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AD________________

Award Number DAMD17-94-J-4113

TITLE: Addition of Olfactory Stimuli to Virtual Reality for Medical Training Applications

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REPORT DATE: July 1999

TYPE OF REPORT: Final

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

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Award Number: DAMD17-94-J-4113
Organization: Artificial Reality Corporation

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____________________ Myron Krueger

____________________ ____________________

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 1999	Final (1 Sep 94 - 30 Jun 99)

4. TITLE AND SUBTITLE
Addition of Olfactory Stimuli to virtual Reality for Medical Training Applications

5. FUNDING NUMBERS
DAMD17-94-J-4113

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution authorized to U.S. Government agencies only (proprietary information, Jul 99). Other requests for this document shall be referred to U.S. Army Medical Research and Materiel Command, 504 Scott Street, Fort Detrick, Maryland 21702-5012.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 Words)***

14. SUBJECT TERMS

15. NUMBER OF PAGES
94

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Limited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

FOREWORD

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N/A For the protection of human subjects, the investigator(s) adhered to policies of applicable Federal Law 45 CFR 46.

N/A In conducting research utilizing recombinant DNA technology, the investigator(s) adhered to current guidelines promulgated by the National Institutes of Health.

N/A In the conduct of research utilizing recombinant DNA, the investigator(s) adhered to the NIH Guidelines for Research Involving Recombinant DNA Molecules.

N/A In the conduct of research involving hazardous organisms, the investigator(s) adhered to the CDC-NIH Guide for Biosafety in Microbiological and Biomedical Laboratories.

M. Krueger

PI - Signature Date

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I. Introduction

This is the final report for DARPA grant DAMD17-94-J-4113 on the introduction of olfactory stimuli into virtual reality for medical training applications. The project addresses the range of issues that are required for such stimuli to be used for this purpose including: odorant delivery, wireless operation, odor representation, odor effects on performance, and graphic simulation. While the purpose of this report is to describe the efforts of the past year and the end state of the project as a whole, it is also desirable to describe enough of the previous years' efforts to provide context for what has been done more recently.

II. Executive Summary

This report describes the results of the DARPA-sponsored effort to determine the state of current technology vis a vis the problem of introducing olfactory stimuli into virtual reality training simulations. Since no history existed from which to determine requirements and no technology existed that was directly suitable for this task, this project was a systems effort touching on a number of technological problems including: odor delivery, wireless tracking, odorant synthesis, graphics simulation, and human performance studies.

II.A. Wireless Operation

Given that odor display is a new capability, it was seen as desirable for participants in immersive virtual reality system to encounter odors in the most natural way possible. This implied the need for completely wireless operation comprising wireless image transmission, wireless odor display, and wireless determination of head position and orientation. All of these have been achieved at different stages of the project, although not yet in an integrated system.

II.B. Odor delivery

A major focus of this effort was on the development of delivery systems which could be used for presenting odors in desktop surgical simulators, HMD-based immersive virtual reality, and CAVE environments. A number of delivery systems were developed and the result of the final iteration is a single system that can be used in all three virtual reality formats.

The resulting delivery system is portable, wearable, and wireless. It can deliver up to 10 odors singly or in combination. It can also control the concentration of the displayed odor over at least a 100:1 range. Its electronic response time is 1 millisecond which is faster than any imaginable head movement of which a virtual reality participant might be capable. This allows the participant to move his head towards or away from a virtual odor source and to perceive the expected increase or decrease in the strength of the stimulus. However, there are additional sources of lag from the wireless communication and the air transport through the tubing to the nose that bring the total lag to over 50 milliseconds which is still fast enough for the application. The system operates over the wide range of orientations that a standing participant might assume.

II.C. Tracking

For odors to be effective in immersive virtual reality systems, the tracking of the participant' head position and orientation should also be wireless. Early in the project, a 40 foot long wireless tracking path was constructed based on overhead optical tracking of head-mounted targets. This system was fast for position and yaw, but slower for pitch and roll, although with current fast framing cameras, it would be satisfactory. A second system with spectacular specifications was designed and its electronics and software algorithms implemented. It created a 6000 x 6000 virtual camera which could provide a 1000 samples per second with sub millimeter accuracy over a 40 foot square area. Unfortunately, the optics turned out to be unreasonably expensive to fabricate. A third technique is being implemented which has a CAVE-sized working volume but which does provide a high sampling rate, stable values, and wireless operation. It works in benign orientations and is being extended to make it more robust.

