A Low Cost Tactor Suit for Vibrotactile Feedback

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Abstract

We constructed low cost tactors for vibrotactile feedback across the human arm for the purpose of providing a physical sensation surrogate for virtual objects. The tactors were built from readily available commercial parts, and provide low amplitude vibration for tactile feedback. The tactors are Velcro mounted on a custom suit designed to ensure localized sensations of each tactor. The suit is designed to be compatible with standard motion capture devices. Our suit provides 24 vibratory tactors in a tactor array on the user's right arm and hand, and can easily be expanded to include the entire torso and body.

1. Introduction

Commercial haptics devices and concomitant research generally focus on new and innovative ways of providing a haptic response to end-effectors, usually the hand. To feel fully immersed in a VR environment, however, one should feel haptic feedback on more than just the hand. Recently a low cost, low weight, and low complexity device has been introduced for VR: the tactor. Formulated with either pneumatic or electronic control, the tactor is essentially a small pressure point or button that can be actuated remotely as a tactile stimulus.

A VR experience of a confined space may be satisfying in a visual but not haptic sense. By flying through the space one can get excellent visual impressions of its shape and relationships. But if one needs to reach inside the space, say to do complex equipment maintenance or repair, then the flying eye and the disembodied hand are no longer adequate paradigms for virtual equivalents of physical presence in the scene. Besides the end-effector haptic experience of the Phantom and similar devices, as well as haptic gloves, there seem to be no good devices and software interfaces to give a user a sense of confined immersion. Thus, applications which require experiencing and testing the feasibility

of physical access for the entire body cannot be supported in realistic (i.e. low) cost VR configurations.

The computations involved in using tactors as a surrogate for physical contact use collision detection between each tactor location on the body and the virtual object geometry. Point-to-object collision checking algorithms are simple and fast [10]. Motion capture is used to find the body pose in 3D space; the 3D tactor locations are computed from the body pose and the known positioning of the tactors on the subject. Intersections between tactor locations and virtual object geometry is checked hierarchically with bounding volumes then with detailed object geometry to optimize performance. Once a collision is detected, its corresponding tactor is energized. Although some latency is unavoidable, the vibrotactile sensation is meant to augment a visual (stereo) view of the scene and aid the user in establishing a collision-free pose in the space.

2. Related Work

Tan [7] presents a "wearable haptic display for situational awareness in [an] altered-gravity environment". Using a tactor array worn on the back, subjects tested the system on a NASA reduced gravity aircraft (a aircraft that moves in and out of free-fall). The focus of these experiments were how the subjects felt various haptic sensations in altered gravity [8].

The Naval Aerospace Medical Research Laboratory is researching the use of tactor arrays. The Tactile Situation Awareness System (TSAS) has the goal of helping pilots perceive orientation, targeting, and situation awareness information though an array of tactors worn over the torso in a flight jacket. Apparently the experience is natural enough for both quick learning (10 seconds or so) and correct interpretation [4]. Cholewiak, from Princeton's Cutaneous Communication Lab, has focused on using haptics to aid sensory-impaired (blind and deaf) and elderly individuals [3]. Recent research at MIT places tactors in a vest to convey information to the wearer [6]. Their vest uses Nitinol, a
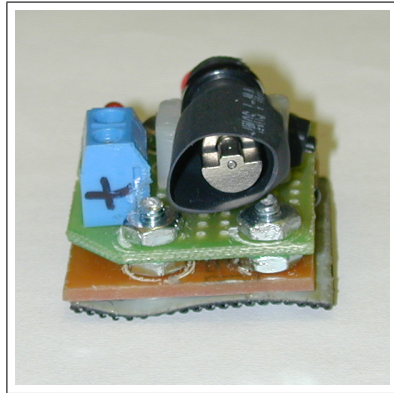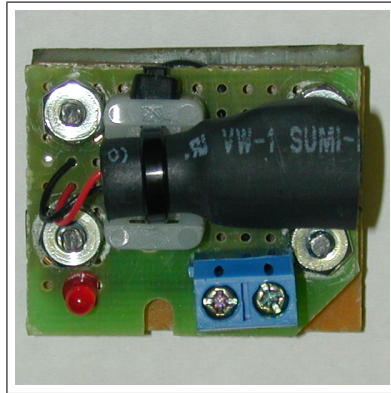
(a) Front view   (b) Top view   (c) Bottom view

Figure 1. Tactor Pictures

shape memory alloy.

3. The Tactor

To induce tactile stimulation, we used small vibrating motors similar to those used in cell phones and pagers. These tactors have a footprint of 28 mm x 34 mm (1 1/8" x 1 3/8"), and are 20 mm (7/8") high. They take up to 1.6V DC, and 100 mA. The tactors are relatively small, and still manage to provide sufficient tactile feedback: they can be felt through moderately thick clothing. Figure 1 shows pictures of the tactors. The tactors have Velcro backing for attachment to the tactor suit.

