A Framework for Adaptive Training and Games in Virtual Reality Rehabilitation Environments

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Abstract

The training of severely disabled individuals on the use of electric power wheelchairs creates many challenges, particularly in the case of children. The adjustment of equipment and training on a per-patient basis in an environment with limited specialists and resources often leads to a reduced amount of training time per patient. Virtual reality rehabilitation has recently been proven an effective way to supplement patient rehabilitation, although some important challenges remain including high setup/equipment costs and time-consuming continual adjustments to the simulation as patients improve. We propose a design for a flexible, low-cost rehabilitation system that uses virtual reality training and games to engage patients in effective instruction on the use of powered wheelchairs. We also propose a novel framework based on Bayesian networks for self-adjusting adaptive training in virtual rehabilitation environments. Preliminary results from a user evaluation and feedback from our rehabilitation specialist collaborators support the effectiveness of our approach.

CR Categories: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality;

Keywords: virtual reality, rehabilitation, adaptive training, virtual games

Links: DL PDF VIDEO

1 Introduction

Typically, patients being trained on the use of the electric power wheelchairs must have their wheelchairs and training regimes highly customized to their specific needs and capabilities. This presents a problem because the number of rehabilitation specialists and power wheelchairs available on hand at any time is limited. As a result, patients are quite limited in terms of the amount of time they may receive training from a specialist.

However, virtual reality training offers potential solutions to many challenges associated with rehabilitation medicine and power wheelchair training. For example, previous research has shown that skills acquired in virtual reality wheelchair training can transfer effectively to real-world wheelchair use [Erren-Wolters et al. 2007] [Cooper et al. 2002] [Ma et al. 2007] and virtual reality has also been shown to improve training results through the use of virtual reality rehabilitation games [Jung et al. 2006] [King et al. 2010] [Xu et al. 2010] [Brederode et al. 2005] that engage and motivate patients to complete longer, more effective training sessions [Jack et al. 2001].

Given these benefits, a virtual reality power wheelchair training system was designed and implemented with collaboration and feedback from a group of rehabilitation specialists and clinicians with expertise in a wide range of rehabilitation medicine including power wheelchair training. Our virtual reality training system is unique in that it was designed to be low-overhead, portable, and focused on indoor training environments that are interactive in a reasonably realistic way. The system offers standard training modes and interactive virtual reality games for increased patient engagement. A particularly unique feature in comparison to similar approaches is that the system provides a framework to allow clinicians to design, build, and customize interactive indoor rehabilitation training environments that can dynamically respond to user actions in a meaningful way. The effectiveness of our approach was supported by the results of a preliminary user evaluation and feedback from our rehabilitation specialist collaborators.

However, an additional challenge faced by virtual reality rehabilitation systems is that as a patient's abilities change over time, the system must be continually adjusted to provide the appropriate level of challenge. To address this, we propose a novel, flexible, adaptive framework based on Bayesian networks to allow clinicians to probabilistically measure a rehabilitation patient's performance in several skill areas at once and intelligently adapt the virtual reality training appropriately.

2 Related Work

Several approaches to virtual wheelchair training have been made in recent years using a variety of proposed techniques. At one end of the scale, Niniss et al. [2005] proposed an immersive virtual wheelchair training system whereby an actual power wheelchair rests on a raised hydraulic platform that can tilt in response to the user's movements in the virtual environment which is displayed on a 110 degree panoramic screen. Despite its highly immersive features, one of the goals of virtual reality rehabilitation is to increase the amount of training time per patient in a realistic rehabilitation setting where resources are not unlimited, and a system such as the one implemented by Niniss et al. [2005] is not ideal given that its apparatus cost is higher than that of an actual power wheelchair and availability will still be limited to one patient at a time and customizing it on a per-patient basis remains time consuming.

At the other end of the scale, there are systems such as the one developed by Spaeth et al. [2008] which simply uses an ordinary projector and a power wheelchair fitted with a special head-brace to track the head position. The patient controls virtual racing cars which are shown on the projector as a 2D top-down visualization of a race track. Although systems such as these satisfy the goal of creating a low-cost automated supplement to real-world power

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wheelchair training, as the authors point out, the simplistic non-immersive game-like interaction is more focused on measurement of patient responses over time, and the skills learned are not readily applicable to use of powered wheelchairs in the real world [Spaeth et al. 2008].

