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Annotated Surgical Manipulation for Simulator-based Surgical Skill-transfer using SiRE – Simulation Record Editor

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This paper outlines the efforts for developing a framework for annotation of recorded surgical procedures toward the goal of simulator-based skill-transfer in surgery. The framework is based on SiRE – Simulation Record Editor – an application that allows medical teachers to produce variations and make perfect example surgical procedures even without surgical manipulation skills. By using SiRE, physical properties of the recorded manipulation can be modified interactively and accurately. Edited examples can be annotated as they are intended as self-learning media in surgical training of the future.

Introduction

Research of medical Virtual Reality (VR) has been focusing on the realism of visual and haptic feedback of simulation (for example [1, 2]). However, in the medical field, realism is not the only key element of successful simulator-based training. Modelling and evaluation of surgical skills [3, 4, 5] are emerging as a major research field. Studies on manual skill-transfer have introduced a record-and-play approach with the aid of haptic devices. Such studies aim for the benefits of using digital data [6, 7]:

- Freedom of time, location and number of teachees
- Direct and exact feeling of the model with unlimited repetition

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- Flexibility of learning strategies
- Recorded digital data can be evaluated and modified

This approach is usually demonstrated in writing with a pen [6, 8]. If similar approach was possible in surgery, the dominant master-apprentice teaching methodology could be changed for the better. In the complex surgical field, however, to understand the recorded example manipulation is not trivial. While research on using VR for understanding complex concepts continues [9], the need for annotation to describe surgeon's line of thought has been acknowledged [10, 11]. So far, annotation has been applied to the traditional teaching media, such as video, and the main task of the authors is to investigate annotation as an essential part of surgical training simulation.

A framework for surgical skill-transfer based on annotation of recorded surgical simulation is being developed. The example manipulation and comments are included into a Simulation Record (SR) which is accessible through the training simulation. In addition, the recorded example surgical procedures can be made interactive at will so that the user can perform at any stage of the recorded simulation. The goal of this approach is to create a virtual self-learning environment that would reduce the need for time-consuming one-on-one instruction. Case-specific knowledge and the manual skill are encapsulated into Annotated Simulation Records (ASRs).

Before annotation, it is important to have meaningful recorded example manipulation. SiRE – Simulation Record Editor – allows editing of recorded physics-based simulation. Two scenarios for editing were identified: making of variations and perfecting example surgical procedures. With SiRE, the recorded manipulation can be fine-tuned so that errors would be omitted out in the example. This possibility is only present in VR and it reduces the need for annotation on the differences between what was done and what should have been done during the surgical procedure. Variable approaches can be created from the original SR by scaling its trajectory data. The scaling allows even a person without true manipulation skills to edit SRs. Recorded manipulation can be edited interactively and accurately by using two editing methods: re-recording and setting key values that are used for scaling the original trajectory. The simulation engine can be utilized for setting the key values.

The paper is organized as follows. First, a brief overview of the annotation framework is given. The remaining sections discuss a part of the framework, a simulation record editor, in more detailed manner including preliminary results.

Related Work

To achieve the fore-mentioned benefits of digital data in surgical training is challenging. The medical field is complex (in nature) and the need for annotation of surgical manipulation has been realized. The Virtual Rounds concept [10] highlighted the need for a full simulation system instead of mere simulation engine in medical

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training. In that concept, annotation is an important aspect that facilitates asynchronous teaching and self-learning process. Immersive Electronic Books (IEBooks) [11] supports self-learning from recorded simulation. IEBooks are surgical procedures recorded with video cameras by using image processing techniques. IEBooks can be annotated by linking text, audio messages, video clips and images. Past surgical procedures can be viewed in an immersive virtual environment. IEBooks are intended as a learning environment for surgical decision-making. Therefore, interaction of the user is restricted to three-dimensional viewing without any support for surgical manipulation with haptic devices.

In order to facilitate surgical training in various cases, scene building applications have been developed [12, 13, 14]. These systems support changeable and modifiable anatomy and interaction models. This paper introduces an application that allows changeable and modifiable example manipulation.