II.D. Odor Synthesis

Our initial partners assured us that getting the odors needed would not be difficult. This turned out to be incorrect. While the light molecules found in flowers and fruits are well understood and vegetation should be tractable with existing techniques, the heavier chemicals in tissues and bodily fluids have not received much attention and are not of interest to the fragrance industry. The very mention of fuels, combustion products, and explosives strikes fear in the hearts of those with the skills to synthesize them. Moreover, many of the synthesized odors that we were able to get hold of or to get formulated for us were not very convincing. There is a need for a breakthrough in this area.

II.E. Odor Studies

Two major studies were conducted to determine the effects of odors on skills needed to perform surgery. The first showed that odors could improve spatial reasoning to a degree that was of both statistical and practical significance. The second study showed no significant improvement in the performance of manual dexterity tasks from the presence of any of the odors considered.

III. Wireless Odor Display System

The final odor display system is the deliverable for this project. Its purpose is to present odors to a participant in an immersive HMD system at appropriate moments in virtual reality training experiences.

While it was not appreciated at the beginning of the project, this device is quite unusual in that it is a portable fluid and vapor handling system that works with a wide variety of corrosive chemicals and must operate in a wide range of orientations. Even defining the requirements was not straightforward, for many of the needs could only be ascertained by having a delivery device with which to measure them. For instance, the amount of odorant that needed to be added to an air stream breathed through a mask or whether pulse width modulation of odor release could be used to control concentration were not to be found in any publication. Indeed, the level of instrumentation used in past olfactory research makes some of it suspect. Multiple odor delivery and head-tracked delivery had been only crudely attempted if at all.

III.A. Presentation Formats

Three presentation formats were considered for odor delivery during the project:

• an enclosed training booth for surgical training

• a portable, wireless unit that could be worn by users as they participate in training in a simulator for dismounted personnel and which could deliver odors contingent on their body movements and their location and events in the virtual environment.

• a CAVE environment in which the participant is surrounded by projection screens and his head and hand movements are tracked as he moves around a 10'x10' space.

Since the training booth is quite small and the odor output can be placed close to the user's face like a microphone, it was found that the portable delivery system designed for immersive environments could also be used in this space provided that a ventilation panel was placed behind the participant's head to evacuate the odor immediately after it was introduced.

On the other hand, the CAVE contains an enormous amount of air and demands a much different approach if the entire volume is to be odorized. Several such room odorizing systems were tested in a CAVE-sized room. It was found that not only was it difficult to evacuate the odors once they were introduced, it was also difficult to introduce the odors so that they would be simultaneously available everywhere in the CAVE. Indeed, it would take a minute for a new odor to circulate around the space. Thus, by the time a person standing in the corners of the room detected a new odor, people standing in the center would already have habituated to it.

It is possible to improve the performance somewhat by introducing the odors uniformly (no small trick) through a porous floor and then to evacuate them immediately through a porous ceiling. The problem is that CAVE environments are open at the top to allow an image to be projected onto the floor. They are also open at one end so participants can enter and exit. Laminar flow could only be maintained by either giving up the imagery on the floor or by rear projecting it from below. The result is a complete redesign of the CAVE which is not likely to be welcome to owners of existing CAVEs or even to appeal to those building new ones.

From 1984-88, the PI implemented a gesture-controlled highly interactive virtual wind tunnel for Pratt & Whitney.[Krueger][Foley] (This project was the direct inspiration for NASA's virtual wind tunnel. Both were demonstrated in Tomorrow's Realities Gallery at SIGGRAPH 91.) One small experiment with this system was a study of rectangular walls to create micro climates for growing plants. The air flow through that space was fiendishly complex, infinitely more so than that inside a jet engine. One of the most striking features was the tendency for some bodies of air to become entrained in the space and other flows to meander throughout it for long periods of time before finding the exit. This experience does not bode well for any scheme for rapid room odorizing and reodorizing. The room odorizing systems that have been done cost $.5M-$1M, only work with a single odor at a time, and still only claim 100 odor changes per hour.

