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A Haptic Enabled Virtual Reality Framework for Orthopedic Surgical Training and Interventions

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Abstract

Modern technological innovations have led to the development of virtual-reality based systems that are gaining importance in the field of medicine due to their potential advantages over conventional approaches. These systems can offer safe and viable environments for surgical training, skills enhancement, and also assist clinicians during different stages of treatment. Despite several advancements in this field, the availability of virtual-reality systems especially for patient-centric training and complex invasive surgical procedures remains elusive as majority of the currently available systems are geared towards minimally invasive surgery or utilize non-patient specific models.

In this paper, we present a new software framework, RoboPlan, that integrates several components, ranging from patient-specific anatomic models to intra-operative navigation and haptics, in an attempt to overcome some of the constraints present in the available systems and bridge the gaps between pre-operative simulator systems and actual intra-operative surgical scenarios. Our framework incorporates various custom modules that enable advanced visualizations and immersive experiences. The proposed system can serve as an effective tool for anatomy training, surgical planning, diagnosis, and

real-time intra-operative surgical guidance. We aim to extend the presented framework to facilitate realistic training in invasive interventions in specialties like orthopedic surgery that involves complex musculoskeletal structures and mechanical instruments.

Index Terms: virtual reality, haptics, force feedback, virtual surgery, and orthopedics

1. Introduction

Despite several technological advancements in the medical field, conventional methods, based on animal models, inanimate models like mannequins, and preceptor-apprenticeship model, continue to dominate as the primary means of imparting surgical training or continuing medical education in a majority of surgical specialties. These traditional methods, although well adopted, have several drawbacks. For instance, cadavers cannot yield appropriate physiological response and cannot be used to practice real time scenarios. Mannequins and animal models cannot sufficiently provide the desired inter-patient variability and realistic anatomic representations. Moreover, cadavers and animal models are not reusable and allow for only a restricted number of pathological scenarios to be practiced. Furthermore, their usage may involve ethical issues, complex logistics, and only a few trainees can be trained on a cadaver or an animal. The rising costs and unavailability of operating room time, risks associated with practicing procedures on patients and the time restrictions imposed on training limit the preceptor-apprenticeship model and most importantly can compromise patient safety. These drawbacks along with other factors like technological advancements, rising patient awareness, increased sub-specialization, and especially, patient safety issues, challenge the traditional methods of training [1, 3] and necessitate the need for novel alternatives for surgical training and skills enhancement.

Recent technological advancements have led to the development of virtual reality (VR) based systems that can potentially imitate all aspects of complex, dynamic surgical scenarios in virtual spaces and offer safe, viable alternatives to the conventional approaches [14, 17]. These systems can provide the clinicians with virtual, three-dimensional (3D) visualizations of the anatomical organs during different stages of treatment and offer efficient means for surgical skills training and enhancement, quantitative evaluation and real-time feedback [16], as well as diagnosis, planning, and exploration of novel surgical techniques that can directly benefit clinicians and patients. Unlike traditional approaches, VR systems offer reusability, enhanced performance and training efficacy, reduced surgery times, surgical errors, costs and risks associated with the acquisition of new skills [9, 13, 10, 2].

In recent years, VR-based surgical simulation systems have emerged as powerful candidates in the medical domain and are gaining importance especially in the pre-operative settings wherein they provide a predefined, controlled training environment, with standardized and reproducible scenarios, without compromising patient safety [2]. Most of the simulation systems for training have gained recognition primarily in the field of minimally invasive surgery (MIS) [4] like endoscopic gastro-intestinal surgery or arthroscopic knee surgery. Although popular, MIS procedures represent only a small fraction of the approaches for surgical interventions and the majority of such interventions are still performed using an open incision [3]. However, similar techniques have so far not evolved for general surgery and, in particular, invasive orthopedic surgery. Moreover, most of the developed simulators often lack haptics feedback, usually incorporate simple virtual anatomic models that lack soft tissue details, and can only demonstrate specific surgical tasks. Additionally, many available simulator systems do not utilize patient-specific anatomical models which, further limits their use in imparting realistic training. Today, there is a need for sophisticated, patient-centric VR-based tools that can bridge the gap between the available pre-operative simulator systems and the actual intra-operative surgical scenarios and also facilitate training in invasive interventions in specialties like orthopedic surgery that involves significantly complex musculoskeletal structures and mechanical instruments.

