The Haptic Laser: Multi-Sensation Tactile Feedback for At-a-Distance Physical Space Perception and Interaction

Francis Iannacci[1], Erik Turnquist[1], Daniel Avrahami[2], and Shwetak N. Patel[1]

[1]Computer Science & Engineering
DUB Group, University of Washington
Seattle, WA 98195 USA
{iannacci, erikturn, shwetak}@cs.washington.edu

[2]Intel Labs Seattle
1100 NE 45th Street
Seattle, WA 98105
daniel.avrahami@intel.com

ABSTRACT

We present the Haptic Laser, a system for providing a range of tactile sensations to represent a physical environment at-a-distance. The Haptic Laser is a handheld device that simulates interaction with physical surfaces as a user targets objects of interest (e.g., a light switch, TV, etc). Using simple computer vision techniques for scene analysis and laser range finding for calculating distance, the Haptic Laser extracts information about the physical environment and conveys it haptically through a collection of hardware actuators. Pointing the Haptic Laser around a room, for example, presents the user with information about the presence of objects, transitions, and edges through touch rather than, or in addition to, vision. The Haptic Laser extends current work on haptic touch screens and pens, and is designed to allow for haptic feedback from a distance using multiple feedback channels.

Author Keywords

Haptic feedback, ubiquitous computing, computer vision, motor control, at-a-distance interaction.

ACM Classification Keywords

H5.2 [Information interfaces and presentation]: User Interfaces. - Graphical user interfaces.

General Terms

Design

INTRODUCTION

As computing continues to move off the desktop and into the physical world, there will be an increasing need to interact with various computational systems and physical widgets at a distance. The most common scenarios for at-a-distance interaction currently include video gaming (e.g., the Nintendo Wii), and presentations where both speaker and audience want to interact with out-of-reach displays. In the future, computational abilities promise to be embedded in a wide range of objects, creating intelligent environments full of remote interaction targets.

In this paper, we present Haptic Laser, a handheld device that uses a laser pointer and a camera to extract features from the physical environment and two vibration motors, a solenoid and a servo motor to convey those features haptically. In particular, the Haptic Laser encodes the targeted region's *macro-texture* (which we define as a measure of the density of differentiable objects in the target region), the *physical distance* to the current target, and the sensations of *moving across a bump or an edge*.

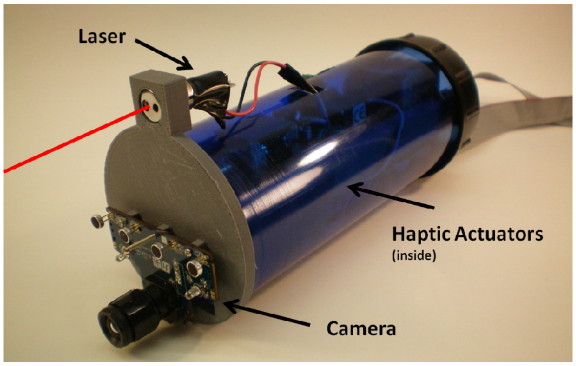

Figure 2: The Haptic Laser handheld device

Unlike the Wii, which uses an infrared tracking system to detect the position of the Wii-mote relative to IR markers placed in the environment, the Haptic Laser contains both the environment analysis and the haptic feedback systems in one device. It is thus able to provide tactile feedback about uninstrumented physical environments. Rather than just presenting distance information as in existing work [2, 13], our system conveys both distance-to-target and contextual information of the targeted space.

The Haptic Laser is thus designed to enable a set of new applications in both virtual and physical domains. For interacting with *virtual* environments, the Haptic Laser can be used as a sort of self-contained Wii-mote to assist the user in pointing to objects on a large screen display. Traditional laser-pointing interaction has been shown to be significantly slower and less accurate than direct physical contact or mouse-based selection [7]. Allowing users to feel ridges, edges, and other displayed visual artifacts as they sweep the Haptic Laser across the screen is designed to improve remote targeting accuracy. For interacting with *physical* environments, the Haptic Laser can be used to experience and explore arbitrary physical spaces. This is designed to be useful for finding and interacting with devices in an intelligent environment (i.e., the haptics allow

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the user to feel and discriminate between physical objects from a distance) or as an assistive technology to help a low-vision, blind, or deaf-blind user understand the physical composition of a room. Like existing space perception devices, the Haptic Laser conveys the distance from the user to a targeted surface. Unlike prior work, however, Haptic Laser provides feedback about which regions might contain objects for further exploration and interaction.