Commercial desktop training simulators such as Wheelsim[1] offer reasonable immersion and are low-cost, but typically lack the possibility for specialists to adjust environments to patients' needs, and do not provide realistic interactions between objects in the simulation (for example, in Wheelsim, collisions simply result the virtual wheelchair stopping instantaneously). This is an issue given that previous research has shown that realistic physical interactions between objects in virtual reality rehabilitation simulations are important for ensuring that skills learned are more effectively transferred to the real world [Ma et al. 2007].

By automating the task of constantly adjusting patient exercies to provide the optimal challenge level, specialists can have additional time to work with more patients. Several previously implemented virtual reality rehabilitation systems use a single metric, for example, how long it took to complete a task or what the range of motion was, and then slightly increment the difficulty level accordingly [Jack et al. 2001]. Other systems make use of a game-based levelling system in their virtual rehabilitation training. As patients successfully complete levels, they automatically move on to more challenging levels [King et al. 2010]. While such systems are simple to implement and successfully provide some degree of automatic adaption, they are not able to measure nor address the enormous range of disabilities and residual capabilities that patients may have, and they do not make full use of the background knowledge and skills of the rehabilitation specialists. While previous work by Ma et. al. [2007] has proposed adaptive virtual reality games for rehabilitation that attempt to measure a much wider range of patient skills and adapt according to each patient's unique skill set, the skill estimation and adaption rules are hard-coded into the games, thereby not enabling rehabilitation specialists to apply their expertise and specialized domain knowledge to modify them as needed.

To address this challenge, we propose a novel, flexible framework for adaptive virtual reality rehabilitation training and games based on Bayesian networks. Although previous research has proposed Bayesian networks as a way to measure student performance in online web-based multimedia educational games [Cheng et al. 2009], to the best of our knowledge, this is the first attempt to adapt this concept to adaptive virtual reality rehabilitation.

3 System Design

3.1 Customizable Virtual Reality Environment

To handle different computer hardware configurations, the proposed virtual reality system was designed as a stand-alone open-source 3D application capable of running on any modern desktop or laptop using any standard operating system (Mac, Linux, or Windows). The system requires no specialized input hardware, but can instead use any input device with the appropriate drivers to convert the input into mouse movements or keystrokes. This allows the system to handle the myriad of input devices that patients may use to control their power wheelchairs including standard joysticks, button trays, pressure-sensitive headrests, etc. The Open-Source Graphics Rendering Engine (OGRE[2]) was selected as the 3D graphics engine due to its substantial feature set, open-source nature, and the successful use in previous rehabilitation systems [Ma et al. 2007].

To encourage the transfer of skills learned in the virtual reality environment to the real world, interactions between the virtual wheelchair and other objects in the simulation were realistically modelled using the Newton Game Dynamics[3] physics engine. Newton was chosen due to being open source and its integration with OGRE through the OGRENewt[4] API. Furthermore, previous research has concluded that game engines could play an important role in developing realistic, effective rehabilitation systems [Grant et al. 2004].

A key challenge posed by the rehabilitation collaborators involved in the project was the desire to allow clinicians to easily design and modify virtual environments for their patients so that they could practice manoeuvres such as navigating around the patient's house. In order to achieve this, an XML scene node based framework was designed and implemented as a 3D-modelling plug-in tool (see Figure 1). Using this tool, clinicians can change the layout of training rooms, adjust the position, scale, and rotation of objects, and even assign physical properties such as object mass. The resulting customized environments are stored in XML format which can also be modified directly as shown in Figure 1. To the best of our knowledge, this ability to provide clinicians with a flexible, extensible means by which to customize their virtual reality training environments is a feature not provided by any other virtual reality power wheelchair training environment.