The work showcased in this paper is a step forward in this direction. The presented framework, RoboPlan, incorporates both pre- and intra- operative components of a surgical scenario and provides a comprehensive platform equipped with haptics, visualization, and intra-operative navigation capabilities. Our software framework integrates haptics and navigation technologies with synchronized and realistic visualizations of multimodality imaging data for pre- and intra- operative surgical training and interventions. Multimodality imaging data typically involves images from two or more imaging modalities, such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) that can help gain additional structural details. The haptics capabilities enable perception of real-time and sensitive tactile or kinesthetic interactions between surgical tools and tissues, the visualization capabilities facilitate interactive, patient-specific two-dimensional (2D) and three-dimensional (3D) visualizations of multi-modality data, and the localization tools allow the tracking of position and orientation of surgical tools with respect to the patient's anatomy in real-time. Our developed software allows clinicians to examine re-sliced views of different image volumes, like computed tomography (CT) and magnetic resonance (MR), at various angles along with highly detailed 3D representations of the corresponding anatomic organs, thereby facilitating easy identification of the spatial correlation of the anatomical features in 2D and 3D spaces graphically as well as haptically through tactile feedback.

Orthopedic surgical procedures require extensive training and skills practice due to the involvement of sophisticated and significantly complex musculoskeletal anatomies. We exemplify the utility of our framework in this domain by encompassing a continuum of visualization modes ranging from interactive 2D image modalities to highly intricate 3D model of a patient's knee showcasing heterogeneous tissue properties, localization tools for intra-operative surgical guidance, and force-feedback modules for interactive exploration of distinct tissue anatomies and tool tissue interactions. The developed software can serve as an effective tool for anatomy education, diagnosis, surgical training, real-time intra-operative surgical guidance, and exploration of novel surgical techniques for various phases of surgical tasks. The presented framework is highly modular and can be easily extended to other specialty areas.

The rest of the paper is organized as follows: Section 2 delineates the key functional components of the software framework along with their operational details. The next section presents key implementation details of the core components. The subsequent section demonstrates the applicability of our system. The last section summarizes the main conclusions and discusses possible future improvements.

2. Framework Description

The developed framework, RoboPlan, comprises of three key functional modules: (i) Patient-specific modeling and representation; (ii) Haptics; and, (iii) Localization. The details for these modules are given below.

2.1. Data modeling and representation

Pre-operative 2D imaging data, e.g. from MR and CT, is the fundamental source of information for subject-specific VR-based systems. However, volumetric models obtained by stacking the 2D image data slices are not adequate to provide the required level-of-detail (LoD) and realism that are expected from a realistic surgical training system and cannot be effectively used for tasks like anatomical volume estimation. Explicit modeling, based on parametric or polygonal representations, of the patient-specific anatomic structures is necessary to address such issues. Moreover, accurate modeling of the involved anatomic details is also critical to envisage the restorative functional outcomes of different surgical procedures.

Our framework utilizes multi-modality imaging data to construct high-quality, 3D polygonal mesh models for subject-specific anatomical organs. For instance, it exploits CT data to extract hard tissue structures like bones using region growing, morphology, and thresholding techniques [11] or MR data to segment both hard and soft tissue structures like tendons, ligaments, fascia, skin, nerves, and blood vessels. Full 3D representations of the segmented organs are then generated. Further details of our tissue modeling approach are given in [20].

2.2. Haptics

Haptic feedback provides a sense of touch during a surgical task and enhances the ability to distinguish among various tissue types. It is critical for realistic VR-based training as well as the dexterous skills required during surgery. In training, it aids with the early phase of psychomotor skill acquisition and during surgery, it helps to reduce learning curves, fatigue, surgical errors resulting from force-induced damage, and operative times by about 40% [8, 22, 7]. It is a necessity especially in situations involving partly or totally occluded structures or surgical environments with poor visibility

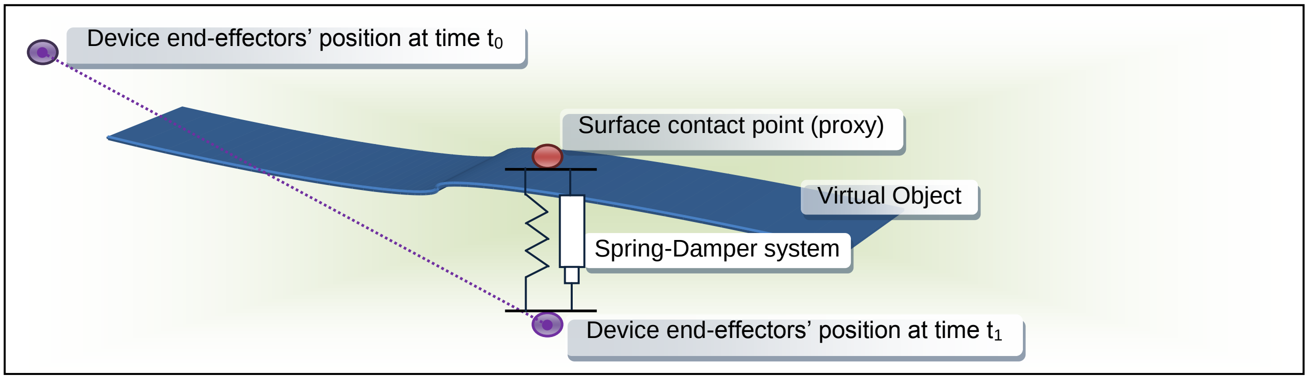

Figure 1: Constrained Proxy approach to compute contact interaction force between the virtual object and the device end-effector. The force is calculated by stretching a virtual spring-damper between the haptic device position and the proxy position.

