Comprehensive Data Visualization for CFD and Forest Growth Simulations in eRobotics Systems for Forest Planning and Storm Damage Prevention

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***Abstract*—CFD and forest growth simulators are very special systems that are difficult to handle and require specific knowledge in the addressed domains; furthermore, commonly provided visualizations of the results are hard to understand and analyze, in particular to people not so deeply involved in the specific area of expertise. The need for such simulations became clear in 2007 when the windstorm "Kyrill" hit Europe and caused massive damages to the forests. Proper storm and growth simulations can support forest planning to prevent such damages in the future. The recently introduced concepts of eRobotics aim to bridge the gap between expert systems and comprehensive software applications by supporting the understanding of complex simulation results with realistic virtual environments. In this paper, we extend the eRobotics approach to forest planning domains, where forestry-related simulations are combined with intuitive visualization approaches in order to act as decision support system to optimize future forest developments under ecological and sustainable aspects.**

Keywords-computational fluid dynamics; forest growth simulations; data visualization; VR simulation systems; eRobotics;

I. INTRODUCTION

The simulation of flows of fluid substances is a major field of research in many different areas of computer science and engineering and widely applied in virtual prototyping. Apart from these technical domains, CFD simulations can also be applied in the fields of forest planning where the inclusion of ecological and sustainable aspects influence the future development of the forest. A recent example was the windstorm Kyrill that hit Germany in 2007 and caused massive damages, which have been quantified to 2.4 billion Euro (5.8 billion Euro across whole Europe). Approximately half of the costs in Germany and one third of the costs in Europe were related to damages cause to the forests. Due to the fact that especially spruces are shallow-rooted tree species that are not very resistant to strong winds, approximately 15% of the whole spruce stands in the German state of North Rhine-Westphalia were destroyed in one night, which summed up to 15.7 million solid cubic meters of round timber [1]. The insurance industry classified Kyrill as the most expensive natural disaster in Europe. In order to prevent such enormous ecological and economic damages in the future, storm simulations are an essential task in forest planning domains. Regarding the growing number of occurring windstorms and resulting damage over the last decades, simulation technology and tools for comprehensive analysis and interpretation of the generated results are becoming increasingly important, even in domains like forest planning, which have not been a typical application area in the past. Apart from storm simulations, forest growth simulations must not be neglected for the realization of a decision support system (DSS) in forest planning.

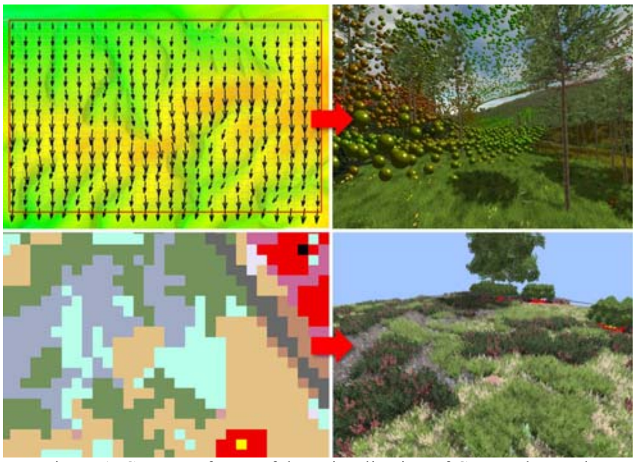

Figure 1. Common forms of data visualization of CFD and growth simulators are hard to understand. eRobotics aim for an intuitive understanding with the help of modern data visualization approaches and realistic virtual environments.

Since CFD and forest growth simulation tools are typical examples for systems that are used by experts with domain-specific knowledge, the visualizations of the results are mostly functional and not intuitively understandable without specific expertise. In this contribution, we introduce a framework that focuses on the convenient integration of accurate CFD and forest growth simulations in forestry domains as well as the intuitive visualization of the generated simulation data for comprehensive analysis and interpretation in realistic virtual environments as illustrated in Figure 1. In Section 2, related work regarding the eRobotics approach, CFD simulations and data visualization as well as forest growth simulators is introduced. Section 3 details the integration into an eRobotics-capable system and compares different interactive data visualization approaches considering its application in forest planning domains. Section 4 shows the practical application of the presented approaches and presents a case study that compares simulated and actual storm damages caused by the windstorm Kyrill in the Schmallenberg area in Germany in order to demonstrate the simulation accuracy, as well as the benefits arising from a comprehensive data visualization; furthermore, an approach for the comprehensive visualization of forest growth simulation results in life-like 3D environments will be introduced. Finally, Section 5 concludes this work.