RELATED WORK

Systems that provide tactile feedback for at-a-distance interaction have been the subject of much research, including the assistive technology community's work on digital walking aids for the visually impaired. These technologies have largely focused on conveying distance information, obtained through range-finding sensors, through either auditory feedback (e.g., MiniGuide [6]) or single actuator tactile feedback (e.g., TactileWand [2], Teletact [13], Haptic Torch [14], and [15]). However, these way-finding technologies are less useful for exploring a physical space because they allow only single point probing of distance, and do not convey contextual information about the space or transitions in the environment. In contrast, our technique simultaneously presents distance and a summary of the targeted region, thus communicating context without requiring point-by-point sweeping.

The work most closely related to the Haptic Laser is Fingersight [12]. While both Haptic Laser and Fingersight are camera-based and use computer vision techniques for scene analysis, the Fingersight device is limited to a single channel of information presented via vibration feedback. By using several distinct types of tactile feedback, Haptic Laser removes this limitation, enabling multiple independent channels of information to be presented simultaneously from a single device.

Significant work in at-a-distance interaction has focused on selection and control of devices in an environment (e.g., [8, 11]). Projects in this space have used lasers to help users target and interact with individual computing devices in the environment [8, 9]. Other work has investigated the ways to hold a laser-based targeting device to improve accuracy [7]. However, exploring real-time haptic feedback has been limited for these applications.

Finally, other related systems provide haptic feedback for direct physical interactions with touch screens [10], stylus-based interaction [5], and more recently for interactions with virtual objects (e.g., the Wii). While most of this work has been limited to conveying information about the virtual environment, our primary contribution is in providing haptic feedback about the physical world from a distance.

THE HAPTIC LASER EXPERIENCE

The Haptic Laser usage experience is partly built on the metaphor of a telescoping stick. Our intent is not to convey small details of the physical environment (e.g., surface texture), but rather to provide general contextual information that is useful for at-a-distance pointing tasks. Important features include the ability to feel (1) the macro-texture of the targeted region (by modulating two vibration motors), (2) a relative measure of distance to the space the user is exploring (by changing the Haptic Laser's center of mass, similar to [3]), and (3) edges or sharp transitions (by activating the solenoid).

The Haptic Laser conveys macro-texture as a sensation similar of dragging a rod across a surface. Surfaces that have a non-uniform appearance (i.e., coarse macrotexture), such as a home entertainment system, result in more intense vibration feedback than uniform surfaces such as walls or whiteboards. To convey distance, the Haptic Laser's center of mass shifts as the user explores targets at different distances. Moving from a surface that is nearby to one that is across the room results in a center-of-mass shift away from the user, a sensation modeled on a stick extending to maintain contact with a physical surface. In the case of large, abrupt changes in distance, such as the transition between a table and the floor, the device produces a recoil-like sensation. This feedback is similar to the feeling of a stick rapidly extending or retracting.

IMPLEMENTATION DETAILS

The Haptic Laser prototype consists of two main components: the computer vision and the haptic systems. To generate the experience described above in a reasonable form factor, the Haptic Laser consists of a front-mounted camera, a laser diode, 3 small motors, and a single solenoid. The power and the processing for our prototype reside on an external portable computer that is linked to the Haptic Laser through a cable. In the future, we plan to integrate both computing and power into the Haptic Laser device itself, to make it an entirely self-contained device.