The conclusion of this investigation was that it would be impractical to odorize existing CAVEs if rapid odor changes were desired. However, it would be possible for the participant to wear the delivery system designed for immersive environments and to provide sufficient ventilation to immediately dilute and to quickly evacuate the odors after they are introduced. For military personnel, the delivery system would be a small fraction of the weight of the field pack they would normally carry.

The result is that a single delivery system can be made to work without too much compromise in the three primary virtual reality formats.

III.B. Capabilities

The final delivery device [Photo 1] had the following attributes:

- portable
- wearable
- wireless
- 10 odors
- simultaneous display of multiple odors
- 600 seconds of continuous display of each odor, enough to support a one hour experience
- wide range of orientations

III.C. Requirements

Much of the effort in designing the final delivery system went into the identification of the requirements and the testing of previous design approaches against those requirements. Therefore the many requirements for the odor delivery system will be elaborated upon below. These fall into the following categories:

- the physical requirements of a portable device.
- the functional requirements of an odor delivery system for virtual reality experiences.
- the operational requirements of a system which must work in an experimental setting.
- the organizational requirements of such a system in order for it to be employed by the end user.

Since the requirements for use by dismounted personnel are the most stringent, they will be the ones discussed below.

III.C.1. Physical Requirements

To understand the requirement that the delivery system must work in immersive virtual reality applications, it is necessary to make the PI's argument about the advantages of such systems.

In spite of the hype surrounding immersive virtual reality, these systems not only do not deliver on the basic promise of the concept, they also fail to fully implement it. That this omission is not noted more urgently has been the biggest surprise in the field's development.

Immersive systems purport to allow participants to naturally interact with virtual environments using their whole bodies. To the extent that they couple head movement to image generation, they do this very well. However, the BOOM™ provides this same capability with better visual images. What is missing is the ability to walk naturally around the virtual world thus engaging the entire body in the act of perception which is how we operate in the real world. We have a lifetime invested in interpreting the world in terms of the height of our eyes from the floor, the length of our stride, and the posture of our body.

A very few experimental systems permit a person to walk around a virtual world, but these systems are still connected to the computer by wires. The most important object in the real world, the wire, is invisible in the virtual one which means that either the user has to constantly worry about tripping over it or someone in the real world has to handle the wire for him. A truly immersive virtual reality system would be completely untethered. Wireless head tracking and wireless virtual image transmission were achieved earlier in the program. What remained was wireless odor delivery. Thus, wireless operation is a requirement of the final delivery system.

III.C.1.a. Portable

Wireless operation suggests but does not require that the system be portable. By itself, portability primarily implies a weight that can be carried comfortably. The weight requirement established at the beginning of the program was 10 lbs for the odor delivery capability by itself. It was assumed that the soldier of the future would be geared for chemical warfare and would have external power and clean air sources that could also support the delivery system. The weight of these subsystems is not attributed to the odor delivery system. However, it is presumed that low power and light weight air systems are also desirable design criteria.

III.C.1.b. Wearable

The system must be packaged in a way that makes it comfortable to carry.

The biggest issue here was where the delivery system should be worn—on the back, around the waist, or on the head. On the head would imply much lighter weight, shorter tubing and perhaps no tubing, and therefore no pressurized air system. On the back is less challenging but implies a tube to the head which can be flexed as the head turns.

III.C.2. Functional Requirements

In addition, there are the requirements imposed by the desire to deliver odors at the appropriate moments in virtual reality simulations.

III.C.2.a. Odors

Up to ten odors must be available for display. This number seemed to be sufficient for most training scenarios that we considered. Obviously, more odors would provide the possibility of a richer experience, but it is a rare day when a person can remember ten odors that they encountered during it. Time will tell whether a significantly larger number would be desirable. Besides, with the current odorant repertoire, it is unlikely that more than ten odorants could be found that could be used to simulate a single situation.

III.C.2.b. Multi Odor Display

The odors must be deliverable either singly or in combination. Most odors will be used one at a time because people are not very good at identifying the ingredients when even a small number of odors are mixed. However, when exact simulation is not the goal, several odorants can be mixed together to represent different but related odor sources. For instance, pine smell is composed of a few primary chemicals, e.g. a-pinene, b-pinene, d3-carene, and b-phellandrene.[Pine] By varying the proportions of these chemicals a variety of evergreen plants can be suggested. Since few modern people have a calibrated knowledge of the smells of particular species, it is likely that no one will notice. Think of this approach as impressionistic as opposed to realistic odor painting.