The tactor assembly consists of a red LED and a motor in a simple parallel circuit. The motor, shown in figure 2 has an off-center weight, which, when rotating, provides the vibration. The motors vibrate at about 60 Hz, depending on the amount of power supplied. Power is connected to the tactor via the light blue terminal block. The rest of the
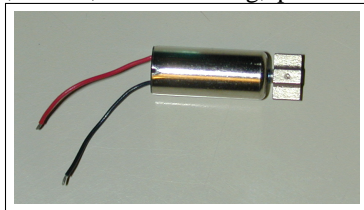

Figure 2: Vibrating Motor

tactor components are concerned with attaching the motor to the tactor, and the tactor to the Velcro on the underside. The black rubber housing around the motor is heatshrinkable tubing, and is intended to keep objects away from the rotating motor. The motor is mounted on a cable mount (similar to the ones used to attach a coaxial cable to a wall or floor) in order to firmly attach it to the rest of the tactor. The tactor assembly is tightly bolted together so that the vibrations are not absorbed by the tactor connections. All the tactor parts were purchased from a electronics

supply catalog.

3.1. Tactor Control

To control the pager motors, we used a relay cards that connect to a computer's parallel port. Each device has eight relays that are used to turn on and off the pager motors. The use of this board requires the user to be wired to the controlling PC. Although we looked into wireless kits, they were deemed not presently feasible, as the commercially available wireless kits use infrared that would conflict with the infrared motion capture system we used. Wireless versions are clearly desirable for the future.

Since we used relay boards, their output is binary and cannot be modulated in amplitude. Instead we can modulate the frequency of the vibration by rapidly switching the tactor on and off. Customized tactor control boards, such as the TactaBoard described by Lindeman [5], would be a better hardware controller choice for the future. The TactaBoard can control up to 16 tactors, can be chained to other TactaBoards, and plugs into a computer's serial port.

3.2. Motion Capture

The system puts the user in an Ascension Technologies ReActor, which is a room-sized optical motion capture device. The user wears a suit with up to 30 infrared transmitters placed on the outside. For our application, only transmitters placed on the arm are needed. The ReActor has infrared cameras along the frame, which record the 3D location of each of the transmitters in real-time. A stereo projector screen (6' high by 15' wide) covers one side of the ReActor frame, and provides the user with immersive visual feedback. The ReActor is ideal for motion capture

because it is large enough to move around freely in and it is completely wireless. Other motion capture devices can be used with our tactor system, although the metal content of the tactor motions may not be conducive to electromagnetic systems.

4. The Suit

Initially, we tried attaching the tactors to the user by placing them on Velcro straps, which were then wrapped around the user's arm. This allowed for a very flexible design, as anybody can easily strap the tactors on over clothing. However, we found that the tactors' vibrations were transmitted through the strap, so the sensation was not as localized as we desired.

We decided to use a long-sleeve, skin-tight shirt designed for athletic use. The shirt, manufactured by Under Armour (Turf Shirt, item 0032), is thin enough to transmit the vibrations and strong enough to endure the sewing necessary to affix the Velcro to the shirt. The skin-tight aspect ensured that the tactors would always lie flat against the subject's skin and yet allow free movement. The elasticity of the suit also admits many different sized people.

The Velcro for the tactors are 2.5 cm (1") squares. The ReActor uses infrared transmitters that are 5 cm (2") circles and thus the Velcro attachments for these are 5 cm (2") squares. Long strips of Velcro are used to secure the ReActor's motion capture wires that run between the infrared transmitters and the battery pack on the user's waist. This suit can be seen in figure 3, and with the tactors attached in figure 4. Although this suit was designed to work with the ReActor, similar Velcro pieces could easily be attached for other commercial motion capture systems.

Currently the suit can hold 24 tactors on the right arm, as shown in figures 3, 4 and 5. The tactors are arranged in six "rings" of four tactors each, spaced uniformly along the forearm and upper arm. The proximal upper arm ring has only two tactors, and the other two tactors of this ring are on the point of the elbow and the back of the hand. Additional tactors can easily be added to the rest of the suit.

For the hands, we used regular glove liners, as they are inexpensive, thin enough to transmit the vibrations, and also skin-tight. The gloves had to hold a number of motion capture transmitters, as well as one tactor on the back of the hand.

