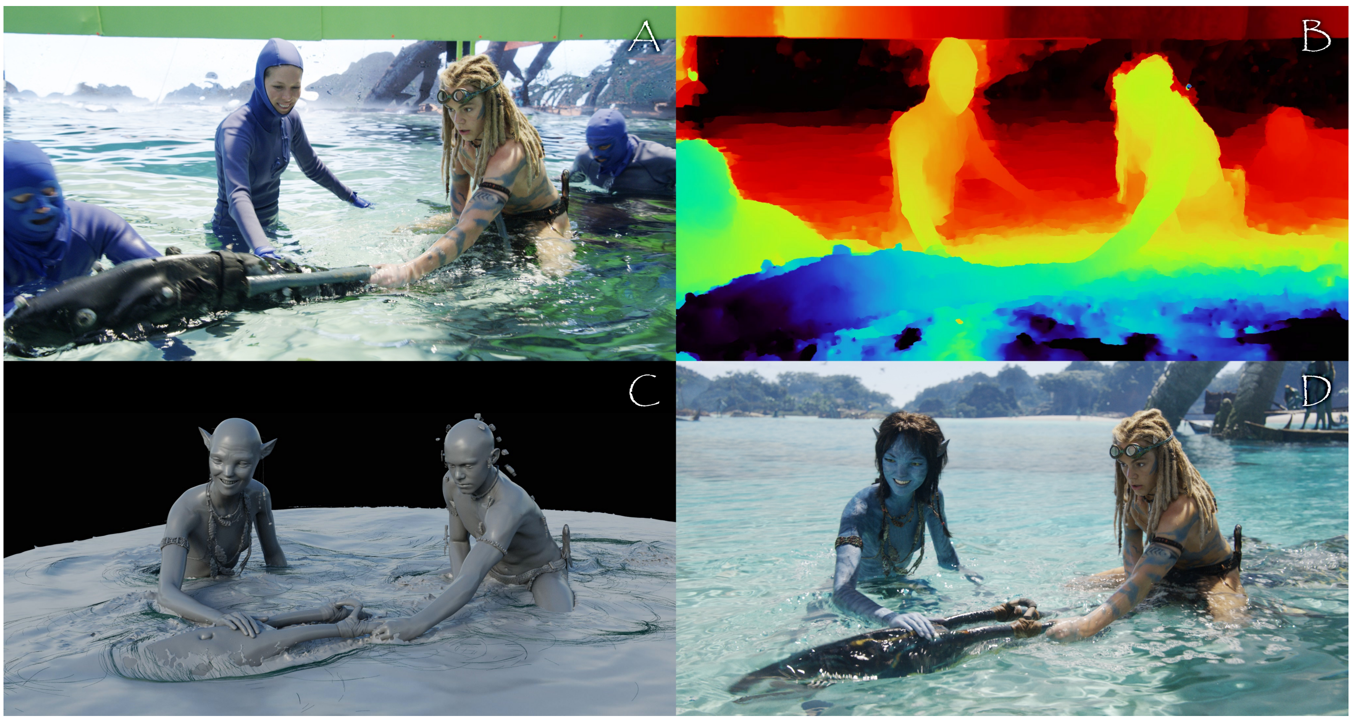

Figure 1: (a) Photographic plate; (b) machine-vision reconstructed per-pixel depth; (c) simulation, driven by feature-fitted procedural waves and motion-matched characters; (d) the final compositing result. ©2025 20th Century Studios / Lightstorm Entertainment. All Rights Reserved. ©2026 Wētā FX Ltd.

Abstract

We present a novel production workflow that augments per-frame surface reconstruction with sparse, supervisor-selected feature tracks that capture the dominant temporal motion of the photographed water surface. By tracking stable visual cues such as foam patterns, waterline intersections, and set contacts over time, we derive a temporally coherent representation of the live-action water. This representation is used to drive both parametric procedural wave models and downstream water simulations with fluxed animated boundaries (FAB) [Stomakhin and Selle 2017], ensuring consistent energy transfer and phase stability.

This approach significantly reduces manual matching, improves robustness on long shots with multiple interacting wave systems, and enables high-fidelity interaction between live-action water, CG extensions, and digital characters. We focus on practical implementation details, limitations, and lessons learned deploying this system in production.

SIGGRAPH Talks '26, Los Angeles, CA, USA

ACM ISBN 979-8-4007-2541-8/26/07
https://doi.org/10.1145/3799818.3812067

ACM Reference Format:
Sam Cole, Nicholas Illingworth, Alexey Stomakhin, and Sean Flynn. 2026. Blurring the Line Between Real and Digital Water in Avatar: Fire and Ash. In *Special Interest Group on Computer Graphics and Interactive Techniques Conference Talks (SIGGRAPH Talks '26), July 19–23, 2026, Los Angeles, CA, USA*. ACM, New York, NY, USA, 3 pages. https://doi.org/10.1145/3799818.3812067

1 Introduction

Water has long been one of the most challenging phenomena to integrate seamlessly between photographed and simulated elements in visual effects production. On *Avatar: Fire and Ash*, this challenge intensified due to an increased number of shots requiring CG extension of live-action water and close interaction between the water surface and digital characters. These shots frequently involved long takes, complex wave interactions, and stereo 3D constraints, leaving little room for traditional compositing-based fixes.