II. RELATED WORK

In recent papers, we introduced concepts and application areas of eRobotics and related multi-domain VR simulation systems [2] [3]. As depicted in Figure 2, these systems combine a powerful simulation and render framework with the help of a central semantic database based on the principles of semantic world modeling. Originally intended for the application in robotics-related contexts, eRobotics systems can also be applied in further domains. An important aspect of eRobotics is to combine modern computer graphic approaches with complex simulations in order to improve the comprehensibility and accessibility of complex datasets or simulation results [4]. The broad range of available data in combination with advanced rendering techniques is not only used to improve the accuracy of simulation tasks - like fluid dynamics in this case - but also to generate a realistic virtual mapping of the actual environment, predestinated for intuitive data visualization of the performed storm and forest growth simulations. Finally, eRobotics applications aim to apply the GPU for simulation purposes and data visualization approaches are suitable examples for this application area.

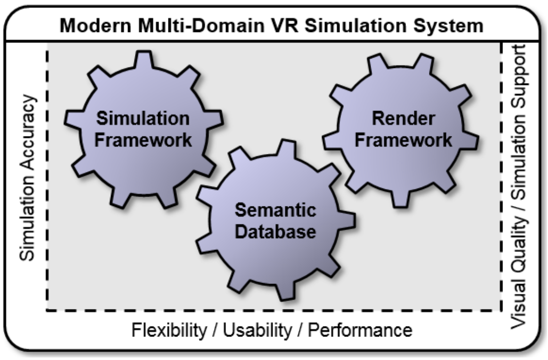

Figure 2. Concept of an eRobotics-capable multi-domain VR simulation system that combines complex simulations and attractive virtual worlds with the help of a central semantic graph database.

A. *CFD Simulation and Data Visualization*

Currently, a broad range of CFD simulators exist, where each of them focuses on different aspects like accuracy or performance as demanded by specific application areas. Traditionally, CFD calculations are closely related to high-performance computing due to their computational complexity; consequently, they are separated from real-time capable vector field visualization approaches. Even though GPU-based CFD simulations exist that similarly simulate and visualize the fluid flow in real-time [5] [6], these approaches are mainly intended for game engines since they apply a simple but rapid Navier-Stokes solver for incompressible fluids geared towards visual quality and performance instead of physical realism. Regarding the desired storm simulation, the CFD software toolkit WindStation™ is an ideal choice [7]. It focuses on the accurate calculation of airflow over complex topography and applies the CFD solver Canyon, which is a generalized coordinate system solver based on a control-volume approach [8]. Canyon solves the full 3D Navier-Stokes equations for mass conservation, momentum conservation, energy conservation and turbulence quantities using the k-epsilon model [9]. Terrain roughness is also taken into account through the ground shear stress modeling as well as temperature imposition or heat flux imposition. WindStation™ also features a range of simple visualizations as shown in the top-left image of Figure 1.

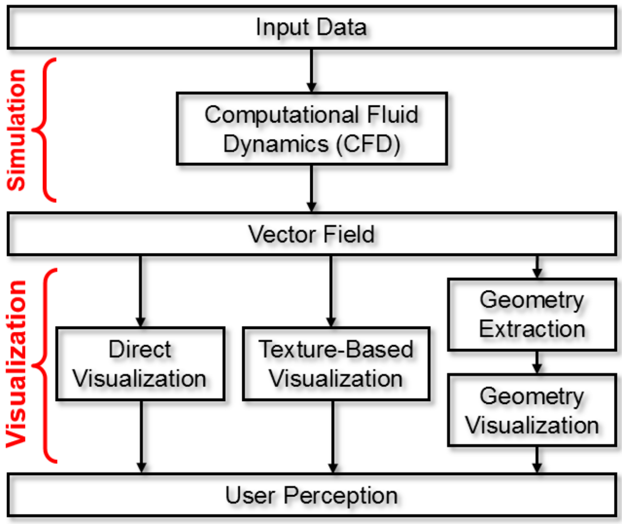

Figure 3. Illustration of the common simulation and visualization process for flow simulations.