[23]. Despite these significant benefits, absence of haptic interaction remains the most important limitation of the currently available systems [8, 12] mainly because high fidelity rendering of haptics within a virtual environment is not trivial and presents many challenges at both software and hardware levels.

Commonly deployed methods for haptics rendering are normally classified as point based, ray-based, and 3D object-based, depending upon the modeling of the employed probe or surgical tool. In a point based technique, the probe is modeled as a point so, only the tip of the tool interacts with the virtual objects whereas in a ray-based technique, the probe is modeled as a line segment and, in the object-based technique the probing tool is modeled as a set of points, line segments, and polygons.

Our application platform integrates a phantom haptic device with 6 degrees of freedom (DoF) input and 3DoF force feedback, to enable tactile sensations and enhance the perception of clinicians during a surgical task. The 3D anatomical model is rendered using a proxy scheme [18]. A Proxy is a point that attempts to follow the probe tip or the end effector position but is constrained to be on the surface of the geometric object. Figure 1 illustrates the proxy concept with the proxy point located on the surface at a distance closest to the device position, located inside the surface. The 3D model is rendered in a "contact" mode that resists the penetration into the surface as opposed to the "constraint" mode which constraints the proxy position to the geometry's surface when the probe falls within a specified distance threshold. The resistive force between the probing tool and the proxy is computed based on a spring-damper system that stretches between the end-effector position of the device and the proxy or the surface contact point (SCP).

2.3. Localization

Localization enables the tracking of position and orientation of the surgical instruments with respect to a patient's anatomy through the use of an optical or electromagnetic tracking device. It provides an efficient means to combine the pre-operative data, in the form of image scans, with the intra-operative tool's localization data that can provide additional information to the surgeons and help facilitate effective decision making.

Our developed framework integrates an optical tracking device and renders the real-time position and orientation information of the 3D representations of the surgical instruments with respect to the virtual anatomical model. It shows the real-time tracking information, re-sliced volume slices based on the position of the tracked instrument, as well as the 3D polygonal model representation. The software framework uses a paired-point based rigid body registration technique to establish spatial correspondence between the physical patient space and virtual 2D and 3D data space [11]. This step is crucial for proper alignment of the different coordinate systems involved in the virtual and actual physical spaces. Next section presents some of the key details of our framework implementation.

3. Framework Implementation

3.1. System Details

We developed and tested the framework on a Microsoft Windows based personal computer with Intel® Xeon® Quad-core 2.0 GHz processor, 128 MB RAM, and NVIDIA Quadro FX550 graphics card. To incorporate the haptics and localization functionality, we employed a Phantom Omni device [19] which has been shown to obtain high reliability [21] and a NDI Polaris Optical Tracker [15], respectively. The software was developed using C++, OpenGL, Qt, and the Open Haptics Toolkit.

3.2. Core Components

The overall framework comprises of three core components namely, haptics, localization, and graphics, which run simultaneously in a multi-threaded manner at a high frequency. Following sub-sections present the implementation details of these key components.

3.2.1. Haptics

Haptics technology can provide the clinicians with an immersive experience by supplementing their dexterous, kinesthetic, and cognitive abilities during virtual tool and tissue interactions. We use a Phantom Omni (SensAble Technologies) haptic device to incorporate tactile functionality and manipulate surgical tools or instruments during the training mode. The haptic device takes a 6DoF (force and torque) kinematic information as input that can represent the position and angle of a surgical tool at a given instance and can be used to return a 3DoF (translational) force reflexion in case of a collision. Figure 2 illustrates all the six joints of the haptic device. As shown in figure 2, three joints in the device permit rotational movements and the other three support translational movements. The device has physical workspace dimensions of 160w x 120h x 70d mm and permits a maximum exertable force of 3.3N at nominal or orthogonal arms position.