III.C.2.c. Intensity Control

For the delivery system to do its job, it is not enough to simply display odor, it must be able to display it in the appropriate strength for each moment in the experience. Several of our earlier delivery systems were completely successful at displaying many odors, but were totally unable to present some of the more subtle ones. Betadine which is used as an antiseptic prior to surgery has a clear smell when it is applied to a large part of the body, but the odor produced by passive evaporation of this material was almost undetectable.

In addition to being able to present the odor in the required intensity, it is necessary to be able to vary that intensity as the participant moves closer to or away from the odor source in the virtual environment. It is this coupling of odor stimuli with physical behavior that we felt was the most successful aspect of odors in virtual experiences. Controlling the strength of an odor by head movement not only made the scene seem more real, but it also made the odor itself seem more real and more believably bound to its graphic source.

III.C.2.d. Dynamic Range

There is another reason that it is necessary to be able to control the intensity of an odor. People's sensitivity to odors varies enormously--by several orders of magnitude. Thus, a range of odors that is perfectly obvious to one person may be imperceptible to another.

It is possible to argue that these individual differences do not matter. What matters is what the real concentration of the odors are in the real world situation to be simulated. Ah, but how do we know what that concentration is? We have no instruments for measuring odors as humans perceive them. In fact, we really have no instruments for measuring odors at all. Instead, we have instruments for measuring chemicals. The strength of odors emanating from hog farms is measured by panels of people who smell air samples diluted in measured proportions until they cannot smell them anymore. Even if such panels could be afforded, telling someone that they do not have a good enough sense of smell to appreciate the simulation is no way to get support for a new technology.

A person's sense of smell is roughly exponential. The least noticeable difference is about 1.1 times the current concentration.[Smith] Successive perceptions based on head movements may be able to make use of that kind of difference. But for many purposes faint, present, and strong concentrations might be enough. However, most technological approaches for delivery systems involve linear as opposed to logarithmic control and apparently impressive linear resolution may not provide enough dynamic range for a given individual's experience. Providing the same perceptual experience for individuals with very different odor sensitivities may require an extremely sophisticated delivery system. Varying the concentrations of the liquid odorants is an alternative to a sophisticated delivery system—albeit a cumbersome one.

Furthermore given that the final system is the only variable concentration, multiple-odor delivery system available, it would also be desirable if it could be used for studies of the psychophysics of smell, studying people's ability to experience odors in the laboratory. Many such experiments can be imagined and the results of some of these would have been useful to have in designing the delivery system itself. The odor research that has been done has not contemplated applications and so the questions that immediately occur to someone who wants to exploit odor effects have in many cases not been asked, let alone answered.

III.C.2.e. Consistency

It is desirable that the odor concentrations and the odors themselves be the same from one session to another and from one installation to another. This requirement is more demanding than it seems at first glance. Much of the formal research that has been done has used peppermint as the odorant, but what is peppermint? There are a number of ways of producing this odor from natural materials or artificial ones and the kind of peppermint used is almost never specified in the research papers. With traditional techniques for producing odorants from natural materials there is almost no way of maintaining precise control of the chemistry of the resulting product. Starting with pure chemicals gives a developer much better control of the ingredients, but may result in less vivid odors.

III.C.2.f. Speed

While speed is not a dimension that is typically associated with odors, it is relevant in this application. If odors are to be experienced as part of physical behavior, they have to be displayed at the speed of that behavior not at the supposed speed of the sense of smell. A person walking at four miles per hour is moving 70 inches per second which is more rapidly than many people realize. Odors which are delivered after a noticeable lag will not be associated with the appropriate sources in the virtual world. Note that this argument is not negated by the fact that odor perception itself is not that fast. A sensation delayed in time and displaced in space is incorrect. Therefore, very fast response is desirable. Since it takes about

1/20 second for the air to be transported through the tubing from the delivery system to the nose, that is the lag of the system unless it is mounted on the head.

Speed is also an issue in that pulse width modulation is the technique that we use to control the intensity of the odor.

III.C.2.g. Odor Duration

The delivery system must contain enough odorant material to support a meaningful training experience. Given current virtual reality technology, people do not wear a head-mounted display for more than an hour. During that period, there needs to be enough odorant to display odors as they are encountered in the experience.