5. Sampling

The critical decision in designing the tactor suit was how many tactors to place on the arm. The trade-off is between having a large number of tactors to make it seem as realistic as possible versus their computing and hardware requirements. More tactors require additional hardware to control
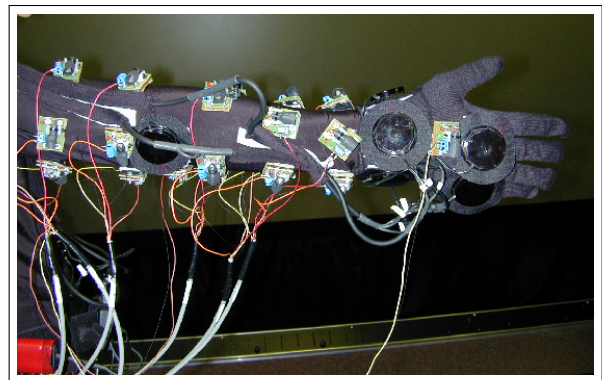

Figure 3. Suit without the tactors

Figure 4. Suit with the tactors attached

them, and more computations to detect collisions of all the tactor locations with the virtual objects in the scene.

5.1. The Arm

The human arm has tactile receptors over its entire surface. A sensation moving along the arm feels like continuous movement. In reality, the individual tactile receptors fire in sequence, and the brain interprets this as continuous movement.

The average adult human has 1.8 m^2 of skin surface area, and the arm (with hand) is about 9% of that area [1]. Thus, the adult human arm has about 0.162 m^2 (162,000 mm^2) of skin surface area.

Ideally, we would have a separate tactor for each nerve ending. This is impossible with current technology, as the human hand has as many as 200 nerve endings per
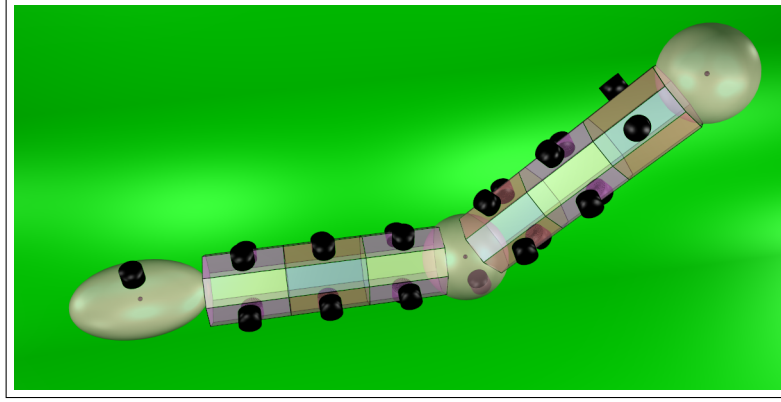
Figure 5. Tactor Placements on the Arm (24 tactors)

square centimeter, and 17,000 nerve endings per hand. Nevertheless, this is a useful metric, as it is the "real world" situation that haptics should try to approach. There are much fewer tactile receptors on the rest of the arm, yielding about 20,000 receptors on the hand and arm combined. With a arm surface area of 162,000 mm^2, this yields an average area of about 8 mm^2 per tactile receptor. For the hand the average tactor size would be 1/2 mm^2. For comparison, this area is shown as the small black square in figure 6; clearly such tactor footprints are not possible today for both mechanical and communication reasons.
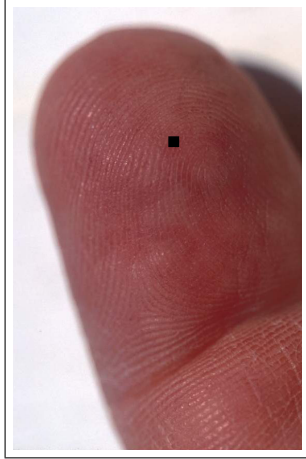

Figure 6: 1/2 mm^2 Tactor Size

A function $f(x)$ to determine the theoretical maximum number of tactors that could be placed on the hand and arm is simply as follows, where x is the area of the tactors in square millimeters. As the tactor area x decreases, the number of tactors placeable on the arm, $f(x)$, approaches formula 1.

$$f(x) = \frac{1.62 * 10^5}{x} \qquad (1)$$

5.2. Two-Point Limen

Burdea [2] discusses the two-point limen, which involves placing two sharp objects (such as the points of a draftsman's compass) close to each other on various parts of the body and finding the threshold (or limen) above which the person can tell that there are two distinct points. Each area of the body has a different limen distance, and ranges from

2.5 mm for the fingertip to 67 mm for the thigh. Many factors can increase sensitivity (and thus decrease the limen), including warmth and practice. Conversely, there are factors that can decrease sensitivity (and thus increase the limen) such as old age and cold.

Data for the two-point limen varies slightly depending on the source, as is to be expected of experimental results. We use the experimental results from Weinstein (48 right-handed individuals, half male) [9], shown in table 1. The values shown are averaged and rounded for gender and right or left side. The limen distance generally decreases (the sensitivity increases) with the increase in distal distance from the shoulder.

