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Interactive authoring of example surgical procedures from recorded physics-based simulation

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Abstract. This paper presents a method for authoring of recorded physics-based simulation including editing of haptic data through interactive simulation. Edited haptic data is intended to be used for simulator-based self-learning of example surgical procedures made by medical teachers. Existing methods have a trade-off between interactivity of editing and flexibility of playback of a past simulation. The trade-off is addressed in the proposed method.

Keywords: surgical simulation; authoring; haptics

1. Background

Research and development of Virtual Reality (VR) for surgery has mainly focused on increasing realism of visual and haptic feedback of simulation [1, 2], yet, realism alone is not sufficient for VR-based surgical training. Only a few medical schools (for example [3]) have included VR-based training in their curriculum. Motor-skill transfer studies have proposed record and play approach for training of manual skills, such as writing [4, 5]. In the complex surgical field, however, teacher's recorded example manipulation and interaction should be explained and annotation of haptic data has been proposed [6]. The authors are developing a novel approach for surgical skill-transfer based on annotation of recorded surgical simulation. Example manipulation and comments from the teacher can be observed in playback of a simulation record, which is accessible to residents together with interactive physics-based simulation.

For the use of recorded simulation as skill-transfer medium, editing of recorded manipulation toward perfect examples is indispensable. The teacher must be allowed to make mistakes during recording of manipulation and to correct them afterwards.

This paper proposes a method for interactive authoring of recorded physics-based simulation. SiRE – Simulation Record Editor – is presented as a novel application for authoring perfect examples. Technical problems derive from the underlying data formats. Existing methods have a trade-off between interactivity of editing and flexibility of playback of past simulations. The proposed method is demonstrated in a simulation consisting of interaction with soft tissue in a case of palpation of the aorta which aims for diagnosis of soft and hard tissue before cardiovascular surgery.

User's input data can be recorded at high accuracy without affecting interactivity of the simulation. The input data is typically haptic interface dependant raw position and posture data which does not describe events in the simulation but only the input that results in the events. This data describes the user's manipulation completely with constant data size. The input data is preferred as the permanent storage format. Yet, the

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user should be able to edit recorded simulation on the basis of simulated physical phenomena that are easier to comprehend than the raw-data. A method that provides both interactive editing and flexible playback is described in this paper.

2. Methodology

Fig. 1 illustrates the proposed method for SiRE's architecture which is divided into two processes, playback and simulation, and two data layers, raw-data and serialized states. The method is based on switching playback to simulation and synchronization of the raw-data, the serialized states and the playback. Re-simulation from the start is successfully avoided even though playback can be skimmed freely. Re-simulation of the edited section is necessary and results in a short delay. In a typical case where the user edits a few second sections of the simulation record, the time to wait for the updated playback is consequently just a few seconds.