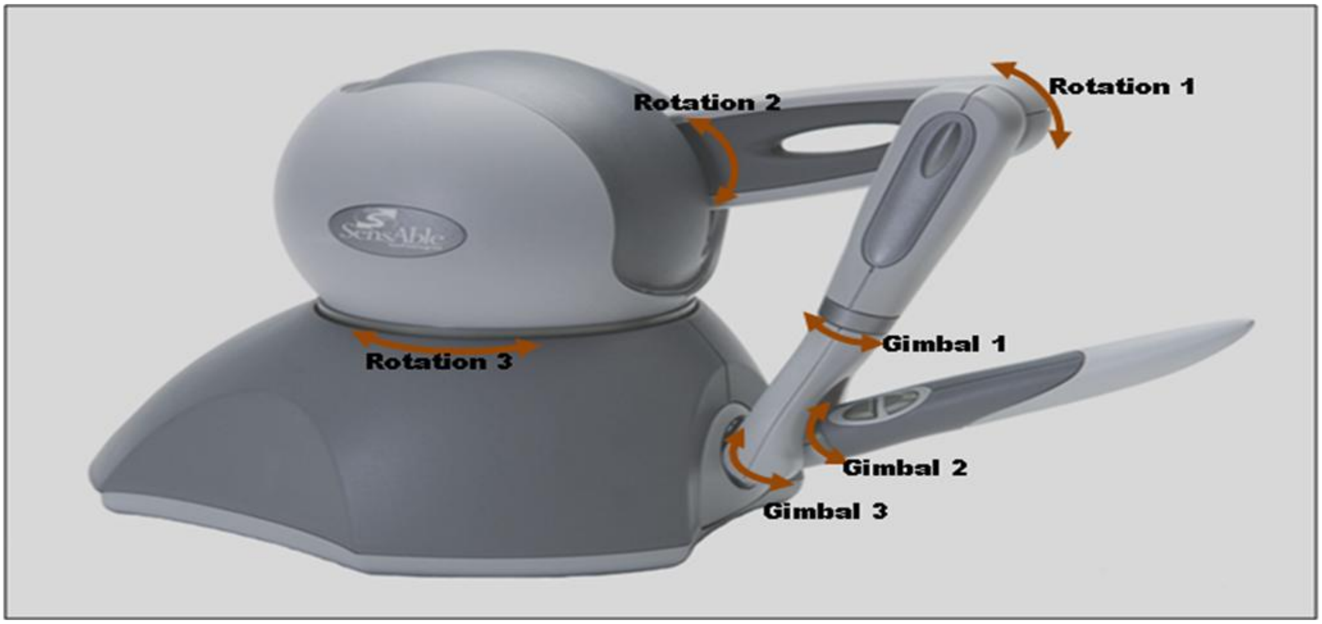

Figure 2: Detailed overview of the joints and the motion supported by the PHANToM Omni Haptic device.

For realistic haptics feedback, it is critical to have efficient collision detection and response mechanisms. Collision detection primarily deals with the detection of contact between a surgical tool and tissues whereas collision response mainly deals with the determination of force feedback or responses such as deformation force field computations. Our framework utilizes the HLAPI and HDAPI libraries of the Open Haptics toolkit [18] for tool tissue collision detection and response functionality at the desired update rate. In each frame the haptics thread receives the 6DoF input information (position and orientation) and computes the reaction (translational) forces (force reflexion) which, are then fed back to the user. The forces are constrained to be within the maximal permissible exertable threshold along each of the orthogonal positions. We currently deploy a point based haptics rendering scheme [5] to render the tip of the surgical tool(s) or haptic device end effector, often referred to as a Haptic Interface Point (HIP), and use real-time collision detection to compute interactions between the virtual surgical tool(s) and 3D anatomical objects. In the current implementation, the force computation is primarily based on a spring-damper force model. The spring force ($\vec{F}_s$) is calculated using Hooke's law as shown in equation 1:

$$\vec{F}_s = k \, .(\Delta\vec{d}) \quad \text{Where} \quad \Delta\vec{d} = \vec{X}_{proxy} - \vec{X}_{probe} \qquad (1)$$

In this equation, k is the spring's stiffness coefficient and $\Delta\vec{d}$ represents the displacement between the proxy and the HIP. The damping force ($\vec{F}_d$) is computed using the following equation:

$$\vec{F}_d = -b.(\Delta\vec{v}) \quad \text{Where} \quad \Delta\vec{v} = \vec{V}_{proxy} - \vec{V}_{probe} \qquad (2)$$

In the above equation, b represents the coefficient of damping and $\Delta\vec{v}$ represents the relative velocity between the two points connected by spring at the time of collision. Combining equations (1) and (2) we can determine the total force ($\vec{F}_t$) as shown in equation 3.

$$\vec{F}_t = \vec{F}_s + \vec{F}_d = k.(\Delta\vec{d}) - b.(\Delta\vec{v}) \qquad (3)$$

Our framework utilizes highly detailed, patient specific 3D anatomical models incorporating various distinct tissue classes such as bones, muscles, ligaments, fascia, adipose tissue, and tendons. This allows each anatomical element to be handled separately and assigned different tissue material properties such as stiffness, damping, friction, and texture based on the individual tissue class represented by it. These properties are taken into account during the contact force computations. For example, considering distinct tissue stiffness and damping characteristics, equations (1)-(3) can be rewritten to determine the single point contact force and cumulative force when multiple points in the contact region are involved for more realistic tactile feedback and deformations. Cumulative force can be computed through the sum of initial contact point force and its neighboring points' forces, as shown in equation 4.

