Dexmo: An Inexpensive and Lightweight Mechanical Exoskeleton for Motion Capture and Force Feedback in VR

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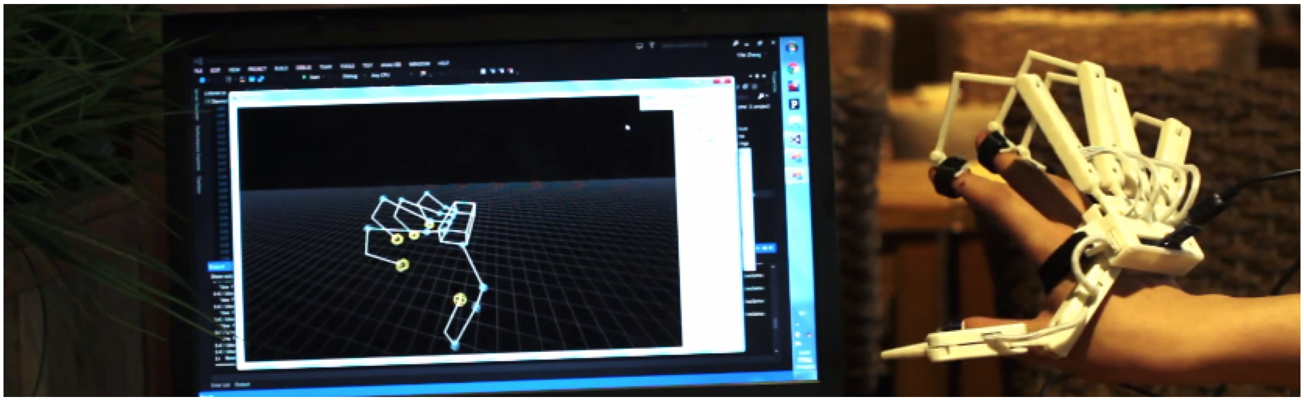

Figure 1. A person using Dexmo to control a virtual exoskeleton model in virtual reality.

ABSTRACT

We present Dexmo: an inexpensive and lightweight mechanical exoskeleton system for motion capturing and force feedback in virtual reality applications. Dexmo combines multiple types of sensors, actuation units and link rod structures to provide users with a pleasant virtual reality experience. The device tracks the user's motion and uniquely provides passive force feedback. In combination with a 3D graphics rendered environment, Dexmo provides the user with a realistic sensation of interaction when a user is for example grasping an object. An initial evaluation with 20 participants demonstrate that the device is working reliably and that the addition of force feedback resulted in a significant reduction in error rate. Informal comments by the participants were overwhelmingly positive.

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation (e.g. HCI): Input devices and strategies

Author Keywords

Virtual reality; force feedback; exoskeleton; motion capture

INTRODUCTION

There are many ways for people to bring their motion into the the virtual world, however, there is little feedback *back* to the real world. Current force feedback devices are bulky, non-portable, expensive and difficult to manufacture. There is still a lack of a light, easy-to-use and affordable force feedback approach for people to touch or sense in the digital world.

In this paper we present Dexmo, a mechanical exoskeleton that is a lightweight, inexpensive, compact, reliable and safe solution for providing force feedback and motion capture in augmented and virtual reality environments. Figure 1 illustrates a user wearing Dexmo and using it to interact with a virtual world. Rather than applying torque control at each individual joint of the exoskeleton directly, Dexmo uses a micro servo unit to shift stopping blocks linearly to stop the rotation of all joints, and forms a rigid body.

While achieving a similar sensation to the user as prior methods, our approach has three advantages. First, it can be made much smaller and more affordable. Since the joint does not need to actively provide a torque, there is no need for expensive motors, complex transmissions or sensor modules. Second, only a small shifting servo is needed, and all the bending moment provided by the users is directly exerted to the rigid body in the mechanism instead of the motor, making it more durable, and less torque is required from the servo thus cut the cost. Third, it is safer because the mechanism does not actively apply forces to the user. If the controlling unit malfunctions, no harm will be inflicted.

