HIPS - A Virtual Reality Hip Prosthesis Implantation Simulator

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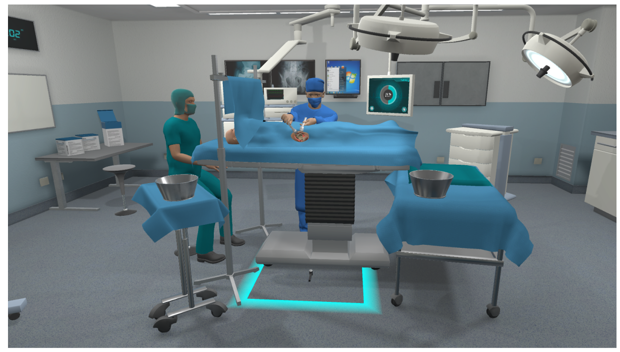

Abstract

We present the first VR training simulator for hip replacement surgeries. We solved the main challenges of this task – high and stable forces during the milling process while simultaneously a very sensitive feedback is required – by using an industrial robot for the force output and the development of a novel massively parallel haptic rendering algorithm with support for material removal.

Index Terms: Human-centered computing—Human computer interaction—Interaction devices—Haptic devices

1 Introduction

Many people are affected by arthritis. The prevalence of getting osteoarthritis increases with age: from 9% in the age of 20 up to more than 90% in the age of 65 and up [5]. The most affected joint is the hip. A standard therapy to relive the affected people's pain and other complications is a prosthesis implant. Actually, hip replacement arthroplasty is known as one of the most cost-efficient major procedures with regards to the expected quality of life during and following the treatment [3]. In Germany, there have been more than 140000 hip joint endoprostheses implanted in 2016 alone, making total hip arthroplasty the 6th most common surgical procedure [2]. Due to an increasingly aging population there will be an increasing demand for surgeons offering this surgical procedure in the future.

The benefit to the quality of life of a hip replacements depends mainly on the surgeons' experience: They have to chose an appropriate prosthesis for each individual patient and implant it correctly. The most complicated part of the surgery is the milling of parts of the hip in order to fit the prosthesis. Even very small errors in the milling procedure can result in complications following the surgery, such as dislocations [1]. Hence, the experience of the surgeon is a very important factor for the success of surgery. Unfortunately, it is very complicated and time consuming to learn the necessary skills to perform a hip replacement. Usually, prospective surgeons need to practice on the hips of deceased people that donated their body after their death. This resource is very scarce and as the procedure is irreversible; trainees can only use each hip twice (once per side) to practice. This affects the reproducibility in case of errors. This is crucial because the porosity of the bones and consequently, the force that has to be applied during milling, varies individually.

We present the first VR-based training simulator for the training of hips surgeries to overcome these limitations in the current training. It reduces the need for physical hips in the training process of prospective surgeons and medical students dramatically while simultaneously providing direct feedback of the success, giving hints for assistance and guaranteeing reproducible results. The main challenge when developing such a simulator is an adequate representation of the milling process. During a surgery, the surgeon does not *see* where and how he mills, but he only *feels* it because the situs is usually just large enough to fit the reamer. Consequently, a realistic haptic feedback is an essential part of our simulator. This is highly non-trivial because the milling procedure requires high forces while it simultaneously has to be very sensitive. This is challenging for both the hardware and the software. We decided to use a KUKA LBR robotic arm for the force feedback because other commercially available devices cannot provide the required forces. However, the KUKA LBR was originally not built for haptic feedback. Hence, we have implemented novel control algorithms. Moreover, we have developed a novel haptic rendering algorithm that provides stable and continuous forces and torques during the milling process. The core is our new GPU-based collision detection scheme with support for material removal at haptic rates. In order to make the training as realistic as possible, we put the trainee into a realistic operation room environment via a head mounted display (HMD).