$$\vec{F}_t' = F_s' + F_d' = \sum k_i.(\Delta\vec{d}_i) + \sum - b_i\ .(\Delta\vec{v}_i) \qquad (4)$$

$$\vec{F}_s' = \sum k_i\ .(\Delta\overrightarrow{d_i})\ and\ \vec{F}_d' = \sum - b_i.(\Delta\vec{v}_i) \qquad (5)$$

The total force $(\vec{F}_t')$ is further constrained to ensure smoothness of the feedback force and stability of the haptic device. The final feedback or response force $(\vec{F}_r)$ is generated using the following equation:

$$\vec{F}_r = \begin{cases} \vec{F}_t', & \|\vec{F}_t'\| \le \theta \\ \vec{F}_{max}, & \|\vec{F}_t'\| > \theta \end{cases} \qquad (6)$$

Where θ represents the threshold that constraints the total force $\vec{F}_t'$ and $\vec{F}_{max}$ represents the maximum allowable force. The inclusion of material specific properties for each tissue class aids in easy differentiation of heterogeneous tissue types such as bones, muscles, and nerves, and can help distinguish critical tissue structures from the less critical ones. It also results in more realistic tactile perception as the haptic contact forces are generated based on distinct tissue properties of the interacting tissue structures. Our approach is currently being extended to incorporate the object-based haptic rendering mechanisms and deformation force field computations based on finite element modeling.

3.2.2. Localization

The localization system provides real-time information about the position and orientation of the surgical instruments with respect to the patient's anatomy in the physical and virtual spaces. We use NDI Polaris Optical Tracker [15] to obtain the 6 DoF tracking data of the surgical instruments and govern the position and orientation of the surgical tools in the virtual space with respect to the 3D anatomical model. The mapping between the physical and virtual spaces is established through a paired-point rigid body registration mechanism. In the rigid body registration approach, a set of landmark points is selected in the physical patient space or the actual anatomical object and matched with a corresponding set of fiducials selected in the virtual coordinate space or displayed MR volume. The mapping transformation mainly comprises of rotation and translation components as shown in the equations below.

$$\vec{S}_v = F_t(\vec{S}_p) \quad \text{Where} \quad F_t = R_{pv}.\vec{S}_p + \vec{T}_{pv} \qquad (7)$$

In the above equations, $\vec{S}_v$ and $\vec{S}_p$ represent the coordinates vectors in the virtual and physical patient spaces respectively. Function, F_t represents the rigid body transformation comprising of the rotation matrix R_{pv} and the translation vector $\vec{T}_{pv}$. The success of registration is measured by computing the fiducial registration error (FRE). The FRE is evaluated using the following equation.

$$FRE = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left\|\vec{S}_v - R_t.\vec{S}_p\right\|^2} \qquad (8)$$

In the above equation, N represents the number of feature points selected for registration, $\vec{S}_v$ and $\vec{S}_p$ are the coordinate vectors of the matched pairs of points in the virtual and physical patient spaces respectively, and R_t is the registration transformation. The registration is discarded if the FRE exceeds a user defined threshold.

3.2.3. Graphics

The graphics component provides the image processing, 2D and 3D visualization, and user interface capabilities for the localization and haptics devices. It provides a graphical user interface (GUI) to load multi-modality pre-operative CT and MR imaging scans, which can be registered using a voxel-similarity-based registration algorithm [11]. The interface allows interactive multi-planar (axial, sagittal, and coronal) 2D visualizations of the pre-operative image volumes along with their re-sliced

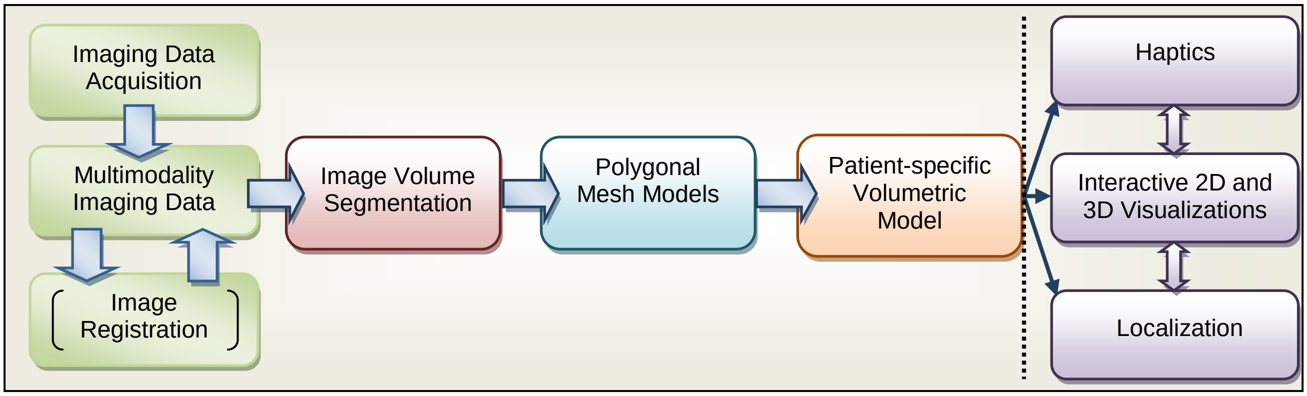

Figure 3: High level illustration of the graphics pipeline as implemented in our developed framework.