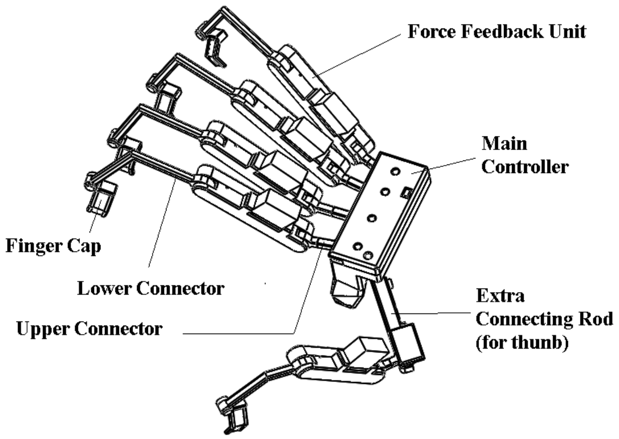

Figure 2. The mechanical design of the exoskeleton.

BACKGROUND

Early attempts to implement haptic interfaces for human hands include the PHANTOM [7], which measures users' hand position with a grounded robotic arm and exerts controlled point force vector on users' hand. PHANTOM achieved precise stiffness control by adjusting the torque of three DC brushed motors with encoders. This technology is essentially a transmission between the motors and the human hand. Therefore the workspace for the user and the mobility is highly limited. Moreover, this system fails to produce feedback for individual fingers, reducing the credibility of the haptic experience.

The Rutgers Master II ND [2] utilizes pneumatic actuators arranged in center of palm and achieves force feedback by directly driving the fingers. This device uses the non-contact Hall effect and IR sensors for motion capturing for durability reasons, yet this approach raises manufacture costs. Specifications of the RMII-ND haptic glove are comparable to those of the CyberGrasp [9], another well-known haptic glove system. CyberGrasp uses resistive bend sensors for motion capturing. This system uses a DC motor and cable-pulley transmissions on an exoskeleton to pull users' finger backward in order to simulate the exerted force ("active haptics"). Primarily intended for corporations, the army and medical rehabilitation, CyberGrasp system is not a consumer-grade product. While these two systems are capable of offering precise force control, they are large in size and expansive due to complexity of the design.

Other systems include 'Haptic Telexistence" [8], HIRO III [3], a Japanese system [5] and RML Glove [6]. While this latter system introduced a passive elastic element (springs) in their mechanical exoskeleton, it uses motors directly to apply torque on the joints. This setup makes it impossible to provide rigid force feedback.

Our system Dexmo, in contrast, uses active passive force feedback, which largely reduces the size by integrating all the drivers on one single device. This novel approach allow us to create a light-weight device with a low manufacturing cost.

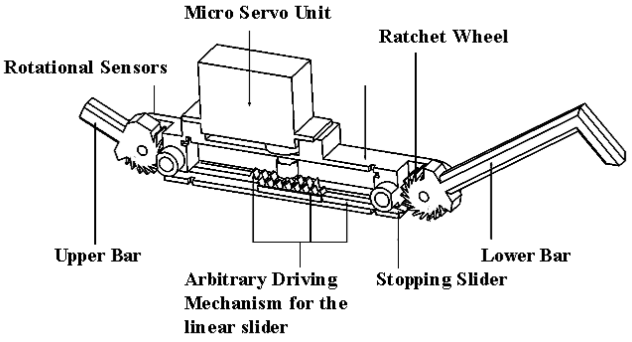

Figure 3. The mechanical design of the force feedback unit.

SYSTEM DESIGN

The Dexmo exoskeleton mainly consists of the following components: main controller, force feedback units, upper and lower connectors and finger caps (Figure 2). The finger caps are attached to users' individual fingers, and the main controller is attached to the back of the user's hand. Each force feedback unit has two degrees of freedom of rotation on the same plane, and they are mechanically jointed to the main controller and the finger caps via connector bars, forming a link-bar mechanism. A special extra piece of linkage is introduced for the thumb skeleton. The rotational axis of sensors at two ends are orthogonal so the exoskeleton does not block the users' thumb movement.

The design of the force feedback unit is shown in Figure 3. The force feedback unit is the core of the design of Dexmo, it consists both the sensory module as well as the actuation module. Two rotational sensors are installed to the case and they detects the relative rotation of both ends to the case. A micro servo unit drives two stopping sliders and locks the ratchet wheel firmly in place when the force feedback unit is activated. The transmission mechanism can be arbitrary. In this case we used a crown gear connected to the end of the servo, and two teeth bars lying in parallel with each other that points in opposite directions.

The accuracy for each joint is limited by the sampling rate of the analog-to-digital (ADC) converters. For our device, we used a 12 bit ADC, which means we can collect angular data at a 0.09 degree accuracy in theory. However since this is a wearable device there is not rigid connection and the actual accuracy is around 0.5 degrees. The response time for the force feedback unit greatly depends on the type of actuator implemented. The response time of the coreless motors in our design has a response time of around 50 ms.