A mechanism for editing recorded simulation using suitable data formats and managing their synchronization has been proposed [15]. The editing of SRs has not been clearly addressed in the studies so far from the user's point of view. This paper focuses on the algorithms that enable editing suitable for the surgical context.

Annotation Framework

The design of the annotation framework for simulator-based surgical skill-transfer has been affected by the need for annotation and the benefits of digital data, especially recorded VR. In this paper, only one of the major elements of the framework, authoring of SRs by editing physics-based simulation, is discussed in detail.

The Concept

Figure 1 presents an approach for a novel teaching and learning methodology based on ASRs. Surgical procedures are captured by recording the user's manipulation on the simulator at the best possible accuracy. SR contains the manipulation as well as the visual playback which is easy to control for the user. The SR is annotated by the teacher to demonstrate pedagogical points within the SR's scope. The annotation data acts as knowledge transfer medium whereas the recorded manipulation contains the motor-skill. A self-learning scenario is produced for the students who can gain knowledge from the annotations and interact with the same simulated surgical setting. The framework is designed for indirect simulator-mediated teaching of surgery.

Processes for the production of ASRs are *recording*, *editing*, and *annotation*. Processes can be shared between individuals so that a surgeon is not required to be involved in all the phases. Instead, editing and annotation can be left to a general medical teacher in the cases that do not require description of the surgeon's line of

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thought. The medical teacher can produce examples after the surgeon's manipulation has been recorded.

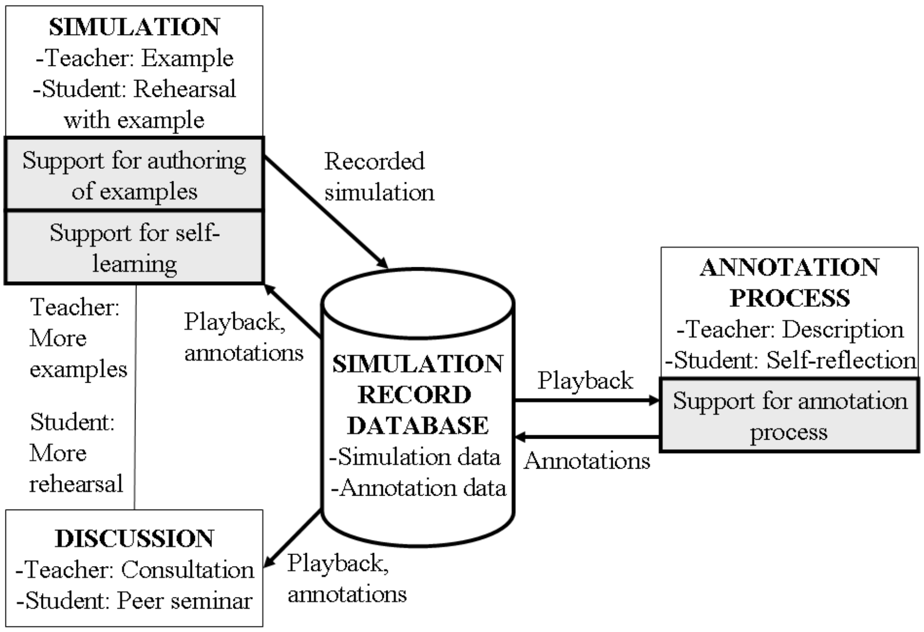

Figure 1. ASRs for simulator-based surgical skill-transfer. The system's support has three targets: authoring of SRs, annotation of SRs and self-learning using ASRs.

The Role of Annotation

Traditionally, text-books have been annotated by underlining, drawing, sketching and commenting. The notes have definite value for an individual studying the content. In addition, personal annotations can be useful to others, and annotations can make consensus within the readers explicit [16]. Nowadays, annotation of any multimedia objects is possible. Annotation of VR is a natural extension of this development.

