Electromagnetism for Haptic Interaction with Virtual Objects

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***Abstract*— Haptic interaction with virtual objects can be enhanced by applying directional forces resembling those experienced when interacting with a physical object. Magnetism is a viable method to achieve these reactional forces. This experimental system combines an electromagnet with a wearable array of permanent magnets to generate forces which are paired with a visual display.**

I. INTRODUCTION

In order to create tactile sensations for virtual interaction, there are a handful of methodologies which can be applied. Direct force, pressurization, and vibration can all accomplish a sensation of tactile contact, though improvements are still necessary to either increase the realism of the experience or make the system more practical for use. Another approach, which this device takes, is using magnetic fields to generate forces.

The repulsion of two like charges results in a force applied to surrounding particles. Permanent magnets will exhibit such an affect when two magnets are held so that the same poles face each other. At the macroscopic level, if a magnet is held in one hand while bringing one pole near the pole of another permanent magnet, a force will be exerted on grasping fingers. Instead of grasping, permanent magnets could be attached to a wearable glove. Then, performing the task would create equal-and-opposite forces. The direction of these forces would closely resemble the forces experienced through most exploratory procedures. The methodology is hence presumed to have a significant potential for realistic virtual simulation.

One advantage of using magnetic force is that the sensations can be in free space since the fields can reach away from the magnet itself. Meshing magnetic fields could allow various surfaces to be simulated with varying geometries. However, to control the forces when these surfaces are being explored and to create changing surfaces, the use of opposing permanent magnets could be ineffective. Alternatively, the use of electromagnets could provide a dynamic and an adaptable experience. This is accomplished, in this device, by varying the output of an electromagnet to adjust the repulsive force. Magnitudes could be assigned to particular locations and the intensity varied depending on the contour of the surface being simulated. Modulation of the magnetic field output could aid in simulating harder surfaces. Theoretically, many 3-dimensional shapes could be simulated depending on the apparatus.

An eventual goal of this technology would be to have wearable electromagnets in a glove so that enclosure of a virtual object could be possible. The strength versus size comparison of available electromagnets is the key limitation. As a proof-of-concept, the device described in this paper constrains user motion and narrows the scope of possible virtual objects to be simulated while still demonstrating its feasibility. It works to test the efficacy of electromagnets and permanent magnets to provide realistic forces. In the experimental scenario, the device is capable of simulating the feeling of a ball being dropped in the palm of the hand.

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II. RELATED WORK

A. Force Feedback

One method of applying forces to the fingers and hands is through direct actuator contact. The FEELEX uses a plane of actuated pins to generate contours [1]. While the generated forces can be comparable to real-world haptic experiences, the system lacks portability and the ability to simulate portions of some 3-dimensional objects (i.e. spheres, inverted pyramids, etc.). The CyberGrasp, made by CyberGlove Systems LLC, produces grasp forces by a network of tendons connected to the fingers via an exoskeleton [2]. The wearable device allows interaction with, and handling of, virtual objects while also providing force feedback to the user. Even though the forces may be delivered to the flexor side of the finger, the device pulls the fingers from the extensor side. If this type of system is not entirely refined, this style of device could restrict active touch. The ability to sense and predict movement is an involved challenge. The standalone haptic glove with opposing electromagnets, which was proposed in the introduction, would face a similar challenge. However, the focus of this preliminary design involves a pre-existing virtual object which can be actively explored.

B. Near Surface Haptics

The other aim of the design in this paper it to allow interaction with virtual objects in free-space. The CyberGrasp accomplishes this since in consists of a wearable device attached to the hands. One other method is through focused ultrasound. The UltraHaptics system requires no contact with tools or physical surfaces and hands are unadorned [3]. The system induces a shear wave in the skin tissue to trigger the mechanoreceptors and generate a haptic sensation. An intrinsic benefit is obtaining force feedback in mid-air. In order to simulate an object or 3-dimensional surface, this type of system would require substantial tracking capabilities in order to ensure proper force intensities. It also requires appropriate interaction distances from the system (i.e. there are some limitations concerning mobility).