As illustrated in Figure 3 and stated by Weiskopf [10], visualization approaches can roughly be categorized into direct, texture-based and geometry-based visualizations. Popular examples for direct visualizations are hedgehogs, oriented lines as well as glyph-based approaches, which aim to show local features of the vector field. Texture-based approaches process the vector field in order to display two- or three-dimensional output textures. Popular approaches are based on line integral convolution (LIC) introduced by Cabral and Leedom [11]. The key idea is to blur an input texture along field lines from a given vector field in order to properly visualize the specific characteristics of a fluid flow. Oriented Line Integral Convolution (OLIC) further integrates the information of the flow direction into the visualization [12]. Recent approaches also apply GPU-based LIC-techniques to visualize multivariate data [13]. Finally, geometry-based visualization approaches aim to support the understanding of specific flow properties of the vector field by moving objects through it. These approaches are known under the term particle tracing [14].

B. *Forest Growth Simulators*

Many forest and plant growth simulation models have been developed until today, where each one of them focuses on specific plant species or vegetation zones. Two recent examples suitable for the desired application areas are the SILVA forest growth simulator [15] (SILVA is the Latin word for wood or forest) and the GraS (Grassland-Succession-Model) ground vegetation growth simulator [16]. Both simulators are based on a range of observations and parameters, which predict the growth behavior very close to independent real world observations; however, the common form of result presentation are tables, charts or maps as illustrated in the lower left part of Figure 1. This figure shows an exemplary output texture of the GraS simulator. Each color in the visualization represents a specific combination of occurring foliage and plant species, which evolve over time to other kinds of vegetation zones depending on the local conditions. These results need to be interpreted and analyzed by forest and plant experts. The state of the art render framework implemented in the developed eRobotics systems is well suited to map the generated simulation results to life-like virtual environments in order to enable the interactive and intuitive exploration and interpretation [2].

III. WIND SIMULATION AND VISUALIZATION FOR FOREST PLANNING DOMAINS

The approaches presented in this paper are part of the "Virtual Forest" project, which is further detailed in Chapter 4. The project's goal is to provide a comprehensive multi-purpose software tool for forestry-related domains in order to predict future forest developments with the help of forest growth simulations and to prevent future storm damages by using CFD simulations. Following the concepts of the general data visualization pipeline shown in Figure 3, the realized storm simulation is separated into a simulation and visualization part. There are two reasons for this: first, this approach grants maximum flexibility. The vector field generator can easily be exchanged without the need to modify the visualization module and vice versa. Second, an accurate flow simulation is computationally expensive and usually carried out on the CPU while visualization approaches can efficiently be implemented on the GPU and run in real-time. Highly accurate, high-resolution vector fields can be calculated in an offline process but visualized in a real-time environment, giving the user the possibility to interactively explore the generated flow field in intuitive ways. The implementation into the eRobotics system is illustrated in Figure 4.

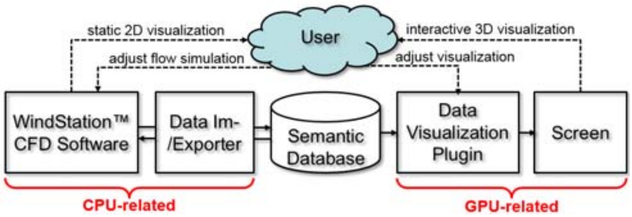

Figure 4. Illustration of the implemented storm simulation and visualization pipeline.

The WindStation™ toolkit is used to calculate the wind vector field. Required information like the topography or ground roughness are exported from the semantic database, which contains all gathered data related to the Virtual Forest project. The user can conveniently set up the wind simulation parameters and have a first look at the results before the data is imported to the eRobotics system for further analysis with the help of advanced visualization approaches that can be displayed in highly realistic virtual model of the actual environment. In the following sub-sections, approaches related to the three visualization categories will be detailed and compared considering its application in forest planning. For comparison reasons, all introduced approaches are applied to the same vector field.

A. *Direct Visualization*

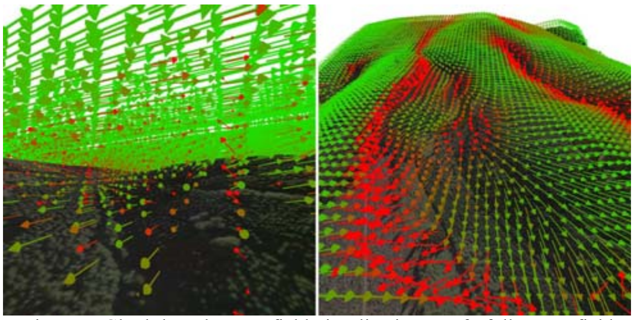

Figure 5. Glyph-based vector field visualizations. Left: full vector field visualization. Right: 2.5D visualization.