volumetric representations at any selected point within the volume. Likewise, the GUI also allows interactive visualizations of the patient-specific 3D models constructed from MR or CT imaging scans. The event handling capabilities of Qt are exploited to provide the interactive functionality. Menu based options are provided to configure the localization and haptic devices through the graphical interface. Figure 3 illustrates the outline of the graphics pipeline as implemented in our framework.

3.3. <u>Integrated View</u>

Figure 4 shows the overall system design of our software framework. It comprises of three key functional modes namely image data-processing and modeling, interactive, and post-processing mode. In the first phase, pre-registered 2D imaging data corresponding to the available modalities is validated and loaded into the system. The data are pre-registered in case data from both MR and CT are available. Subsequently, the 3D anatomical model generated from the 2D imaging data is loaded into the system and some of the required computational parameters are configured. Successful completion of this step establishes a one-to-one correspondence between the 2D imaging data and the derived 3D anatomical model which, can then be analyzed through the interactive visualization interface.

The interactive phase mainly comprises of the localization, haptics engine, and graphics rendering engine that operate synchronously in a multi-threaded environment with each component running in its own separate thread. The localization or tracking component runs concurrently with the haptics and graphics rendering engines and requires a Registration step as a pre-requisite to establish appropriate mappings between the elements of the physical patient space and virtual space. Currently, a four-paired-point rigid body registration scheme is deployed that is carried out through the GUI based menu options. The system monitors the tracking device and continuously updates the virtual tracking tool position and orientation in the virtual scene based on the captured tracking data. During navigation, the system also re-slices the volume depending on the position of the tracked surgical tools.

The haptics engine monitors the phantom device status, detects the surgical tool, tissue collisions, and computes the collision response vector based on the position of the surgical tool tip or device end effector and the 3D polygonal model, using the proxy approach [6], which is then transmitted to the user through the servomotors embedded in the device. It seizes the 6DoF input information in the Cartesian space, as captured by the three optical encoders in the PHANToM device, and computes the feedback contact force, between the virtual anatomical model and the surgical tool, if a collision is detected. The force feedback ensures a one to one correspondence between the physical tool tip and the virtual tool tip. The captured input information is used to establish the position and orientation of the surgical tool in the virtual space by the graphics engine.