The force feedback function of Dexmo works as follows: when the user moves their hands and fingers around, the data is sent back to the upper computer which is converted into 3D graphics in a virtual space. The virtual hand moves with the user in real time. When a collision is detected between the virtual hand and an virtual object, a command is sent back to the device which activates the force feedback units. Inside each force feedback unit, the actuators drive the stopping mechanism and locks the joint in place, which turns the mechanism into a rigid body. This reassembles our physical reality. Just as a person's physical hand touches a real object, the object prevents the finger from moving inwards. The rigid exoskeleton exerts an opposing force to the user's finger tips, and thus provides the user with force feedback.

Motion Capture

When the users move their fingers while wearing Dexmo, its link rod mechanism moves accordingly. The shape of the exoskeleton was designed in a way that fits the user's hand shape so it does not block users' hand movement regardless of whether they are clenching their fist or fully extend their hands. The rotational sensors reads three to four values for the thumb and one to two values for the rest of each finger. The data is collected by the controlling unit and sent to an upper computer where the kinematics regeneration algorithm is performed. The device use the data to draw out a forward kinematics chain for each finger, and calculate out the relevant position of each end point with respect to the origin.

The sensors on Dexmo do not have as many degrees of freedom (DOF) as a human hand. The device only tracks the Metacarpophalangeal joint on each finger directly using rotational sensors, while leaving the other two joints for interpolation. Therefore, to enable skeletal tracking, we assume that there exists a certain relationship between rotation angles at each finger joint when clenching a fist. More specifically, we assume the angles at the Distal Interphalangeal (DIP) joint and the Proximal Interphalangeal (PIP) joint will be $f(x)$ and $g(x)$ respectively, where x is the angle at the Metacarpophalangeal (MCP) joint.

To investigate the assumed linear relationship between $f(x)$ and $g(x)$, we developed a naïve computer vision-based tracking system using a web camera and color straps. These color straps were put on the MCP, PIP, DIP joints and fingertip of user's index finger and the camera is targeted at the side of finger. The system detected these color straps as blobs and then connected the centres of them. These connections were our estimation of the phalanges. Angles between these estimated phalanges were recorded as the user was asked to gently repeat the action of bending a finger inwards.

We used linear regression to fit the dataset 1000 samples in total from five participants with different hand sizes (200 samples per participant). We further assumed PIP and DIP joints on all other fingers have similar relationships as those of the index finger. As the visualization of this model showed a reasonable resemblance to the original hand motion, we proceeded with the simplified tracking model.

Dexmo started with 16 DOF, however, after further investigation we found that 11 DOF is also sufficient for providing enough data to perform the skeletal reconstruction. The positioning of this device can be easily achieved using existing technology: inertial measurement units on both arms, optical tracking, grounded robot arm, etc.

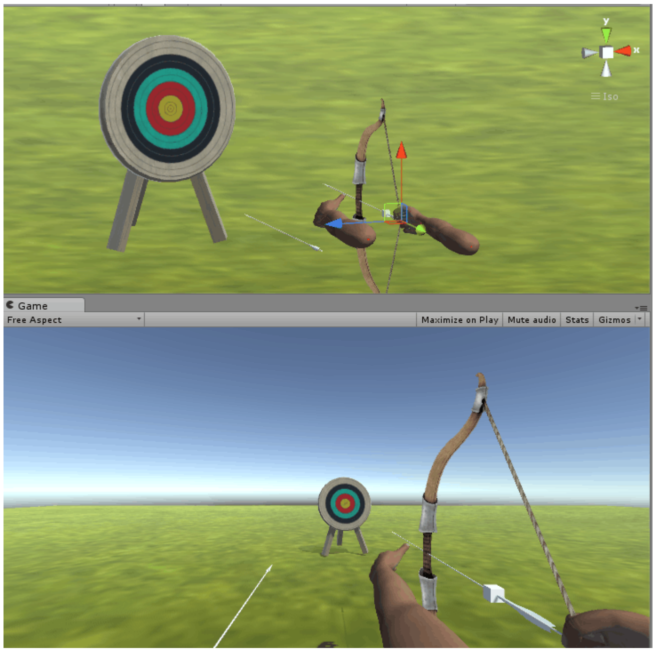

Figure 4. The game scenario used in the evaluation.