Direct visualizations show magnitude and direction of the vector field by using glyphs. Additional data, like pressure, turbulence, temperature, etc., can be visualized by color coding. Figure 5 shows screenshots of a direct visualization of the wind vector field using arrow glyphs. In the left image, the arrows point in wind direction, the wind speed is visualized by the size of the arrows and the arrows' colors represent the local turbulence value (green indicates low turbulence values, red indicates a high turbulence value). While this approach can easily be implemented and achieves clear visualization results in 3D, the figure also illustrates some disadvantages. First, the arrow plot visualization is not suitable for dense or large vector fields due to inherent occlusion effects. Second, the arrow plots get unclear if too much information is encoded into their visualization. The high wind speed in higher altitudes generates large arrows that cover large areas of the image. Relevant information in lower altitudes, like turbulences close to the ground with relative low wind speed, are hard to notice in comparison.

Finally, the visualization results are poor if the magnitude of the velocity changes rapidly. A possible solution to address the named limitations is the reduction of either the amount of visualized information or the amount of arrow glyphs. Specific areas of interest can be defined or a 2D slice of arrows can be visualized for a given height above the ground. The right image of Figure 5 shows a corresponding partial vector field visualization at 10 meters above ground level. The arrows glyphs point in wind direction, the turbulence is encoded into the color and the wind speed is neglected. This visualization method is commonly known as 2.5D visualization, as it projects a single slice of the vector field into the 3D geometry. Relevant Information can more clearly be recognized compared to the full 3D vector field visualization.

B. *Texture-Based Visualization*

Multiple texture-based visualization approaches have been implemented based on line integral convolution (LIC). For the practical application and proper interpretation of the results, the generated textures can directly be projected onto the scene geometry as illustrated in the left part of Figure 6, which shows the results of a standard LIC approach. The textures were generated for the same height layer 10 meters above ground level as the 2.5D visualization shown in Figure 5. Relevant information like local turbulences are clearly visible at the corresponding areas, which allows for an intuitive interpretation of the flow simulation results. The right part shows the results of an OLIC approach, which also depicts the wind direction.

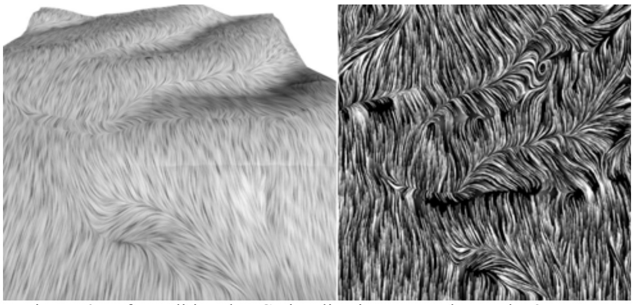

Figure 6. Left: traditional LIC visualization mapped onto the 3D scene. Right: OLIC visualization of the same region that also emphasizes the wind direction.

In order to support the understanding of the generated LIC textures hybrid approaches are suitable, which also include additional flow properties or environmental information. The left part of Figure 7 shows such an implementation that blends the OLIC texture with the matching ortho photos of the corresponding area to put the simulation results into relation with the actual environment. Regarding the application in forest planning domains, the local turbulence value is an essential information. Strong turbulences near the ground can lead to damages to the forest; hence, it must not be neglected in the visualization. The right image shows a visualization that is provided in addition to the left one. This visualization color-codes the turbulence values into the red color channel. In order to prevent a confusing, overloaded visualization, the LIC texture is not included directly; instead, the convolution is applied to the ortho photo to smear the image in wind direction in order to provide information about the wind direction and speed. By providing both visualizations, the forest planner has all the important information precisely and comprehensively in view at all times.

Figure 7. Left: OLIC-visualization blended over the surface's ortho photo. Right: the ortho photo is used as LIC input texture; additionally, the local turbulence value is added to the red color channel.