C. Magnetic Levitation

Previous works typically involve a tangible object, for a user to interact with directly, that is levitated by magnetic fields. Carnegie Mellon University/ Butterfly Haptics LLC, the University of Hawaii-Manoa, and the IBM Thomas J. Watson Research Center have all developed magnetic levitation devices that involve joystick-like interfaces [4]. These devices gain the advantage of have a single moving component for precise and responsive, 6 degrees-of-freedom near frictionless motion with force and torque feedback (Berkelman & Dzadovsky, 2010). They are dissimilar from the proposed device in that the stimuli on the fingers are still produced by a physical object.

Other systems, such as the FingerFlux, use arrays of electromagnets along with permanent magnets at the fingertips to produce attraction, repulsion, vibration, and directional haptic feedback [5]. While the principles are similar to the proposed design, the objectives differ. The FingerFlux aims to assist with guidance for virtual controls, with a focus on 2-dimensional planes. Alternatively, the proposed device aims to create 3-dimensional virtual surfaces. Possibly one of the more relevant devices is a magnetic field based near surface haptic and pointing interface from the National University of Singapore [6]. It functions primarily as a computer mouse and is capable of attraction, repulsion, and vibration. The system includes an electromagnet array with Hall Effect sensors for tracking the position of fingers. The proposed device is not exploring position tracking for the proof-of-concept device, though it could benefit from such techniques.

III. SYSTEM COMPONENTS

A. Visual

An animation of a ball dropping into the palm of a hand was created using trueSpace (Caligari Corporation, version 6.6). The hand was obtained from the object library and the ball was modeled with the settings shown in Figure 1. The hand was set at arbitrary coordinates, though since the position of the ball is dependent on the object info of the hand, these coordinates are presented in Figure 2. The starting position of the ball is shown in Figure 3a, and the ending position in Figure 3b. Gravity was enabled for the simulation so that the physics of the ball drop would be incorporated automatically by the software. The ideal animation was not obtained for the proof-of-concept system,

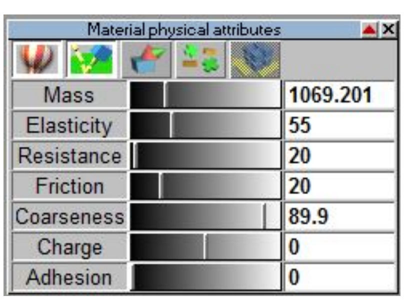


Fig. 1: Physical attributes of the animated ball.

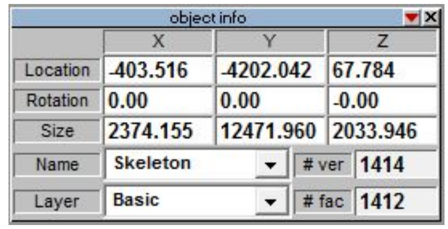
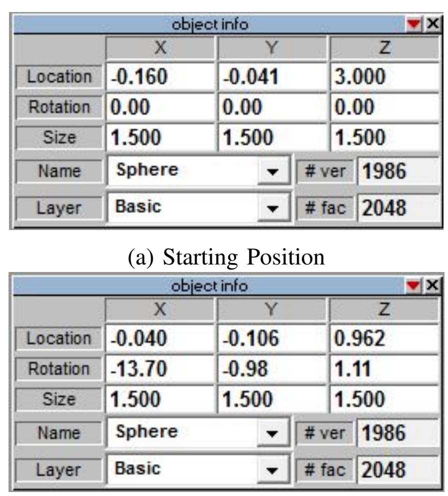


Fig. 2: Coordinates of the virtual hand throughout the duration of the animation.

but the visual created was still sufficient for pairing with the haptic feedback. The animation rendered in trueSpace and then was imported into Sony Vegas where the timed length of the ball being stationary in the hand was adjusted. Also the clip was copied, reversed, and sped up, then added after the original clip for the ball to appear to be lifted up quickly at the end of the video. This produced a visual for when the haptic feedback is disabled. An appropriate background was also added which worked to blend into the potential surrounding test environment. Finally, a short audio clip was placed as further described in the hardware section. This video was played on a laptop during each simulation. Figure 4 shows a screen shot of the video.

The test apparatus also included a light-weight cylinder on top of the platform that the user places a hand under, further described in Experimental Setup. This cylinder was there for a psychological aspect of the experimental setup. It provides a location where a ball could be falling. If there were open space in view of the user, then the haptic effect may be considered unrealistic due to lack of visual comparison. An alternative could be to have users close their eyes. However, since an application for this system would be with virtual reality, testing with a visual component was deemed more appropriate.