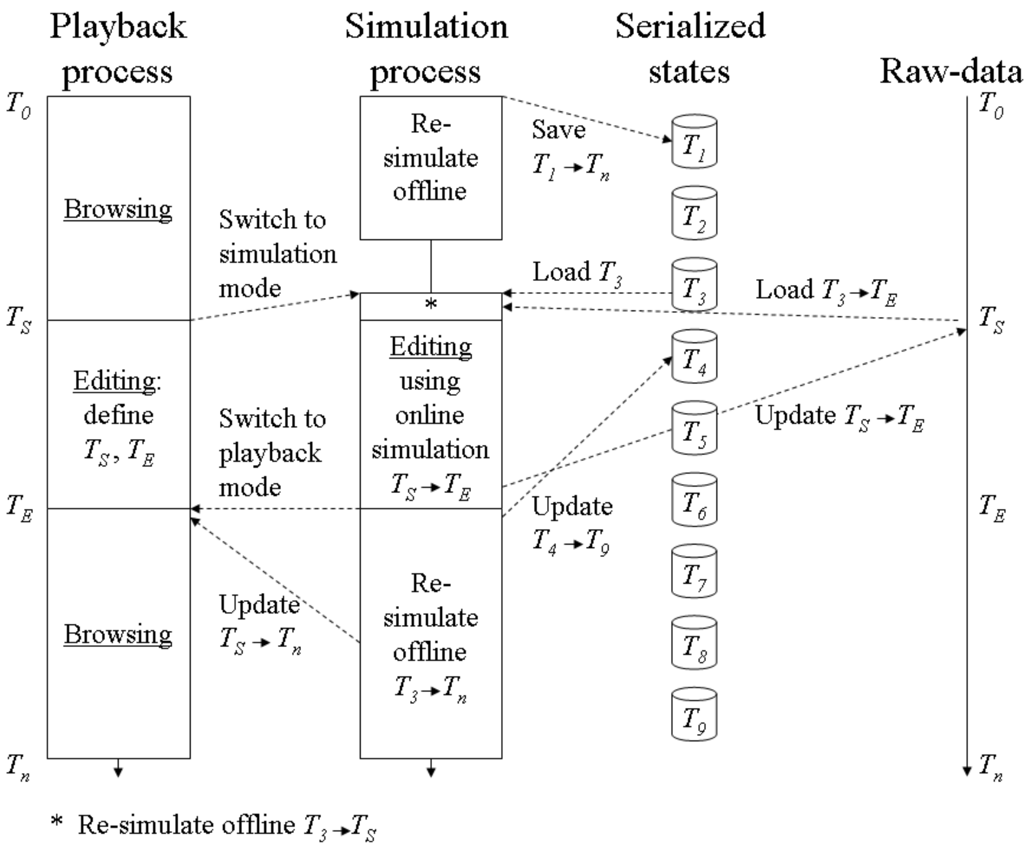

Fig. 1. A method for interactive editing of recorded physics-based simulation. Underlined parts represent user's actions. The user browses the playback and chooses an editable segment by determining T_S and T_E. The simulation is loaded from the serialized state at T_3, previous to T_S. After editing, the segment is re-simulated to update the raw-data and the serialized states. Thus, time required to update the playback is about T_S–T_3. Since each simulation state affects all the states after it, the remaining sections of the playback and the serialized states are updated in T_n–T_E.

2.1 Raw-data

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Raw-data in a typical desktop VR setup with a haptic device covers user's input: position and posture of the manipulator are recorded in the simulator at the best possible accuracy. Time-dependant size of data makes this data format suitable for long term storage. In addition, the accurate input can be used for evaluation of surgical skills.

2.2 Playback process

Time series of organ objects' 3D structure serves as the playback medium. In surgical simulation, deformable organs are represented as with 3D meshes. Deformation is achieved by displacing nodes that constitute the 3D object. Normally, the simulation engine calculates reaction force from which displacement of nodes is computed. 3D structure time series allows direct feeding of displacement from a file with very light computation. Recording and replaying 3D structure at chosen frame-rate is easy to implement into any simulation engine that uses deformable meshes. The user can browse the timeline of the recorded simulation freely because of the light CPU cost.

2.3 Simulation process

Simulation functions in two modes: online and offline. Online simulation is required only for the duration of editing. Offline simulation is executed right before editing, when the starting state of editing is prepared, and after editing, when the result of editing is updated to the playback and serialized states.

2.4 Serialized states

Serialization, writing and reading runtime data of objects in a program onto persistent medium, such as hard disk, is a common programming technique supported in programming languages, such as C++. In SiRE, serialization is used to save markers on the timeline of the simulation, so that the simulation's states can be restored. When editing, the marker is loaded and re-simulation executed until the start of the chosen segment. After the segment has been edited, markers are updated by the re-simulation.

2.5 Demonstration case: palpation of the aorta

Before an open-heart surgery, surgeon identifies stiffness of parts of the aorta by touching in order to block blood flow by clipping. Hard parts in the aorta are caused by thrombi. Clipping on a thrombus or excessive use of force during palpation can result in a fatal injury. Therefore, all areas of the aorta should be examined at proper level of force before clipping. Simulation of palpation of the aorta ensures safe training.

2.6 User interface for interactive editing

Design of SiRE's user interface is to fulfil the following general requirements:

- Start and end of the segment can be chosen.
- Manipulation can be modified according to simulated physical phenomena.

Choosing a section for editing is done by choosing start and end points on the timeline of the simulation record. After this, the section can be replayed by a simple click on a button so that the user can adjust the start and end points further.