C. *Geometry-Based Visualization*

The approaches presented so far only provide static information about the flow. It becomes clear that the visualized information has to be reduced to a single height layer or just a few flow properties in order to keep these visualizations clear and understandable. By using a dynamic approach that moves particles through the vector field, geometry-based visualizations provide the possibility to overcome these limitations and similarly provide the most natural kind of visualizing a flow. Particle tracing requires the solution to an ordinary differential equation (ODE) to compute the trajectory of massless particles in a flow field over time with an initial condition of $x_p(0)=x_0$ for a numerical solution:

$$\frac{\partial x_p}{\partial t} = \tilde{v}(x_p(t), t) \tag{1}$$

, where $x_p(t)$ is the time-dependent particle position, the left term is the tangent to the particle trajectory and ~*v* the approximation of the vector field *v*. CFD calculations generate *v* with a discrete resolution, hence, an appropriate interpolation need to be used to reconstruct particle velocities along their characteristic paths. Fixed step size integration schemes like the classical Euler (see Eq. 2) or Runge-Kutta (see Eq. 3) are common for visualization reasons.

$$x_{t+1} = x_t + \Delta t \cdot f'(t, x_j) \tag{2}$$

$$x_{t+1} = x_t + \frac{\Delta t}{6} \cdot (k_1 + 2k_2 + 2k_3 + k_4) \tag{3}$$

, where

$$k_1 = f'(t, x_j)$$

$$k_2 = f'(t + \frac{\Delta t}{2}, x_j + \frac{\Delta t}{2} k_1)$$

$$k_3 = f'(t + \frac{\Delta t}{2}, x_j + \frac{\Delta t}{2} k_2)$$

$$k_4 = f'(t + \Delta t, x_j + \Delta t k_3)$$

The Euler integration scheme provides a good compromise between precision and performance. With the current implementation and a common desktop PC equipped with a modern GPU, hundreds of thousands particles can be traced and visualized in real-time. Figure 8 shows animation sequences of multiple currently implemented real-time particle tracing visualizations. Local turbulences can easily be recognized by the particles' movement while the turbulence value is encoded into the green and red color channel. Finally, illuminated streamlines can be applied to clearly trace the wind direction in the 3D environment.

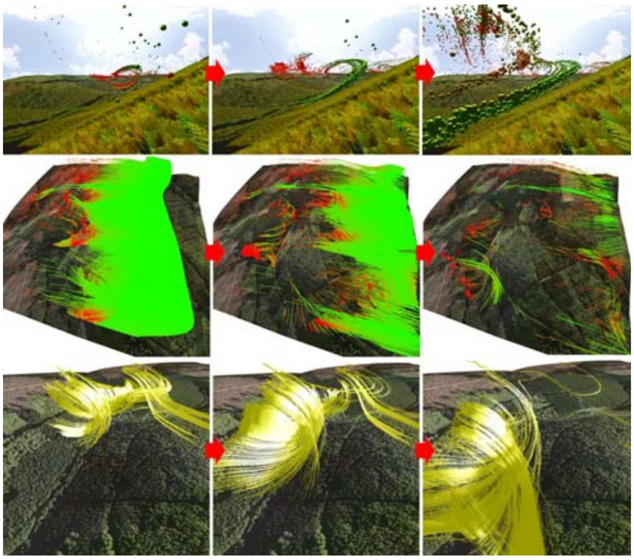

Figure 8. Top row: movement of sphere sprites through the flow field. Middle row: line segments (linelets). Bottom row: illuminated streamlines.

IV. Applications and Results

A novel GIS application for forest planning has been realized with the eRobotics system introduced in Chapter 2. It is part of the Virtual Forest project, which is a joint effort of various partners who combine their know-how in different fields of application in order to realize a virtual reality based framework to identify, visualize and optimize biological and technical processes in a forest environment [17] [18]. An overview of some addressed aspects of the project is given in Figure 9. The GIS system is based on semantic world modeling as well as remote sensing data and processing algorithms.

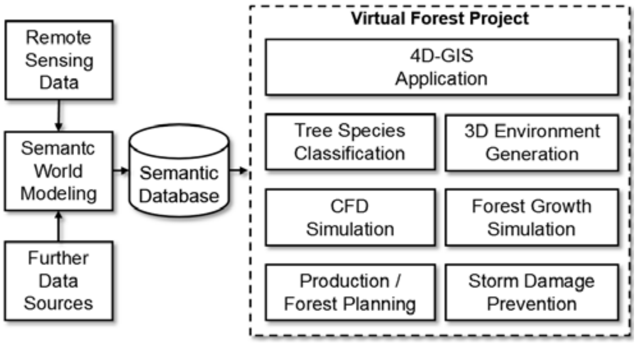

Figure 9. Overview of the Virtual Forest project.