Both knowledge and manipulation skill can be mediated through the ASR which acts as *reference of the simulation system* [10]. ASRs can be used at several levels. For example, an ASR could be annotated to introduce the basic concepts of the scenario. At this point, the existing digital teaching material can be linked to specific segments of the ASR. Later, annotation could reach another level of details for self-learning the surgical procedure as a whole. Students can annotate their experiences as learning diaries, which allows *self-reflection* [10] by making notes of one's progress.

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The authors highlight the importance of the relationship between surgical manipulation and its target. The annotation process aims to define the targets of each segment of manipulation. The framework's objective is to detect the relationships automatically after the targets have been defined by the annotator. This would construct a model of correct manipulation that can be used as evaluation metrics in each segment. Self-learning would be supported by pointing out the user's mistakes compared to the model. In addition, variations of the manipulation could be generated automatically after the targets have been determined in a new anatomical setting.

Design of SiRE – Simulation Record Editor

VR is characterized as a rich and flexible presentation. VR can render high resolution and photorealistic images and realistic haptic sensation. On the other hand, VR can simplify and facilitate understanding the nature of the situation and the manipulation.

In traditional methods, anatomy textbooks and cadavers are the predominant learning media. With these media, perfecting the example manipulation is impossible. Only VR gives the possibility of unlimited repetition of realistic cases that can be improved from the original recorded data.

Surgeons are usually occupied with the clinical work, which often conflicts with teaching responsibility. SiRE allows an different person, a general medical teacher, to make variations of an original recorded manipulation performed by the surgeon.

Data Model

As shown in Figure 2, SiRE's data model is divided into two basic layers: raw input data and visual playback medium. The raw input data covers the complete time series of device-specific data, typically position and posture of manipulator points. For example, with a glove-shaped interface positions and angles of fingers' joints are recorded. The playback medium contains time series of 3D structure of the model. Moreover, the playback can contain any additional information that the simulation engine is capable of simulating, such as force and colliding regions.

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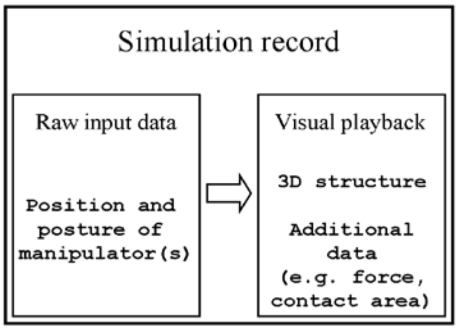

Figure 2. Composition of simulation record.

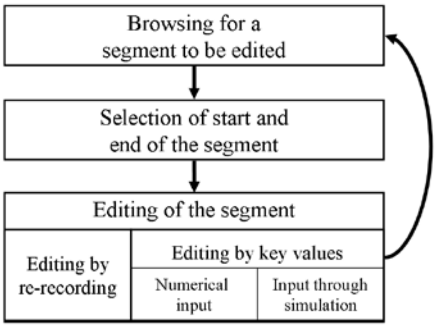

Figure 3. Process for editing SRs with two editing methods.

Design for Editing

For making variations and perfecting examples of surgical manipulation, the following requirements were determined:

- Replacement of total failures in the original manipulation.
- Making variations by replacing selected sections of the original manipulation.
- Correction of very small mistakes with high accuracy.

The need for true manipulation skill should be minimized, so that a person other than a surgeon could be responsible for the editing.

In addition, the editing process should be easy to use. The user should be able to modify an incorrect location of contact between the skin and the scalpel by simply pointing a new location with the haptic interface used in the simulator. Figure 3 shows the editing process of SRs. A segment to be edited is browsed and the segment's start and end points are determined. Then, the segment is edited in the following methods.

Re-recording is an obvious option for an editing method. The original segment is replaced by a new manipulation recorded by the user. However, re-recording can result in manipulation that is not fully continuous. Therefore, differences between the start and the end point of the new and the original manipulation are interpolated. At the moment, the design of SiRE does not address the problem of discontinuity. Re-recording is suitable for correcting total failures and for recording alternative approaches that require very different manipulation than the original one.