Computer Vision System

The Haptic Laser is outfitted with a front-mounted camera for sensing the physical space. We selected the Sony PlayStation Eye Camera because of its fast frame rate (60 frames per second at 640x480 resolution) and relatively low cost. Once an image is captured, the computer vision system performs two primary functions: distance and macro-texture evaluation.

Distance. The approximate distance from the device to an object's surface is calculated using a red laser pointer mounted parallel to the camera. The forward-mounted laser pointer creates a high-intensity dot in the field of view of the camera, which can be tracked in software. Once the laser point is segmented from the image, the vertical sub-pixels from the image origin to the laser point, N_y, is used to calculate physical distance, D, according to:

$$D = \frac{h}{\tan(N_y \theta_r)}$$

where h is the physical distance from the laser pointer to the camera lens and θ_r is the radians per pixel constant specified for the camera. The result across all the frames are low pass filtered to eliminate spurious distance changes.

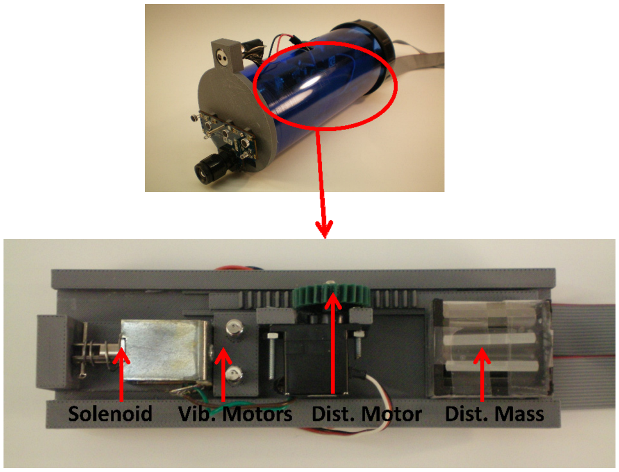

Figure 3: The internal haptic actuator components

Macro-texture. A goal of our computer vision system is differentiating potential objects of interest from their backgrounds. We have observed that many foreground objects, unlike their backgrounds, have numerous small, sharply contrasting regions (such as a laptop on a table). We define image regions with many different contrasting components as having a rough macro-texture, and we use this to identify the presence of foreground objects. The Haptic Laser determines macro-texture based on the number of connected components in an image segment. The algorithm is modified from a well-known texture detection algorithm [1] with performance improvements.

The imaging from the camera is de-noised using a Gaussian blurring and then divided into 20x20 pixel blocks. For each block, two-level adaptive histogram segmentation is used to separate the foreground from background. The group with the largest number of pixels is designated as "background."

For each block, the number of connected components of the background is calculated. If the connected component count is greater than an empirically determined threshold, then the block is considered to have a rough macro-texture. We limit the macro-texture detection search space to a small region centered on the laser point to reduce computational latency. The image search space size changes with the distance from camera to surface so that the physical search space remains a constant size.

Haptic Feedback

The feedback portion of the device is able to convey a rich set of haptic sensations to the user using three main components: two vibration motors, a solenoid, and a servo-controlled mass adjustment system (Figure 2).

Vibration Motors. The Haptic Laser uses two pager motors (maximum speed of 16,000 RPM) mounted laterally inside of the handheld device to provide macro-texture feedback. Motor speed is controlled by an 8-bit pulse width modulated signal, which is sent from a microcontroller to the base of a bipolar junction transistor (TIP31C) connected in series with each motor.

To allow perception of fine differences in vibration intensity, the Haptic Laser operates the motors at slightly different frequencies to create acoustic beats, perceived by the user tactilely as regular pulses. These beats result from the interference between the motors' vibration waves, and have a perceived frequency equal to that of the frequency difference between the motors [4]. To create this small frequency difference, we affixed an additional metal mass to each motor's rotating head. The masses for the two motors differ by 20 mg, resulting in one motor operating more slowly than the other with the same input signal. We found this produces regular beats for a given input signal, and the frequency of the beats increases as the input signal increases. Initially we attempted to maintain the frequency difference using a PID controller, but the quality of feedback suffered from slow settling times and noise.