(a) Starting Position

(b) Ending Position

Fig. 3: Coordinates of the ball at the beginning (a) and end (b) of the animation.

Fig. 4: Frame from the video played during the haptic simulation.

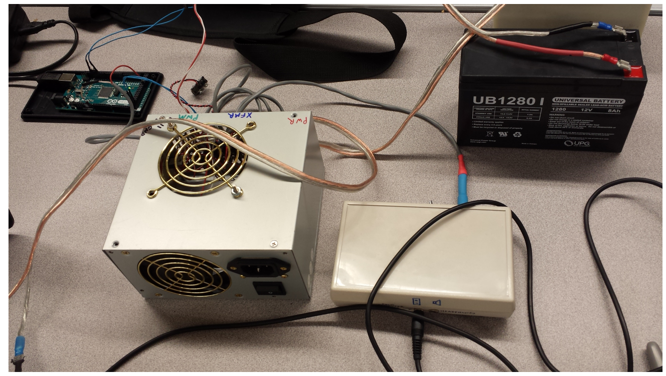


Fig. 6: Full hardware setup including Arduino MEGA 2650, power control subsystem, DTMF decoder subsystem, and 12V battery.

B. Hardware

An Arduino MEGA 2650 was used to store a program and indirectly control an electromagnet. The electromagnet was a modified microwave transformer. For the purposes of this system, it was desired to operate at 12V, 3A minimum. A substantial force was observed in preliminary testing with approximately one inch between a small, permanent magnet and the electromagnet at these conditions.

In order to power the electromagnet to the desired magnitude, the microcontroller output current needed to be amplified from 12.5mA to 5A. This was accomplished using a Darlington Pair configuration of 2N3055 transistors (with current gains of 20 minimum), as show in Figure 5, where the current is first amplified from 12.5mA to 250mA and then to 5A. The load carrying transistor (2nd stage of the Darlington) is protected by a diode. This system could be replaced with a MOSFET (with TTL), or other appropriate controller, if it is able handle an inductive load and have a power supply rating of at least 5A at 12V. Figure 5 shows a schematic of the power control.

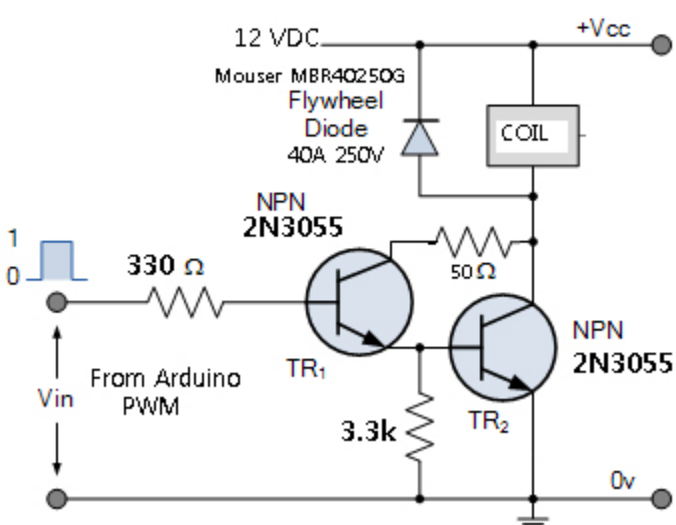


Fig. 5: Schematic for the system power control.

In order to synchronize the video with the haptic feedback, another subsystem was used. It involves a dual-tone multi-frequency (DTMF) decoder paired with a relay so that an output is activated when a certain tone combination is provided as an input to this subsystem. The output in this case, is to the microcontroller. Then, the tone was placed a frame before the ball touches the hand in the animation video. Therefore, connecting to the headphone jack of the computer to this subsystem allows activation of the Arduino MEGA (and triggers the code) when the tone is issued. Figure 6 shows each hardware component along with the 12V power supply.