Editing by key values is an editing method that modifies the original manipulation. A new value given by the user is used for calculating a new raw-data trajectory to result in a satisfactory simulation. The key value can be given numerically by modifying values of physical properties of the simulation visible in the GUI, or by interacting with the simulation directly. When interacting with the simulation directly, at first, the user is given control of the simulation at the segment's start situation. A state of the user-controlled manipulation, chosen by the user, is recorded. The state is

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considered as the new key value, by which the original manipulation is calculated. This approach allows editing another person's manipulation without affecting its individual-dependant properties, such as smoothness of the trajectory or velocity, since the original manipulation is modified from the original recorded data. Numerical editing provides the best accuracy for the new key values, but lacks interaction with the simulation. It is a suitable method for fine-tuning the manipulation and numerical tasks, such as normalization of segments. An example of normalization is setting power level in each segment to a limit value in subtle palpation to avoid excessive force that would result in harmful manipulation. Figure 4 shows an example of how a contact location can be edited by defining a key value.

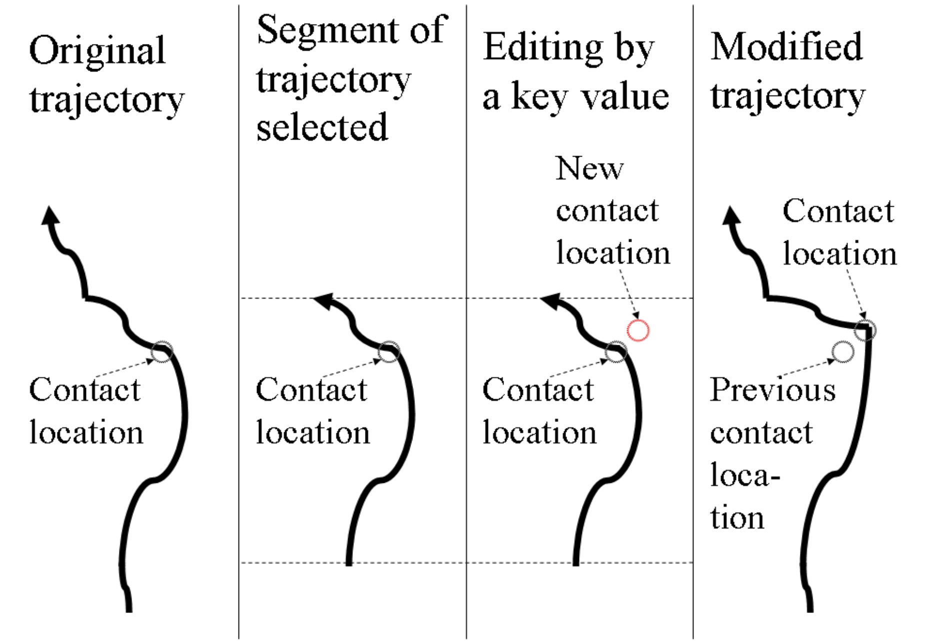

Figure 4. Editing by setting key values. The trajectory is scaled by the given contact position.

Algorithm for Scaling Trajectories

When scaling a trajectory to reach a certain point in the simulation space, the properties of manipulation that are essential in the surgical context have to be taken into account. The trajectory should preserve its smoothness and average velocity after scaling. Therefore, when using position time-series sampled at a constant interval,

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additional points have to be added when the target point (p_t) is further than the trajectory's furthest point (p_n). Consequently, points have to be deleted when the trajectory should be shortened. The algorithm presented in Figure 5 is suitable for such scaling. When the furthest point p_n has been determined, the trajectory is divided in two so that both parts approach p_n. The algorithm is applied to both parts separately. In order to lengthen the trajectory, points are duplicated when lengthening the trajectory and consequently removed when shortening. Thus, smoothness and average velocity remain almost the same as in the original trajectory. (1) is executed in a loop until the remaining distance to the target point becomes smaller than the distance added. The last addition is performed with (2) to ensure perfect accuracy, which is the only modification that affects the average velocity.