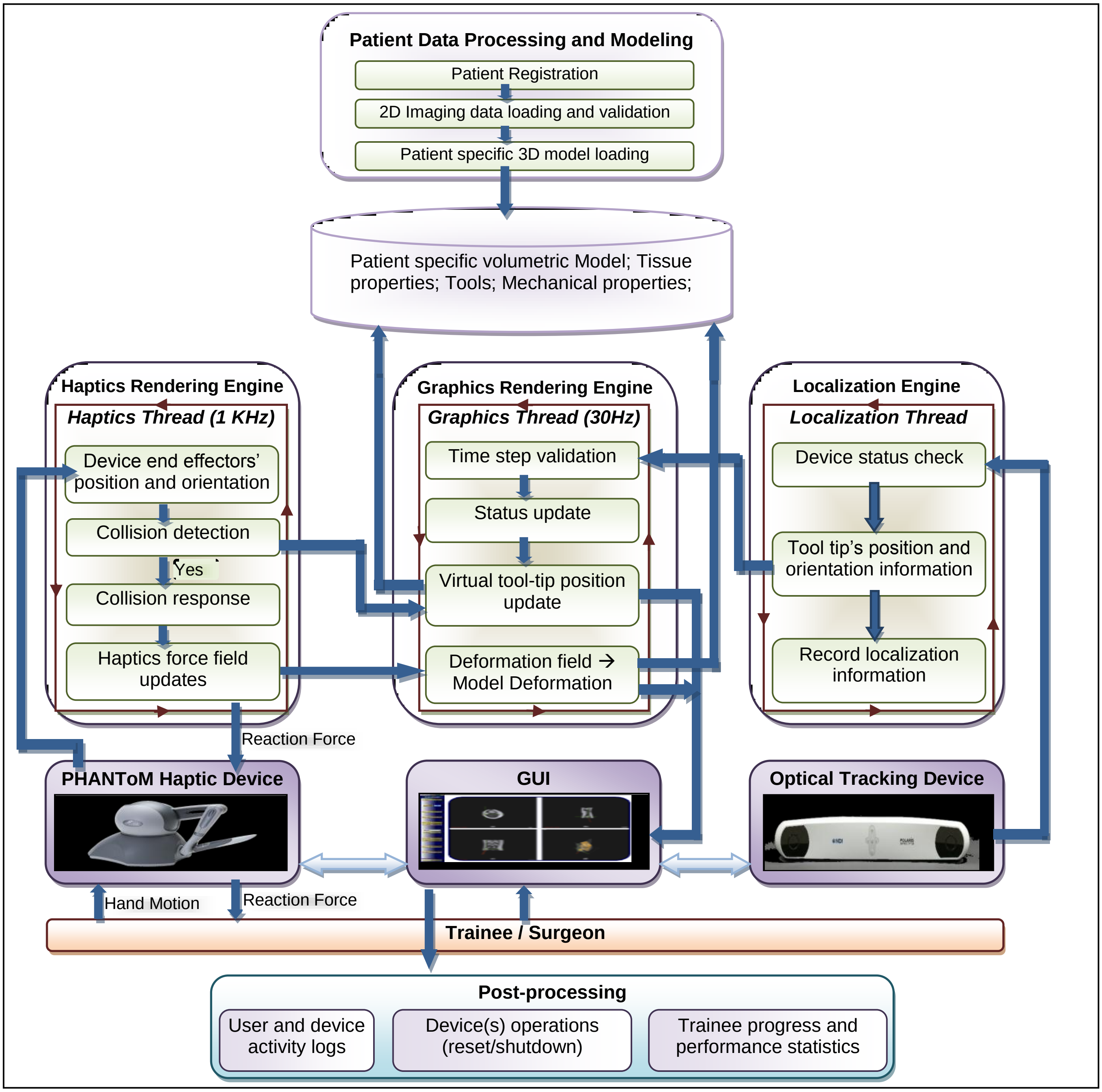

Figure 4: Overall system design of the software framework depicting the main components of the three key functional modes.

The graphics engine provides a collaborative platform for performing various tasks ranging from 3D volume rendering, re-slicing, and interactive display to external device configuration and registration. The haptics and localization engines provide the graphics engine with the most up to date tool information which it uses for surgical tool projections in the virtual space. For realistic visualization and haptics interactions the graphics update rate of 30Hz and haptics update rate of 1000Hz are maintained so as to minimize latency. To avoid delayed perceptions, synchronization among the various components is established through the use of timer events in the multi-threaded environment. In the post-processing phase the external devices are reset and other activity logs are committed.

4. Results

Figure 5 demonstrates the prototype of our proposed system for a human knee. Multi-modality 2D Knee Imaging Data were acquired pre-operatively at a hospital. Spatial correlation is established among the multi-modality data using an image based registration scheme. Figure 5 shows the acquired PD FSE MR Image DICOMS with 1.7mm slice spacing and thickness in the axial, sagittal, coronal, and 3D views. 3D display also shows the reconstructed, patient-specific 3D knee anatomical model derived from the pre-operatively acquired 2D image scans. The system permits direct interactions with the 2D and 3D display windows for tasks such as volume re-slicing, contrast adjustments, zooming, and rotation, through mouse and keyboard inputs. As shown in figure 5, MR image volume is re-sliced at the point of contact in each of the 2D views and the re-sliced (axial, sagittal, coronal) images are superimposed on the 3D model for enhanced visualization. A trainee or user can also interact with the system through the menu options provided on the left hand side to perform tasks like patient registration, loading or reloading of patient specific multi-modality imaging data, anatomic landmark(s) selection and labeling, image-patient registration, hardware configuration, navigation, and haptics activation. The use of highly detailed, multilayered anatomic model makes it possible to explore different tissue classes (bones, skin, muscles, adipose tissue, ligaments, tendons, etc.)