The general idea is to use latest remote sensing technology to gather relevant data, ranging from ortho photos taken by airplanes over multi-spectral satellite data up to vector data like land parcels or specific biotopes and habitat zones, with a high level of actuality. A basic feature of a GIS application is the displaying of available datasets, which is commonly done in an orthographic 2D or simple 3D projection as shown in Figure 10.

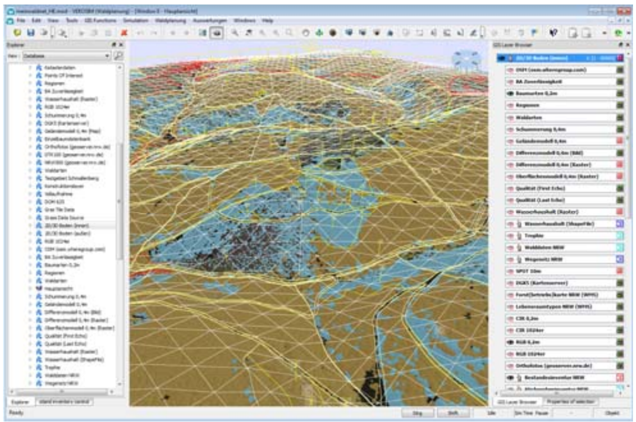

Figure 10. Data visualization as 2D or simple 3D layers.

In order to enable accurate storm damage predictions in future scenarios, a combination of CFD and forest growth simulations is an ideal combination; however, comprehensive data visualization of both areas has mostly been neglected in the past. eRobotics systems put a strong focus on attractive virtual environments for reasons of comprehensive demonstrations. The Virtual Forest does not only unite available datasets in a holistic forestry-related database, it also focuses on the processing of the available data. An example is the tree species map displayed in Figure 10, which was generated using a support vector machines-based approach [19] as well as satellite and LiDAR data. This tree species map is further processed by automated single tree delineation algorithms to generate a single tree inventory [20]. This data is not only helpful for forest planning or economic and ecological analysis as performed by forest workers or related authorities, it further enhances the possibilities for the generation of vivid virtual environments. By incorporating as much semantic information as possible and interpreting or processing them by matching rendering plugins, realistic mappings of life-like, fully dynamic natural environments can be realized, which have not been known from GIS applications in the past. Some examples of the results achieved with the presented GIS system are given in Figure 11. The bottom image of the figure illustrates how vector data and further information are presented to the user in an intuitive way. Borders are visualized as fences while related information are rendered as signs at corresponding locations in order to provide relevant information directly in the 3D environment. Obviously, the same principles can be applied to the visualization of simulation results. While most GIS systems only provide a look into the past by displaying stored data, the developed 4D-GIS also considers the time as fourth dimension. All imported data is not only referred by spatial attributes but also by its time of creation to give an impression about past forest developments. The 4D-GIS uses the available information to apply specialized simulations like storm simulations and forest growth simulations as introduced in Chapter 2 to predict and comprehensively demonstrate possible future forest developments under the consideration of different conditions and treatments.

Figure 11. The rich database of the Virtual Forest in combination with the powerful semantic render framework of the eRobotics system allows to generate vivid virtual real-time environments with little effort.

A. *Storm Damage Prevention*

For evaluation reasons of the integrated CFD simulations, a simulation for an actual area in Schmallenberg, Germany was calculated so that it matches the actual parameters of the windstorm Kyrill. The top image of Figure 12 shows an aerial photo of that region where the storm damaged the forest in a specific area.