C. Code

The time that the simulated ball was to contact the hand was found using a mathematical model for a ball bounce [7]. This model incorporates the coefficient of restitution for the ball. It was hence, an appropriate input which could be varied to create the desired haptic effect. Since the human hand also has a certain magnitude of elasticity, the value assigned was not necessarily based on a ball of a particular material, but rather was adjusted until the desired haptic effect and decay of bounce were obtained. The mathematical model provided an expression for the duration of the bounce cycle at any instance. The equation incorporated in initial velocity. Since the intention for this test of this system was to begin with a ball falling from rest, the equation was adapted to be a function of starting height instead of initial velocity:

$$t_b = r^{i/2}\sqrt{8 * h/g} \tag{1}$$

where t_b is the time (in seconds) at each iteration "i", r is the coefficient of restitution for the ball, h is the height from which the ball is dropped, and g is the acceleration of freefall.

This quantity of time was used in the program to define the time between bounces, rather than the time of contact for each bounce. In this way, the simulated contact time would remain the same for each bounce and would feel more realistic. Therefore, the duration that the electromagnet was powered remained constant, at 100ms, and only the time between powering would shorten.

An exit condition exists from the source of the mathematical model. However, using a constant value proved more reasonable for experimental adjustments. Therefore, the time at 100 bounces was calculated and set as the limit for the minimum time originally (this was later reduced, with the final value presented in the Results). This way, the maximum desirable bounce frequency could be set to generate a more natural feeling effect for a ball bouncing in the palm of the hand. This limit was adjusted during testing as well. Once the limit was reached, a constant output was enabled for the electromagnet (i.e. the ball resting in the palm of the hand). It would turn off after 2 seconds and the virtual ball would lift as was described in the Visual section.

The intensity of the magnetic field was set in the Arduino IDE using analogWrite() from 0 to 255. Proposed settings are provided in the results.

IV. EXPERIMENTAL SETUP

A small pad containing 3 small, permanent neodymium magnets was to be secured to a users hand with Velcro strips in the configuration shown in Figure 7. The pad was intended to be secure with hand movement but not tight enough to be uncomfortable or apply significant pressure to the hand before the experiment. The users hand was to be placed underneath a platform with the palm up and back of the hand resting on a table, as shown in Figure 8. Users were told to align the center of the pad with the center of the cylinder on top of the platform. This provided a better chance at aligning the permanent magnets with the center of the electromagnet so that forces experienced by the user would be direct on the surface of the palm. Also, the magnets would be less likely to experience a significant torque.

The user was permitted to stand or sit, whichever was more comfortable and permitted proper alignment of the hand. When the user was ready, the video would be played and the electromagnet triggered for the user to experience the magnetic haptic feedback. The video and the cylinder were visible during the experiment and hardware remained behind them for limited distraction. It is noted that the tone in the video was not audible since the laptop speakers were not enabled so only the headphone jack received the signal.

Users were permitted to experience multiple times as desired. They were also encouraged, on the second trial, to move the palm of the hand closer to the top of the box (the underside of the platform) to experience the haptic feedback at a greater intensity. Various settings for the magnitude of the magnetic field were tested between users.

Qualitative feedback was collected from voluntary response of the users. The goal of the experiment was to observe the realism of the ball drop with haptic feedback and test if the use of magnetic repulsion was appropriate for this virtual experience.

V. RESULTS

Qualitative feedback provided that the experience was subjectively impressive and that the majority of the users

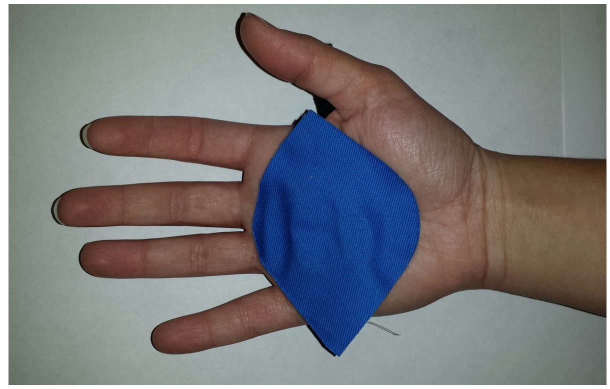


Fig. 7: Wearable pad with three permanent magnets.