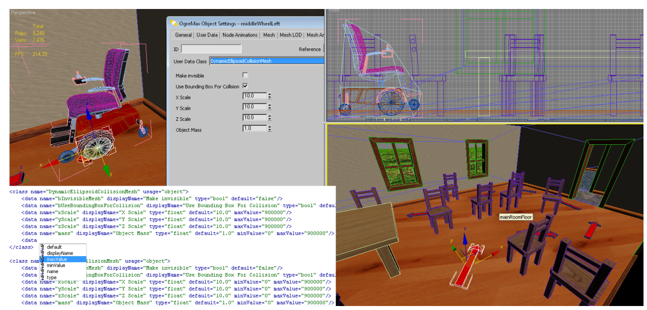

Figure 1: *Interface for customization of the virtual environment.*

The primary advantages of the design chosen are that the issues of cost and power wheelchair availability are both addressed. The computer hardware and software needed to run the system are low-cost and readily available, and can even be used for other purposes when not used for virtual reality training. In light of research demonstrating the ability of interactive games to encourage patient engagement and increase the length and effectiveness of rehabilitation sessions [Jung et al. 2006] [King et al. 2010] [Xu et al. 2010] [Brederode et al. 2005], the system is also capable of training through interactive games which are implemented in the same way as standard training environments, but with the addition of special goals. An example of one such simple rehabilitation game called Virtual Reality Wheelchair Soccer was implemented (see Figure 2) where the goal is to carefully navigate the wheelchair so as to push the ball past two goal posts in a certain amount of time.

3.2 Intelligent Adaption

The second challenge of the implemented framework was to have the system automatically assess a complex range of patient skills, many of which are not independent of each other, and then have the virtual rehabilitation system automatically and intelligently adapt the training simulation accordingly. The designed approach uses

[1]http://www.ottobock.com/

[2]http://www.ogre3d.org/

[3]http://newtondynamics.com/

[4]http://www.ogre3d.org/tikiwiki/OgreNewt

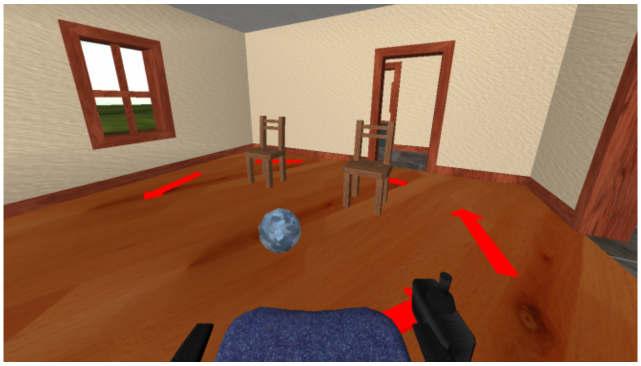

Figure 2: *A simple game of virtual reality soccer where the objective is to carefully maneuver the virtual wheelchair and use it to push the ball past the two goalposts.*

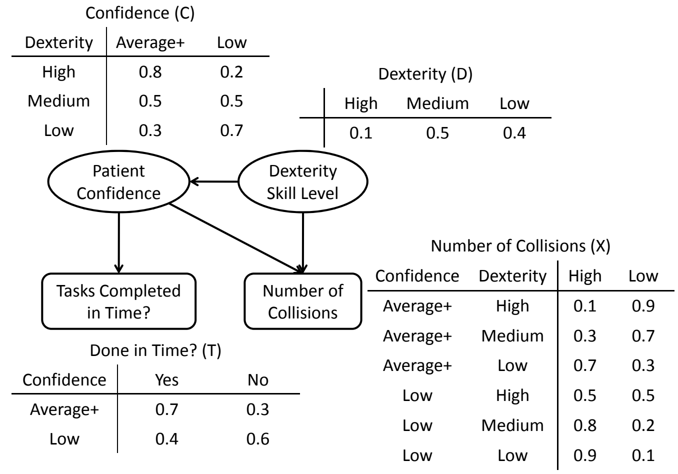

Figure 3: *A sample Bayesian network topology.*

Bayesian networks to attempt to determine patient skill levels in a variety of skill areas based on measurable results collected by completing rehabilitation tasks.

Consider the simple Bayesian network shown in Figure 3. In this example, the rehabilitation specialist is interested in determining the patient's dexterity level based on how long a patient takes to drive through a virtual reality obstacle course, and the number of collisions that occur along the way. Suppose that a patient's confidence level is also known to impact performance and that confidence is affected by the patient's dexterity level as well. The network layout in Figure 3 shows how a rehabilitation specialist might model this. As shown in the figure, the latent variable "Dexterity" increases the measured number of collisions when it is low, but low values for dexterity also increase the probability of a patient having low confidence. Although confidence is another latent variable that cannot be directly measured, we can see that it has an effect on both the length of time it takes for a patient to complete the exercise, and also the number of collisions that will occur along the way.