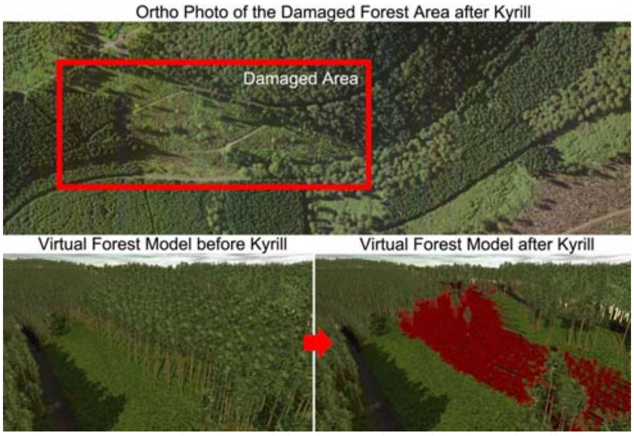

Figure 12. Top: ortho photo of the damaged stand in the Schmallenberg region in Germany. Bottom row: virtual model of the stand before and after the windstorm. Damages areas are marked in red.

The bottom images show the virtual 3D model before and after the storm with the damaged area marked in red. As earlier stated, eRobotics systems aim to visualize complex simulation results in attractive virtual environments. As part of the Virtual Forest project, relevant data like the surface topography and terrain roughness for an accurate wind simulation as well as a close-to-reality virtual mapping of the real forest environment are already available [2]. Figure 13 shows an animation sequence of approximately 100.000 particles, which are traced through the vector field in real-time. This visualization reveals the reason for the massive damage to the specific area. A massive wind front was dammed at the preliminary ridge that subsequently breaks at the shown location, causing heavy turbulences, which finally lead to heavy damage to the stand. This example illustrates how essential proper flow simulations and visualizations are in forest planning domains; as a consequence, windbreaks can be built or more robust, deep-rooted tree species like beeches or oaks can be planted in high-risk regions.

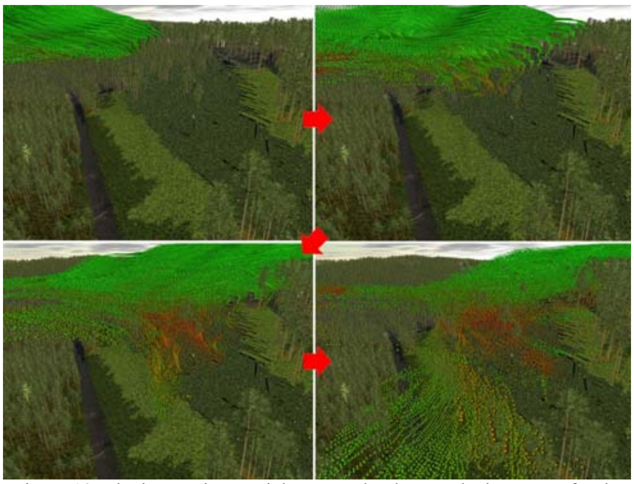

Figure 13. The interactive particle tracer clearly reveals the reason for the damage caused to the corresponding stand.

B. Comprehensive Forest Growth Data Visualization

Even if accurate CFD simulations represent the main approach to prevent future storm damages, the aspects of forest growth and ground vegetation development must not be neglected for a trustable prediction; therefore, the introduced tools SILVA and GraS have been applied to properly simulate the growth and development of the environment under various conditions. While SILVA works on the single tree inventory of the Virtual Forest database and directly manipulates the tree properties, which are automatically rendered to the corresponding locations by the render framework with matching sizes, the GraS simulator generates color-coded textures. Figure 14 shows the corresponding results for a simulation of a specific area over nine years. Each color in the visualization represents a defined combination of occurring foliage and plant species.

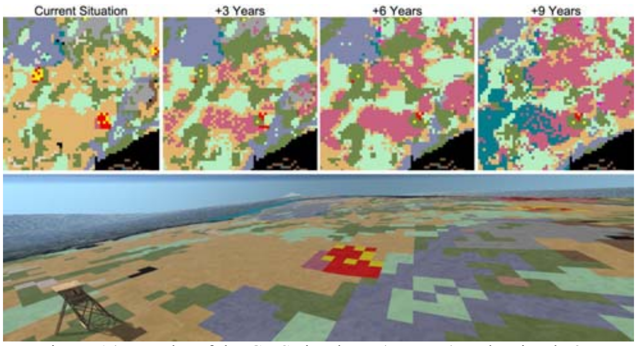

Figure 14. Results of the GraS simulator (top row) and a simple 3D visualization that maps the result textures onto a 3D terrain.