DESIGN TRADE-OFFS AND PARAMETERS

Since Dexmo does not require a tethered power supply it is mobile. Due to Dexmo's compact, light-weight characteristics and low power consumption, Dexmo can run for 4 hours with only a 800mAh battery. Other commercial haptics devices (Cybergrasp) that provide continuous force feedback require much more power than Dexmo.

A similar type of magnetorheological (MR) brake-based exoskeleton [1] uses 5 MR brakes for force feedback,in total it weights over 600 g, while Dexmo weights less than 270 g.

Dexmo is a lot much more inexpensive to manufacture due to its modular design and the avoidance of expensive motors, in contrast to prior solutions. A single motor from a high-end haptics device can cost more than the entire Bill of Materials price for Dexmo.

Finally, Dexmo is also less fragile and more safe compared to the string-pulley-motor type of exoskeletons, since its mechanism is enclosed in a case instead of exposed strings and pulleys, when dropped to the ground or being hit by other impacts, Dexmo stands a higher chance of not being damaged.

However, a disadvantage with Dexmo is that it only provides binary haptics feedback which can only provide feedback about whether something is present, the softness of the digital object will not be perceived.This might lower users' immersive experience. However, Dexmo's Force Feedback Unit (FFU) can be individually controlled, which still allows a user to feel the shape of an irregular shaped object.

Another disadvantage is that Dexmo uses a shifting mechanism which introduces delays to the system. During our testing we found that the delay for each FFU is between 20–40ms, which could affect the users' immersive experience. The continuous type haptics devices generally has a reaction delay lower than 30 ms.

EVALUATION

The efficacy of the system has been verified in informal lab trials. See also our supplemental video which demonstrates the tracking system in action.

The purpose of this evaluation was to validate that Dexmo can be worn and used by typical end-users in a typical playful VR task. As part of future work we will carry out more extensive controlled experiments.

Method

We convenience sampled 20 participants from diverse backgrounds (four art students, three athletes, three engineers, three cleaning ladies, three game developers and four factory workers). There were ten women and ten men recruited in total.

We developed a playful game scenario as games are a common application for VR environments. We built an archery game scenario using Unity[1] and combined it to our device with a head mounted display (see Figure 4 for an illustration).

The main purpose was to validate that the system would work well in a typical VR scenario and to gather users' intial perceptions of the system. In addition, we wanted to investigate if the introduction of the force feedback resulted in an improved performance (lower error rate). We therefore decided to test the null hypothesis H_0 that force feedback (FORCEFEEDBACK condition) does not result in a significant difference in error rate compared to a baseline condition that does not use force feedback (NOFORCEFEEDBACK condition). Our experiment was a within-subjects design with one independent variable with two levels: FORCEFEEDBACK and NOFORCEFEEDBACK).

Participants were asked to pick up an arrow from a basket, put it on a bow, pull the bowstring and then release the arrow to shoot at a target. The score was then recorded. Each participant was first asked to wear the Dexmo exoskeleton with force feedback enabled and then perform the archery task. After an hour of resting to avoid muscle memory, each participant was asked to wear the exoskeleton without the force feedback abilities, and then shoot ten arrows one more time. Their performances were recorded and analyzed afterwards. The conditions were not counterbalanced but this of little consequence in this instance for three reasons. First, participants had a one hour break between the conditions. Second, as the game was very simple, any learning effect is negligible. Third, the condition that could hypothetically benefit from a learning effect was the baseline condition NOFORCEFEEDBACK, which only means we are less likely to be able to reject the null hypothesis.

Results

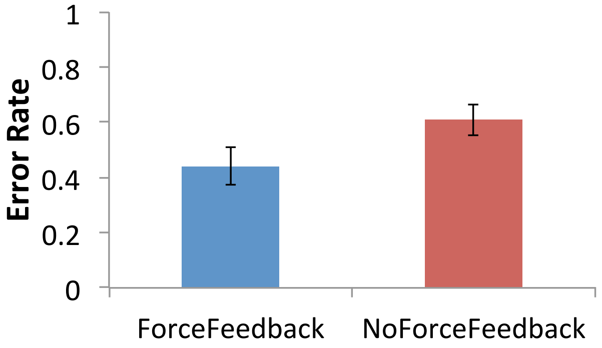

Figure 5. Mean error rate and 95% confidence interval as a function of condition in the formative evaluation.