Once the network topology is defined, specialists can infer the value of the hidden latent variables such as Dexterity and Confidence based on the values of the measured variables. For example, in order to determine the probability that the patient has low dexterity given that they did not finish the exercise on time, and that the number of collisions was high, we could compute this as shown below.

$$\boldsymbol{P(D = Low|T = No, X = High) = \frac{P(D = Low, T = No, X = High)}{P(T = No, X = High)}}$$

$$\boldsymbol{= \frac{\sum_{C\in\{Average+,Low\}} P(C, D = Low, T = No, X = High)}{\sum_{C,D\in\{High,Medium,Low\}} P(C, D, T = No, X = High)} \approx 0.539}$$

Although the example shown uses a simple network with only two measured variables and two latent variables, this framework can be easily scaled to include a large number of latent and measured variables with complex interactions between them. Additional measured variables might include the optimality of the path a patient took through an environment, the ratio of collisions that occurred with objects out-of-sight compared to objects that were in plain view, or the number of collisions that occur while turning rather than simply driving straight, etc. Additional latent variables could include the ability of patients to judge distances, the patient's spatial awareness in regards to objects that are behind them, or the patient's spatial awareness on one side of their field of view compared to another in the case of brain injury, etc. Likewise, the values of the variables in the network need not have only two or three possible values. Clinicians can define as many values as necessary for nodes in the Bayesian network, and express continuous variables as meaningful discrete ranges with as much granularity as necessary. Based on the inferred values of the latent variables, clinicians define which virtual game or training environment should automatically be loaded next to offer the appropriate difficultly level and type of training needed to continue to improve the patient's skills.

4 System Evaluation

4.1 Method

In order to help determine the effectiveness of the implemented system, a small-scale user evaluation was performed. The objective of the experiment was to determine if the virtual reality training system implemented was effective in teaching test participants to navigate around obstacles in an indoor environment any faster than those that did not receive the virtual training. A group of 8 graduate students between the ages of 22 and 28, both male and female, who had never used a power wheelchair before were randomly split into two evenly-sized test groups: the control group and the exper-

Figure 4: *Real-world power wheelchair used in experimental setup.*

imental group. A simple indoor power wheelchair obstacle course was then set up using office chairs and tables that was designed to require approximately 90 seconds to complete without collisions.

Participants in both the control and experimental groups were tasked with completing the course as fast as possible using a "Jazzy 1122" mid-wheel drive type electric power wheelchair with a standard joystick as its control device as shown in Figure 4. Participants in the experimental group first completed a virtual obstacle course in the proposed virtual reality training environment prior to their real-world run, whereas individuals in the control group received no virtual training beforehand. The time taken by each test participant to complete the real-world obstacle course was then recorded.

4.2 Results and Discussion

Participants who used the proposed virtual reality wheelchair training system completed the real world obstacle course on average faster, with a mean time of 81.5 seconds for the experimental group compared to 104.5 seconds for the control group. While the results seem to suggest that the proposed system is effective in training individuals on the use of power wheelchairs, due to the high level of variance between individual completion times (i.e. a standard deviation of 26.51 for the response group, and 43.16 for the control) and the fact that the system was tested on non-disabled individuals, more research is needed before more conclusive results can be drawn.

The completed prototype system was also demonstrated to a group of rehabilitation specialists and clinicians present at the collaborating rehabilitation hospital. Feedback was positive to the point that plans are now currently in motion to begin integration of the proposed system into a part of the rehabilitation training practices used at the hospital.

5 Conclusions and Future Work

A low-overhead, high-availability virtual reality electric wheelchair simulator was designed and implemented with collaboration from rehabilitation specialists with expertise in power wheelchair training. Although the system is primarily designed for use in rehabilitation medicine, it can also be used in a wide variety of other spatial-based training applications such as adaptive driving or machinery operation simulators. A unique feature of the system is its ability to allow clinicians to design, build, and customize interactive indoor training environments that can dynamically respond to user actions in a meaningful way. The problem of an automatic intelligent adaption to the different types and levels of training that a patient may require at different times was addressed by a proposed novel Bayesian network-based adaptive rehabilitation training framework that uses measured variables from a completed training simulation in order to probabilistically determine unknown patient skill levels in a variety of key areas. Based on the demonstration of the completed system and user evaluation, we are preparing the system for incorporation into a real world rehabilitation hospital training program.

Future work will include larger user studies performed on patient groups in order to more precisely measure the efficacy the virtual reality system and its adaptive framework components to improve the system further. We also plan to enhance the virtual reality simulation with online capabilities in order to enable new remote rehabilitation training capabilities.

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