Besides using the algorithm for scaling the trajectory to reach to a certain location defined by the user, it can be applied for scaling on the basis of other properties of the simulation. For example, as in Figure 6, power the user-given value. A tangent vector is formed of the first and the last collision points (p_{col1} and p_{col2}). The vector determines the direction of scaling. Pre-simulation is executed so that a temporary position proceeds along the tangent vector until the user-given power is met at p_c. Distance between the vector $p_{col2}–p_{col1}$ and p_c is calculated with a cross product and the target position p_t is calculated from the difference of distance to the vector $p_{col2}–p_{col1}$ from the points p_c and p_n. The direction of scaling can also be determined simply to $p_t–p_{col1}$, or some other vector, depending on the case.

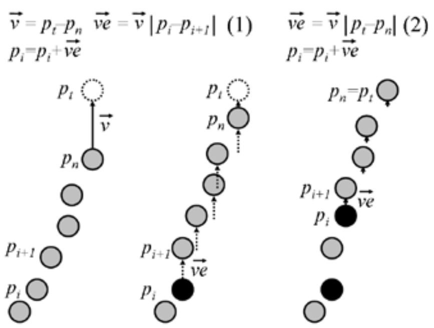

Figure 5. Scaling algorithm for trajectories.

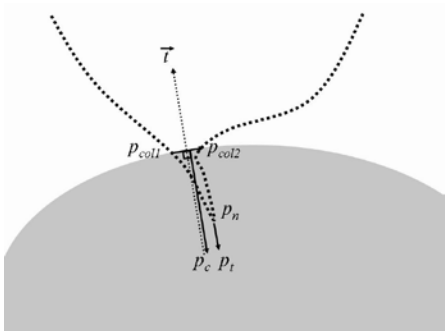

Figure 6. The target position p_t defined by a power value.

Experiment

Preliminary experiment evaluates the scaling algorithm with two criteria: smoothness of motion and average velocity. If both factors remained about the same as in the unedited trajectory, the scaling algorithm can be used without the risk of losing the

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properties of the recorded manipulation that are important in the medical context. Shaking of the hand can be a valuable clue for learning when reviewing recorded manipulation. Smoothness was evaluated with time-integrated squared jerk metrics [17] which compares the difference of acceleration in the trajectory. Smaller value means smoother trajectory. Average velocity should also remain the same.

The experiment procedure is straight-forward. At first, a trajectory is recorded in a simulation and evaluated with the two above-mentioned criteria. The trajectory is scaled up by giving power values at a constant interval. The scaled trajectories are finally compared to the original trajectory.

SiRE was implemented as an add-on to the Medical Virtual reality simulation Library (MVL) [14] system. The MVL runs on a Xeon 3.2 GHz dual processor with 4 GB RAM. The haptic user interface is PHANToM Desktop. The raw input data (position of the 1-point manipulator) was recorded the rate of the haptic loop at about 1000 Hz. The recorded trajectory consisted of a light push against a simulated soft-tissue model with a 0.78 N maximum power. Power value for scaling was increased by 0.2 N up to 1.98 N so that the trajectory gained length. Due to restrictions of the given trajectory information (1 ms sampling) and the mathematical nature of the algorithm, trajectory's shape was not evaluated.

Results

Figure 7 presents the results. Both smoothness and average velocity remained about the same as in the original trajectory. Scaling of trajectory with the algorithm does not reduce the properties of the manipulation essential for surgical assessment. Therefore, by using this algorithm SiRE allows person without manipulation skills to edit SRs without hindering possibilities for objective assessment of the manipulation.