2 System Overview

Our system consists of three main components:

- The *haptic rendering* algorithm that computes collisions of the reamer with the hip and generates forces and torques, including an appropriate friction model. Moreover, it removes the milled parts of the bone.
- The *haptic control* mechanism controls the robot. It receives the forces and torques from the haptic rendering algorithm and

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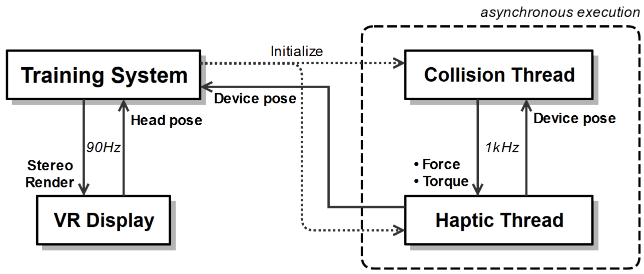

Figure 1: Our system architecture. We have implemented our training system in Unity3D which initalizes two C++ threads that operate asynchronously.

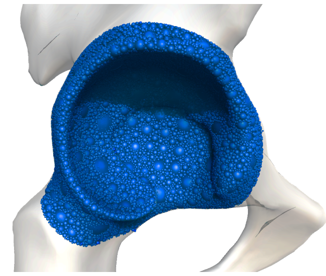

Figure 2: The acetabulum bone partially filled with polydisperse spheres.

transfers it into a stable configuration of the LBR.

- The *virtual environment* controls the rendering of the visualization of the virtual operation room to an HMD and synchronizes the tracking of the robotic arm and the HMD. Moreover, it provides information about the success of the milling process and gives hints to improve.

These components have different requirements for the update frequency: haptic rendering requires 1 KHz to provide stable force feedback [4] while for visual rendering 90 frames per second are sufficient. Hence, we decided to implement our system with an asynchronous multithreaded approach with three main threads. We have kept the interfaces and the amount of data very small to minimize the synchronization overhead. Fig. 1 provides an overview of our complete system architecture.

2.1 Virtual Environment

We have developed the virtual environment using Unity3D. The 3D environment replicates a detailed operation room including a model of the patient and the situs, an animated assistant surgeon that holds the tool to stretch the situs and surgery equipment like monitors to interactively display X-ray photographs and other necessary information. The model of the patient is anatomically correct with a special focus on the operation area and the bones. Furthermore, the training system gives audio and visual feedback about the success of the operation and it provides hints for the trainee.

The Unity3D system initializes the other two asynchronous threads, i.e. the haptic rendering and the haptic control system. During runtime, it renders the scene to the HMD and reads the tracking information from the tracking system provided from a HTC Vive. Moreover, it receives the coordinates of the reamer and displays it in the scene. We use a double buffer approach to exchange data between the threads. This guarantees thread-safe communication without costly synchronization.

2.2 Haptic Rendering

The special challenges for the haptic rendering in our scenario are the high and stable forces and torques while simultaneously a very sensitive feedback is required. Most existing haptic rendering algorithms are restricted to simple point probes, susceptible to noise, such as the Voxmap Pointshell algorithm, or they do not support material removal. Hence, we have developed a new haptic rendering algorithm. The main idea is to represent the bone's volume as a set of polydisperse spheres (see Fig. 2). The reamer tools cutting end has the shape of a perfect hemisphere.

The volumetric representation enables us to compute intersection volumes which we use to implement our simulation of the degradation of the bone material from reaming forces. Moreover, we use a continuous collision detection approach to compute constraint-based forces and torques. Our algorithm runs completely on the GPU and supports friction forces.

2.3 Haptic Control

Due to the safety regulations for industrial robots that operate in the same space as a human worker, remote access to these robots is highly restricted by the robot manufacturer. All embedded functionality of the robot is housed in a black box like dedicated industrial PC, which in KUKAs case has, next to the option to program local Java applications, a remote interface called Fast-Robot-Interface (FRI) that offers limited access to command an overlay over a movement currently executed by the local application. In combination with a placeholder movement, which only compensates the weight of the manipulator, this overlay function can be used to command force representation of a virtual object. Using the FRI enables the KUKA LBR to maintain all the required safety features while allowing limited remote control over the manipulator. Non-critical functionalities, like the handling of the 24V/2A - input/output channels of the robot, are handled with a separate UDP communication to support additional features that can be implemented in the respective handle.

3 Conclusions

We have presented the first VR training simulator for hip prosthesis implantation. The core of our systems is a novel haptic rendering algorithm with support to material removal in combination with a new stable haptic control mechanism for the KUKA LBR. Even if our training simulator is still under development, we already received very positive feedback from surgeons.

Acknowledgments

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