2 Production Challenges

Water surfaces are inherently difficult to capture accurately on set. They cannot be reliably surveyed or LiDAR scanned, and their appearance is dominated by reflection, refraction, and specular behaviour. For *Fire and Ash*, wide-baseline machine-vision camera arrays were used to reconstruct per-pixel depth and generate frame-by-frame water surface meshes, see Figure 1(b). While spatially plausible, these meshes were noisy and temporally unstable, particularly in tank environments where multiple wave systems interacted through reflections and boundaries.

On previous *Avatar* films, these instantaneous meshes were used as guides for manually matching parametric FFT wave surfaces using real-time preview tools. Artists adjusted wave parameters by eye until a satisfactory match was achieved, after which simulations were driven from the matched surface. Residual differences between plate and CG water were resolved in compositing, often requiring stereo-specific warping. While effective for shorter shots and simpler wave patterns, this workflow became fragile on long-duration shots, frequently drifting out of phase and breaking the perceptual coupling between water motion and character performance.

3 Key Insight

As shot complexity increased, it became clear that the primary limitation of the existing workflow was not spatial accuracy per frame, but a lack of temporal coherence. Subtle phase errors accumulated over time, producing motion cues that audiences readily perceived as incorrect, particularly when characters were swimming, riding creatures, or otherwise tightly coupled to the water surface. Stereo constraints further limited the ability to re-time or reposition photographed water without introducing volume and comfort issues.

4 Feature-Driven Tracking

To address these limitations, we developed a workflow that augments per-frame water surface reconstruction with sparse, temporally tracked surface features selected by supervisors as reliable descriptors of the underlying wave motion. These features include foam and bubble patterns, persistent water-set intersections, and waterline contacts with match-moved characters. Tracks are not required to be continuous or uniformly distributed, and features may exist only for subsets of a shot. Extensive camera coverage around the tank allows features to be tracked even when they are offscreen in the hero camera.

In shots where crew members or camera operators were present in the water, their bodies and equipment were match moved and incorporated into the system when their interaction materially affected the surface motion. The tracked features provide temporal structure and phase information that is absent from instantaneous surface reconstruction alone.

5 Parametric Wave Fitting

The tracked feature motion was used to fit a parametric wave model over time, recovering stable phase, orientation, and frequency information even in the presence of multiple interacting and reflected wave systems.

Specifically, given the feature samples $(\boldsymbol{x}_i, t_i)$, with $i = 0, \ldots, N$, where $\boldsymbol{x}_i$ is a feature position at time t_i, and a set of user-defined wave vectors $\boldsymbol{k}_l$, with $l = 0, \ldots, L$, to perform the fitting over, we minimized

$$\sum_{i=0}^{N} w_i \left(\sum_{l=0}^{L} \left[A_l^c \cos(\boldsymbol{k}_l \cdot \boldsymbol{x}_i - \omega_l t_i) + A_l^s \sin(\boldsymbol{k}_l \cdot \boldsymbol{x}_i - \omega_l t_i) \right] - y_i \right)^2 \quad (1)$$

over the amplitudes A_l^c, A_l^s of sine and cosine height fields, corresponding to $\boldsymbol{k}_l$, for all $l = 0, \ldots, L$. Here, y_i is the y-component of $\boldsymbol{x}_i$, ω_l is the angular frequency of the wave with vector $\boldsymbol{k}_l$ computed from the dispersion relation for gravitational waves, and $w_i > 0$ is

Figure 2: Photographic plate and feature-matched procedural wave surface (top) and the final composited result (bottom). ©2025 20th Century Studios / Lightstorm Entertainment. All Rights Reserved. ©2026 Wētā FX Ltd.

the weight associated with the sample i to indicate how reliable or important it is for the fitting procedure.

Expression (1) can be minimized using standard multi-linear regression techniques. Note, that including $\boldsymbol{k} = \boldsymbol{0}$ allows to also determine the constant offset for the overall water level if needed.

6 Simulation

The recovered sine $A_l^s \sin(\boldsymbol{k}_l \cdot \boldsymbol{x} - \omega_l t)$ and cosine $A_l^c \cos(\boldsymbol{k}_l \cdot \boldsymbol{x} - \omega_l t)$ harmonics were further converted into Gerstner (a.k.a. Stokes) waves with an optional artist-provided FFT-based displacement [Horvath 2015], see Figure 2 (top), to drive downstream water and secondaries simulations, ensuring consistent energy transfer between the systems, as outlined in [Stomakhin et al. 2023].

7 Results and Lessons Learned

The resulting workflow significantly reduced manual wave matching and improved robustness on long-duration shots in chaotic tank environments. It enabled high-fidelity interaction between live-action water, CG extensions, and digital characters, and reduced reliance on stereo-specific compositing fixes. While feature and target wave length/direction selection remains a supervised process requiring experienced judgment, the benefits of temporal coherence over per-frame accuracy proved decisive for production.

8 Conclusion

By shifting focus from per-frame surface matching to temporally coherent water motion, this approach enabled a class of shots on *Avatar: Fire and Ash* that would not have been achievable using previous workflows. The techniques presented offer a practical framework for future productions requiring close integration between photographed and simulated water.

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