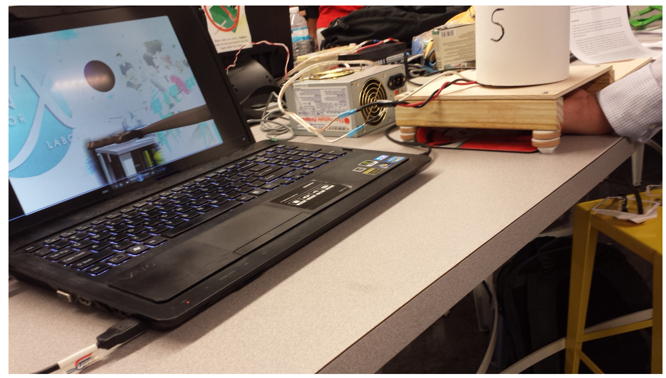


Fig. 8: User position during experimental testing.

received the desired effect of a ball dropping into the hand. However, some users had difficulty aligning the pad to the center of the tube so multiple attempts were needed for position refinement in order to gain the appropriate experience.

A user with experience with haptic devices noted that high frequency vibration was felt after the virtual ball was intended to be stationary. This is likely attributed to the pulse width modulation frequency of the current going through the electromagnet (driven by the microcontroller output).

Various settings for the intensity of the magnetic field were tested. Recommended settings are provided in Table 1. Bouncing is for the intensity from the first contact of the ball until it settles and Stationary refers to when the ball is resting in the hand. The Normal condition is when an adequate simulation was obtained. Half of the users experienced this condition and the other half experienced the intense condition, where the hand would typically be pushed away by the magnetic field forces if not already in contact with the table. It should be noted that for the Normal condition, the current supplied to the electromagnet remained under 3A, while the Intense condition was upwards of 5A.

CONDITION	BOUNCING	STATIONARY
Normal	80	90
Intense	200	210

In addition, an appropriate coefficient of restitution for the ball is 0.1 when dropped from a height of 0.5 meters. Also, an appropriate limit to the time that should be reached, by Equation 1, before the ball rests is 0.0008 seconds.

VI. FUTURE WORK

Different experiments are possible with the same test apparatus. This system could be used to simulate a ping-pong ball dropping on a paddle or similar ball sport. A glove could replace the pad, or the method of connecting the permanent magnets to the pad could be made more flexible, in order to permit haptic exploration of a stationary ball.

Another concept desired to be tested is using an array of electromagnets set at various intensities so that virtual 3-dimensional surfaces can be simulated.

As stated in the introduction, an eventual goal of this technology would be to have wearable electromagnets in a glove so that enclosure of a virtual object could be possible. This way, the experience can truely be in free space and not under the constraints of a box.

VII. CONCLUSION

This proof-of-concept system demonstrated that magnetic fields are appropriate for generating forces for a simplified haptic simulation. In the scenario of a ball drop, the stationary apparatus, where the user had only limited restriction of the hand, the haptic simulation seemed to be accepted by the users. The system can be expanded to incorporate other simulations and can also be improved for a more mobile experience.

APPENDIX

```
// Arduino Code for Ball Drop

void setup()
{
// initialize digital pin as an output
// enable on board LED
//(to be a visual indicator of
electromagnet functioning)
pinMode(13,OUTPUT);

//setup pin for input
//(reading tone generator relay)
pinMode(31,INPUT_PULLUP);
}

// signal to electromagnet in pin 11
// 31 to 53 (enable limit switch control)
// 3A @ 100 and 5A at 200


// initialize count
double i = 0;
//set restitution factor for ball material
//(in combination with hand)
double r = 0.1;
// set initial height of ball drop (m)
double h = 0.5;
// acceleration of freefall on planet
double g = 9.81;
// time the ball is not in contact
for each bounce
double tb;

// For triggering program (and latching)
int k = 0;
int pinval;



void loop()
{
  pinval = digitalRead(31);
  if(pinval==0 || k==1)
  {
    k = 1;
      i = i + 1.0;
      tb = pow(r,i/2)*sqrt(8*h/g);
        if(tb >0.0008){
          // Set intensity for the
          magnetic field
          // pin, magnitude(0 - 255)
          analogWrite(11,200);
          delay(100);
          digitalWrite(13,HIGH);
          analogWrite(11,0);
          delay((int)(1000*tb));
          digitalWrite(13,LOW);
        }
        else{
          analogWrite(11,210);
          digitalWrite(13,HIGH);
          delay(2000);
          analogWrite(11,0);
          digitalWrite(13,LOW);
          k = 0;
          i = 0;
        }
  }
}
```

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