Solenoid. A single 12V pull-type solenoid mounted with 1/8" stroke generates a recoil-like force linearly along the axis of the handheld device to inform the user of an abrupt change in distance (an edge). The solenoid is connected in series with an NPN bipolar junction transistor, and, when actuated with a single 10 ms pulse from the microcontroller to the transistor's base, the solenoid's plunger impacts the rear plastic wall of the device, maximizing the linear force returned to the user (see Figure 2). When not actuated, the solenoid is mechanically reset using a spring connected to the plunger.

Servo Mass Adjustment System. The mass adjustment system changes the handheld device's center of mass to indicate the distance between handheld device and the targeted surface. The sensation felt by the user is similar to that of telescoping stick, where the center of mass moves away from the user as the stick extends. This feedback is generated by a metal mass on a linear track running axially along the motor chassis. A small servo motor adjusts the position of the mass through a rack and pinion gear system.

Motor Control Hardware. The Haptic Laser uses an Arduino Pro 328 (3.3 volts/8 MHz) microcontroller. The tethered computer vision system sends 3-byte packets to the microcontroller via a USB serial connection. Because all three motor systems must be adjustable for each analyzed image, the communication speed between laptop and microcontroller must be at least (3 bytes x 3 packets x 60 Hz) = 4320 bps. To give the computer vision software adequate time to process the image, we chose a communication speed of 115200 bps.

Feedback Mapping Software. The Haptic Laser translates the vision system output into motor control commands. The mapping software sends a single activation pulse to the solenoid when the vision system detects an edge. Distance is mapped to the servos in the following way: distances of 1m or less are mapped to a servo position of 0°, and distances of greater than 10m are mapped to the fully extended position of 180°. Distances between these limits are mapped proportionally along the servo range of motion.

The software translates the macro-texture to a vibration motor intensity by linearly mapping the number of texture items (connected components) in the region around the center of the webcam image to the pulse width. This linear mapping is robust to noise because small changes in pulse width are nearly imperceptible to the user.

DISCUSSION AND FUTURE WORK

The Haptic Laser is designed to provide tactile feedback when exploring and interacting in a space at a distance. Through an informal evaluation, we asked a user to reflect on what he felt using the Haptic Laser in exploring parts of an unknown room, without any visual feedback. He was able to identify the large transitions, such as moving between walls and tables as well as indentifying clusters of objects, which included bundles of cables, backpacks, and books lying on a table. Although preliminary, the user was able to understand the feedback and cited the Wii experience as an analogy. We plan on investigating how the Haptic Laser's tactile feedback can improve targeting beyond that of purely vision-based targeting.

We encountered a number of technical challenges when building the Haptic Laser, including reliably and quickly detecting the laser for distance estimation. The high intensity red dot saturates the webcam's charge coupled devices, causing the dot to appear white. We were able to distinguish the laser point from true white light sources using a software filter that leaves only those sources appearing due to saturation, but bright or reflective environments still proved noisy. Additionally, the software filter was the source of substantial lag between targeting an object and feedback, since it updated the distance estimate only when the laser pointer was stable over a series of camera frames. We intend to explore other ranging technologies for more stable distance estimation, such as TDA laser ranging, and the use of optical filters.

In addition, generating robust haptic feedback was a significant challenge in hardware. The center-of-mass adjustment system was dependent on the device's weight and weight distribution. Its feedback conveyed relative distance clearly, but the prototype's weight distribution made it difficult for the device to communicate absolute distance. Future work will investigate different packaging solutions to make this feedback more robust.

The capabilities enabled by the Haptic Laser open up explorations in the field of assistive technology for individuals with limited vision. Existing solutions have focused on point-wise ranging (e.g., [2] and [6]), whereas the Haptic Laser can potentially deliver a richer experience of relationships between objects and physical transitions. We believe that the Haptic Laser could serve as a platform for investigating multi-sensation at-a-distance haptics in the physical world, thus allowing us to study which haptic feedback mechanisms are most valuable for sighted and visually impaired users in exploring the physical environment.

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