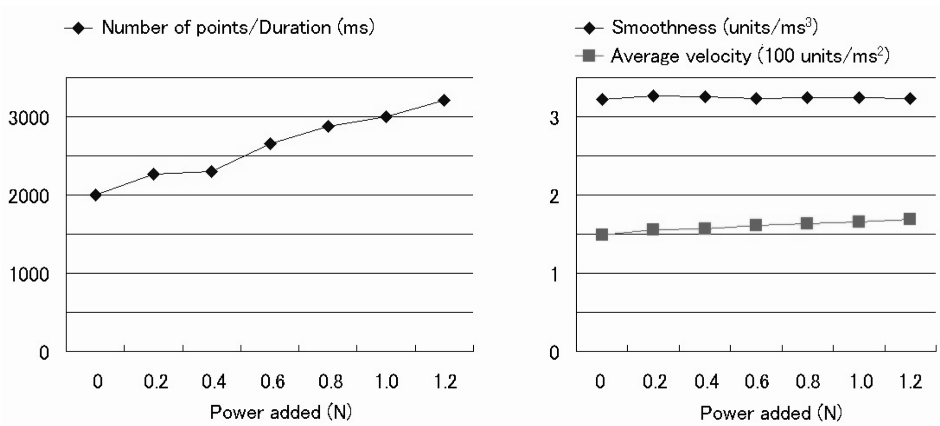

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Figure 7. Results of the experiment. Left: Increase of points in the trajectory. Right: Smoothness and average velocity. The first element at 0 N is the original unedited trajectory. Slight variance in accuracy is due to rounding.

Conclusion

The development of a framework for annotation of recorded surgical procedures was summarized briefly in this paper. The framework includes SiRE – Simulation Record Editor – that allows medical teachers to produce variations and perfecting example surgical procedures from recorded physics-based simulation. SiRE has two editing methods: re-recording and setting of key values through interactive simulation or numerical input. Algorithm for the latter method was validated to preserve the essential properties of manipulation, smoothness and average velocity. The algorithm enables intuitive and accurate editing of SRs even without true manipulation skills. In Figure 8, a SR is being perfected by adding more power into a selected segment.

Next target for the research on SiRE are algorithms that ensure natural continuity of manipulation when new segment of SR is re-recorded and connected to the original SR. The final goal of this research project is to demonstrate that ASRs can act as an indirect teaching media in surgical training. The framework will be available in 2007.

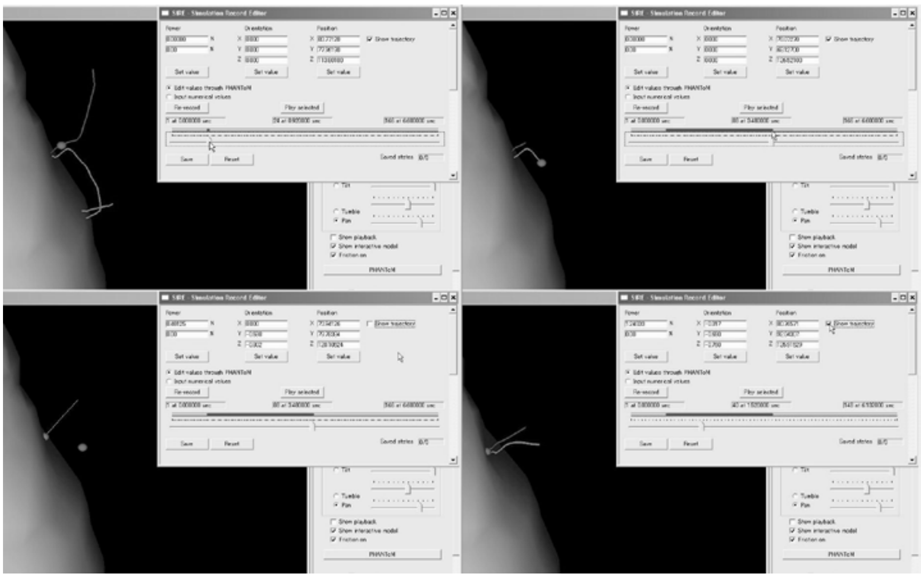

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Figure 8. SR representing palpation of the aorta is perfected by scaling the trajectory. Top left: trajectory of the whole SR is visualized. The SR contains two contacts with the target. Segment's start is determined. Top right: Segment's end determined (segment's borders are shown on top of the timeline). Bottom left: Approaching the new key value. Trajectory is scaled when Set-button is clicked. Bottom right: Updated segment with the scaled trajectory.

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