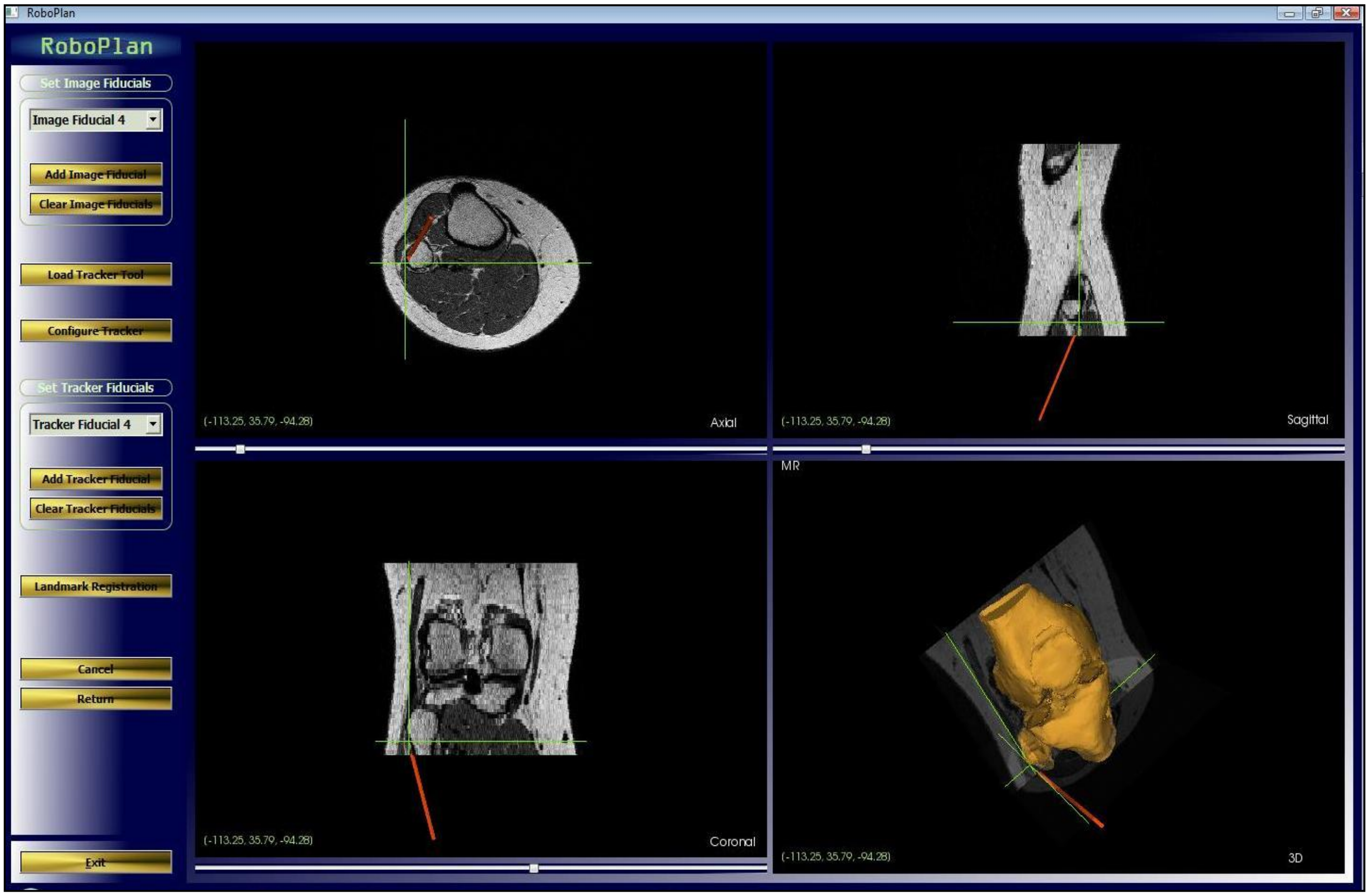

Figure 5: Figure depicts the main user interface of our developed framework. Haptics Exploration of a patients' Knee in 2D (axial, coronal, sagittal) and 3D views is shown. Haptics tool is shown in orange and can be seen in all the views. Only a subset of the patient's Knee 3D model comprising of the trabecular regions of the Femur, Tibia, Fibula, and Patella bones is shown. 3D view illustrates a combined view of the 3D anatomic model with superimposed 2D MR image slices.

individually or in collaboration with other tissue classes both visually and haptically. The trainee controls the surgical tool(s) through the use of Phantom device(s) which can be viewed in the virtual space and tracked intra-operatively by activating the localization engine. The developed system has been evaluated by the orthopedic surgeons and medical residents who provided continuous feedback to improve and refine the developed framework. Initial feedback by the orthopedic surgeons on the prototype of our system is very encouraging and pin points some additional features like deformation modeling that can help its adoption in a variety of clinical applications and medical curriculum.

5. Conclusion

A comprehensive VR-based, haptics enabled software system has been developed. The system enables interactive multi-modality 2D and reconstructed 3D model visualizations, manipulation, navigation, exploration, and assessment of anatomical regions of interest which can potentially benefit the trainees as well as the surgeons in both, pre-operative as well as intra-operative settings with applications ranging from anatomy training, diagnosis, and pre-operative planning to intra-operative surgical guidance. Preliminary feedback by the orthopedic surgeons on the prototype of the system is very promising and suggests some additional features like deformation modeling, tissue-tissue interactions, and robotics that can further strengthen the efficacy of our software and its clinical adoption. We intend to incorporate appropriate biomechanical behavior in our three-dimensional anatomical models through finite element modeling (FEM) based force field computations and soft tissue deformations. We also plan to extend the system to provide tools for performing certain interactive orthopedic tasks like cutting, drilling, and screw fixation.

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