Even if the result textures are presented in a 3D visualization as shown in the bottom image of the figure, they are hard to understand or analyze without further knowledge about the simulator and its specific form of presentation; however, a ground vegetation render approach that was developed and presented in a previous paper [21] can be adapted to interpret these textures and automatically transform them into a realistic, volumetric ground vegetation layer. As illustrated in Figure 15, a new texture atlas was created, which contains all plant species that are currently considered by the GraS simulator. These textures are mapped to billboards in the 3D scene in order to render vegetation fields with matching plant species.


Figure 15. Texture atlas with plant species that are currently considered by the GraS simulator.

The achieved results are shown in Figure 16. This intuitive way of visualization allows an easy interpretation of the results, which is also perfectly suited to be applied for edutainment applications, where students can actually see the growth behavior of specific biotopes under various conditions in a vivid and interactive virtual environment.

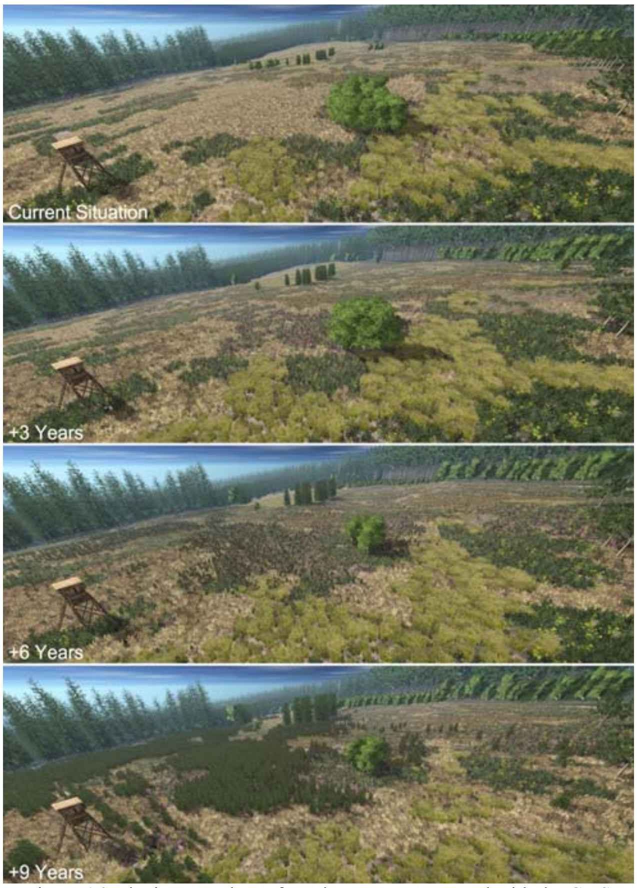

Figure 16. The image colors of result textures generated with the GraS simulator have been mapped to corresponding plant objects in order to generate a close-to-reality visualization in an interactive 3D environment.

It becomes clear that the results of the addressed domains of storm simulation and forest growth simulations become easily understandably when presenting them in realistic virtual mappings of the real environment. Possible damages to the forest can be analyzed and identified more easily when the user can actually navigate through the actual 3D forest environment. Figure 17 shows the application in an interactive multi-screen stereo projection. The user can conveniently alter the wind parameters in the CFD simulation, which results are loaded into the simulation system. In the 3D simulation, he can switch through the presented visualization approaches and locally release particles in the 3D simulation to further analyze specific regions under changing conditions. Similarly, different forest growth simulations with varying conditions can be performed and interactively explored and discussed in the projection in an intuitive and easily understandable way.

Figure 17. Results of the storm and forest growth simulation can comprehensively be presented and discussed in an interactive multi-screen stereo projection.

V. CONCLUSION AND FUTURE WORK

In this paper, we presented a software framework for CFD and forest growth simulations and visualizations for forest planning domains. The presented tool chain allows for convenient integration and setup of matching wind and growth parameters for the simulation while the eRobotics system clearly improves the understanding of the generated results with the help of attractive virtual mappings of the real environment. Multiple real-time visualization approaches have been presented, which are suitable for the data analysis in the forestry domains. A comparison of the simulation results in an actual windfall region demonstrated the accuracy and practicability of the presented wind simulation while the inclusion of a forest and ground vegetation growth simulator enables the accurate planning of forestry measures to grant a sustainable forest development; moreover, forest growth simulations can directly be considered for storm simulations in future scenarios. The presented system is able to act as a decision support system for the forest planner, which enables comprehensive data analysis and identification of high-risk regions to optimize forest planning under economic and ecological aspects.

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