In palpation of the aorta, the most important factor is force since excessive power can damage the patient. Also, direction of manipulation plays a significant role allowing a few different strategies for a surgeon to find hard areas inside the aorta. Therefore, the

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user can edit power by touching the aorta in the interactive simulation through a haptic device, and determine the proper power level by clicking a button. After the power level has been defined, the original manipulation is scaled to the user-given power level by computing the trajectory of the manipulator in the depth dimension against the aorta.

3. Experiment

SiRE was evaluated by measuring computation time of the proposed method against the previous one [6]. The previous method uses raw-data and playback, but lacks serialized states. Therefore, in the start of the editing, the previous method is expected to consume time on re-simulation from the start.

The experiment was implemented on Medical VR simulation Library (MVL) [7] which contains physics-based simulation methods and anatomical models. MVL uses the Finite Element Method for computation of reaction forces and deformation.

Hardware platform consisted of a Xeon 3.2 GHz dual processor with 4 GB RAM and SensAble’s PHANToM Desktop as the haptic interface. Haptic loop was run at about 1000 Hz. The 3D mesh consisted of 1397 nodes, which resulted in a serialized file of 1.53 MB. Saving a state took 25 ms, whereas loading and re-instantiating the object took 100 ms. Serialization was performed at 2.5 sec interval. Playback rate was 25 fps.

Offline re-simulation time was measured for three cases and compared to the online simulation time (as perceived by the user):

- RS1, re-simulation with saving states and updating playback: 133%
- RS2, re-simulation with updating playback only: 122%
- RS3, plain re-simulation (works as rewind): 70%

The previous method uses RS3 for reaching the start of the segment that is edited. Then, updating the playback requires RS2. The proposed method loads the previous state from the serialized file, re-simulates until the start of the segment with RS3, and updates the playback and the serialized states with RS1. The proposed method was expected to demonstrate significant reduction of total re-simulation time when the edited segments are chosen at the second half of the simulation’s timeline.

Fig. 2 a) explains the experiment procedure. 64 sec simulation consisting of frequent deformation of the target organ was recorded. Five 6-second segments were edited and runtime measured with the two methods. The most important factor is time required to seek the start of the segment and to update it, since the updated playback is given to the user. The other factor is the total time required for the update of the edited simulation.

4. Results and discussion

Fig. 2 b) shows the results of the experiment. The proposed method maintained the system’s response within tolerable limits. Updating a 6 sec segment took about 8.8 sec in average. With the previous method, the segment’s updating time increases along the chosen start time. The proposed method requires the less time the closer the segment is to the end of the simulation. The proposed method reduced the total runtime by 34%.

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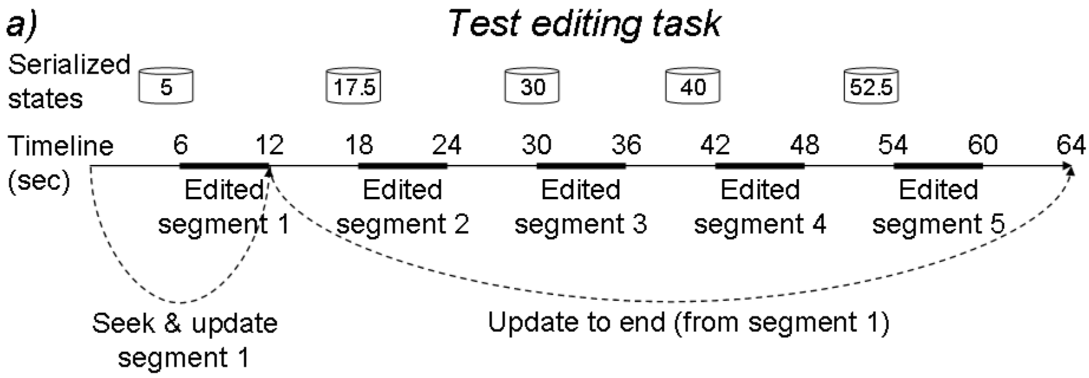

b) *Runtime measurement*

Previous method

Edited segment	Seek & update segment	Update to end	Total
1	11.4	62.4	73.8
2	19.8	48.0	67.8
3	28.2	33.6	61.8
4	36.6	19.2	55.8
5	45.0	4.8	49.8