The mean error rate was 61% (lower 95% confidence interval: 54.9%; upper 95% confidence interval: 67.1%) in the NOFORCEFEEDBACK and 44% (lower 95% confidence interval: 36.7%; upper 95% confidence interval: 51.3%) in the FORCEFEEDBACK condition (see also Figure 5). Repeated measures analysis of variance at significance level $\alpha = 0.05$ showed that this difference was statistically significant ($F_{1,19} = 45.380$, $\eta_p^2 = 0.705$, $p < 0.0001$). The low p-value in conjunction with the high effect size indicate that the detected difference is robust and substantial.

As expected, force feedback had a positive effect on performance. In addition, participants' responses were very positive with representative quotes such as "this is really cool", "it feels very real", "I never had this kind of experience before", "this is very light, it's not as uncomfortable as I expected" and "this looks very futuristic". However, we caution against over-interpretation as there is a likely a novelty effect.

DISCUSSION AND CONCLUSIONS

In this paper we have presented Dexmo: a mechanical exoskeleton system for motion capturing and force feedback. Compared to most the other force feedback devices, Dexmo only provides on/off force feedback, but the shifting mechanism that this design implements helps Dexmo avoid the usage of bulky motors and expensive sensory modules. Thus both the weight and the size of the design can be reduced which results in a light-weight, pleasant and low-cost mass-consumer device.

When the joint is locked, the clutch and lock slider forms a rigid body which makes this design infinitely more rigid than any motor simulated force feedback. This also better models the way users experience the physical world when interacting with rigid bodies. In addition, this design also results in a lower power consumption.

The functionality of Dexmo has been verified in lab measurements (see also the supplemental video). In addition, we have carried out an evaluation with 20 participants. Our results demonstrate that the device is working reliably and are similar to a previously study on the experience of "passive haptics" [4]. In addition, we found that force feedback did result in a significant reduction in error rate. Informal comments by the participants were overwhelmingly positive.

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[1] http://www.unity3d.com

REFERENCES

1. J. Blake and H.B. Gurocak. 2009. Haptic Glove With MR Brakes for Virtual Reality. *Mechatronics, IEEE/ASME Transactions on* 14, 5 (Oct 2009), 606–615. `DOI:` http://dx.doi.org/10.1109/TMECH.2008.2010934
2. M. Bouzit, G. Burdea, G. Popescu, and R. Boian. 2002. The Rutgers Master II-new design force-feedback glove. *Mechatronics, IEEE/ASME Transactions on* 7, 2 (Jun 2002), 256–263. `DOI:` http://dx.doi.org/10.1109/TMECH.2002.1011262
3. T. Endo, H. Kawasaki, T. Mouri, Y. Doi, T. Yoshida, Y. Ishigure, H. Shimomura, M. Matsumura, and K. Koketsu. 2009. Five-fingered haptic interface robot: HIRO III. In *EuroHaptics conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2009. Third Joint*. 458–463. `DOI:` http://dx.doi.org/10.1109/WHC.2009.4810812
4. Brent Edward Insko. 2001. *Passive Haptics Significantly Enhances Virtual Environments*. Ph.D. Dissertation. University of North Carolina at Chapel Hill. http://www.cs.unc.edu/techreports/01-017.pdf
5. T. Koyama, I. Yamano, K. Takemura, and T. Maeno. 2002. Multi-fingered exoskeleton haptic device using passive force feedback for dexterous teleoperation. In *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on*, Vol. 3. 2905–2910 vol.3. `DOI:`http://dx.doi.org/10.1109/IRDS.2002.1041713
6. Zhou Ma and P. Ben-Tzvi. 2015. RML Glove;An Exoskeleton Glove Mechanism With Haptics Feedback. *Mechatronics, IEEE/ASME Transactions on* 20, 2 (April 2015), 641–652. `DOI:` http://dx.doi.org/10.1109/TMECH.2014.2305842
7. T. H. MASSIE. 1994. The PHANToM Haptic Interface : A Device for Probing Virtual Objects. *Proceedings of the ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Chicago, IL, Nov., 1994* (1994). http://ci.nii.ac.jp/naid/10018008840/en/
8. Katsunari Sato, Kouta Minamizawa, Naoki Kawakami, and Susumu Tachi. 2007. Haptic Telexistence. In *ACM SIGGRAPH 2007 Emerging Technologies (SIGGRAPH '07)*. ACM, New York, NY, USA, Article 10. `DOI:` http://dx.doi.org/10.1145/1278280.1278291
9. Cyberglove Systems. 2015. Hand Motion Capturing and Force Feedback with Cybergrasp. (2015). http://www.cyberglovesystems.com/ [Online; accessed 25-September-2015].