Body area	2-pt limen distance
Fingertips (average)	3 mm
Palm	10 mm
Back of hand	17 mm
Forearm	35 mm
Upper arm	39 mm
Shoulder	41 mm

Table 1. Two-point Limen Distances (from [9])

Using this data, we can estimate the number of tactors needed based on the two-point limen distances. The fingers (which are about 1/18 of the area of the arm) have an average limen distance of about 5 mm. This area is a combination of the limen distance for the fingertip and the limen distance for the rest of the fingers. The rest of the hand (which is also about 1/18 the area of the arm) has an average limen distance of at least 10 mm. The rest of the arm (which is 8/9 of the area of the arm) has an average limen distance of about 40 mm. Assuming that a tactor would cover a square whose side was the limen distance length, this would yield about 540 tactors on the arm and hand combined (average

area of 300 mm^2).

5.3. Current Tactor Technology

A number of currently available tactors were examined, and we estimated how many could be placed on the arm. There are many inaccuracies with this (the deformity of the arm's surface area during motion, different arm sizes, non-planarity of the arm, etc.), but it is good as a rough estimate.

One currently available tactor is a pancake pager motor, shown in figure 7. This vibrating motor is 14 mm (0.55") in diameter and 3.3 mm (0.13") thick - smaller than a dime, and about twice as thick. We chose not to use these particular tactors because the solder connections did not appear to be robust enough to remain attached during constant use. Normally they are held in place by customized rigid plastic casing. If we assume that we could place each pancake pager motor in a 20 mm x 20 mm square area, or 400 mm^2, that means we could theoretically place about 405 of them on the arm.

Figure 7: Pancake Pager Motor

We also examined piezoelectric "benders". They come in multiple sizes; the two potential sizes are the smaller size of 3871 mm^2 (6 in^2) in area, of which up to 41 of them could be placed on the arm, and the larger size of 6865 mm^2 (10.64 in^2), of which up to 23 could be placed on the arm.

The pager motor tactors we are using have a footprint of about 1,000 mm^2. If we could place them immediately adjacent to each other, up to 162 of them could fit on the arm. Of course, the wiring and control problems remain and might be solvable through integral mounting within the fabric suit itself.

5.4. Sampling Conclusions

Using these values and equation 1 ($f(x) = 1.62 * 10^5/x$), we can draw a graph of the upper bound of the number of tactors that can be placed on the arm as a function of tactor footprint. This graph is shown in figure 8. Each of the above situations is indicated on the graph. The position of our tactor suit is indicated as well. Note that the vertical axis is logarithmic. Each tactor will have a fixed skin region that will need to be checked for virtual collisions to see if that tactor should be activated.

6. Conclusions

Tactor suit design must trade-off between current technological constraints, the required collision computations for
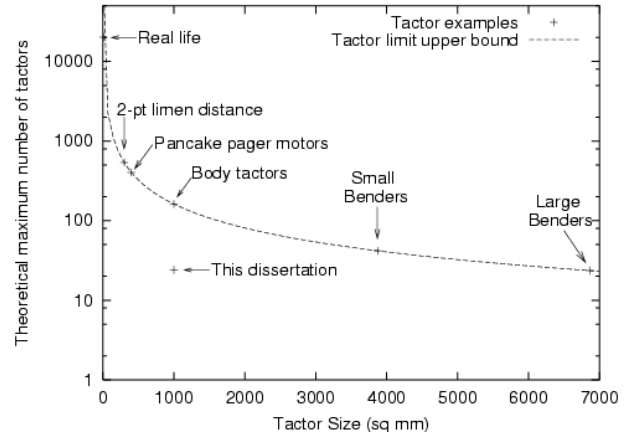

Figure 8. Sampling Graph

each tactor, and the receptor sensitivity on the arm. Our design provides a good balance between the maximum number of tactors desired versus a feasible number of tactors required for a computing application. The skin-tight suit allows the tactors to always be in contact with the skin, while not transmitting the vibrations beyond the tactor area. The tactors presented are a low-cost means of providing vibratory feedback to the skin with modest power requirements.

7. Future Work

The current suit contains 24 tactors on the right arm. This can easily be extended so that tactors can cover both arms and the torso. A skin-tight pair of leggings can be added to hold tactors for the lower half of the body. Other accessories (a skullcap, socks) can be added to allow for tactile feedback across the entire body surface. The main technological issue is how to switch and wire a large number of tactors.

The pancake pager motor in figure 7 is a desirable candidate for our next generation tactor. New technology involving voice coils may also promise a smaller tactor. By sewing or manufacturing the tactors and their wiring directly into the shirt itself, the process of putting on the tactor suit would be greatly simplified.

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