Runtime to update edited segments: 2 min 21 sec
Total runtime: 5 min 15 sec

Proposed method

Edited segment	Seek & update segment	Update to end	Total
1	8.78	69.16	77.94
2	8.43	53.20	61.63
3	8.08	37.24	45.32
4	9.48	21.28	30.76
5	9.13	5.32	14.45

Runtime to update edited segments: 44 sec
Total runtime: 3 min 50 sec

Fig. 2 a) A test task for editing physics-based simulation. b) Runtime measurement results.

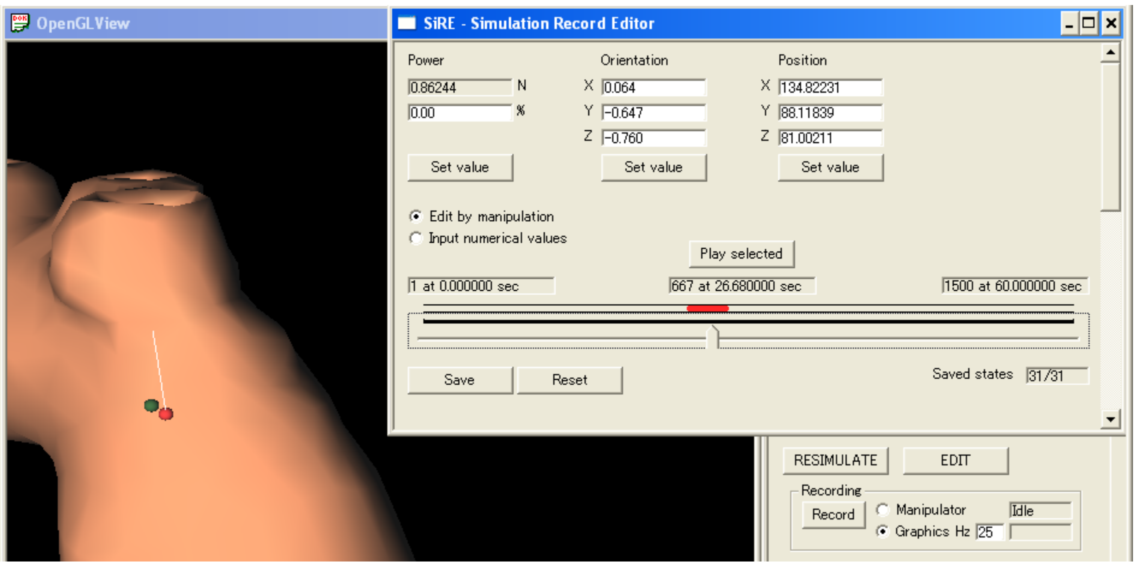

Fig. 3. Editing of power of recorded palpation of the aorta using SiRE. The red manipulator is controlled by the user. The white vector visualizes the reaction force felt. The green one indicates the

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original position in the recorded manipulation. The user is reducing power by keeping the manipulator in a proper position and feeling the power through the haptic device.

Serialized markers avoided re-simulation from the beginning and improved interactive to the user. SiRE's functionality in a case of palpation of the aorta is demonstrated in Fig. 3, in which the user is reducing excessive power in the recorded manipulation.

Although tested with PHANToM Desktop, the design of SiRE is applicable to other interfaces as long as recording of raw-data at the highest accuracy can be implemented.

5. Conclusion

To facilitate authoring of perfect surgical examples on a physics-based simulator, a method for transition between non-interactive playback and interactive simulation was designed, implemented and tested. Recorded surgical manipulation can now be edited on the basis of physical phenomena that are computed in the simulation, yet, the original raw input data remains as the permanent storage format. The proposed method allows interactive editing without hindering flexibility of playback. SiRE – Simulation Record Editor – can be used for authoring of example surgical procedures as a tool for high-tuning recorded simulation toward perfect example manipulation. The proposed method is applicable to typical concurrent surgical simulators and will be applied in other surgical manipulation, for example cutting and suturing, as the future work.

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