However, since people start to habituate to an odor within seconds after they encounter it, it is not necessary to be able to display any odor for the entire duration, because the participants would not be able to smell it anyway. (They also do not notice when an odor they have habituated to is removed. That is a non-event.) Thus, assuming that each encounter with a new odor can be represented by a few seconds of odor display, the amount of odorant required can be modest. One hundred seconds of display per odor is probably more than enough.

III.C.2.h. Quiet

The operation of the delivery system cannot distract from its purpose. Therefore any noise that it makes when operating ideally would be below the threshold of human perception and failing that could be rendered unnoticeable by sound proofing or head phones or masking sounds. There are several potential sources of sound in a delivery system. One is the sound of the odor selection itself. If this sound is noticeable, the participant always receives a combined auditory/olfactory cue which is quite unlike anything that occurs in the real world and therefore disturbing.

Another potential source of sound is from the pressurized air system that will be required if the odorized air must travel through any length of tubing. To the extent that such a sound is continuous and featureless, it is more tolerable.

However, pressurized air may also be needed to drive the odorant materials through the delivery system. If this system involves a feedback loop which monitors the current air pressure and opens a valve to let in more air when it falls below a certain pressure, the result is an intermittent sound which is much more disturbing than a continuous one. The alternative of wearing a bottle of compressed air eliminates this sound at the cost of additional weight.

In general, the fact that virtual reality systems typically include headphones, and audio cues generated as part of the experiences means that the sound created by the delivery system is less important than it would be otherwise.

III.C.2.i. Orientation Insensitive

Since the delivery system is intended to be worn by a person who is physically participating in a virtual world, it must capable of operating during that behavior. In particular, it must be able to tolerate the range of orientations that it will assume as the participant moves, jumps, bends over, etc. This requirement is not so benign given that it is a liquid handling system which typically prefers to know which way is up and which down. Indeed, this problem surfaced in the previous system which operated well during use and only had a problem when carelessly placed on its side on the bench afterwards. In that orientation, the liquid odorants could flow against the pressurized air that forced them through the delivery system and back into the pumps. While the worst did not happen, the hazard was clear.

The minimum requirement is that the system be able to operate during 45° tilts which are the worst that are likely to occur during standing and walking behavior. A desirable level of performance is for the system to operate during 90° rotations which would render it horizontal. Such a posture is the worst that might be assumed by a medic leaning over a casualty without bending his knees, but it might be quite common for infantrymen crawling along the ground. Ideally, the system would continue to operate if the participant stood on his hands or laid it on the bench upside down.

III.C.2.j. Contamination

For odors to be most effective, they must be displayed against a background of no odor. Therefore, it is important that the only odor being perceived is the odor that is supposed to be displayed. Furthermore, because we so completely habituate to odors, it is important that we only smell each odor when it is supposed to be displayed. If an odor is present even in low concentrations in between intended stimuli, the participant may not be able to smell it at all when it is displayed.

There are a number of places where such contamination can occur in the delivery system. Storage techniques like micro encapsulation and impregnated porous polymers leak odor. Thus, it is important that the storage system keep each odor segregated from the other odors and from the user when it is not being displayed. It can also adhere to the tubing between the delivery system and the nose and be re-emitted over time.

The brute force way to avoid this hazard is to provide separate tubing for each odorant all the way to the nose. Another way is to use Teflon tubing which does not adsorb much odor material. Yet another way is to heat the tubing all the way to the nose.

Contamination of the tubing has not been observed to be as much of a problem as expected with this delivery system, although it has not been tested with the most obnoxious odorant materials such as benzyl mercaptan which can be smelled through a gas mask. However, one source of residual odor that the PI had not thought about is the adhesion of strong odorants in high concentration to nasal hairs which causes some smells to linger after the delivery system has stopped displaying them. This phenomenon can also occur in the real world.

The final type of contamination occurs when the ambient environment becomes saturated with odors. This problem can be avoided by filtering the exhaled air, by evacuating it with a ventilation system, or by having a large enough volume of ambient air that the odorized air is quickly diluted after it is exhaled. Other solutions are to filter the ambient air before it is odorized to remove any contamination or to use bottled air which will be odorless.

III.C.2.k. Complete Vaporization

Contamination can also occur due to incomplete vaporization of a previous odorant when a common evaporation chamber is used. The result is that the previous odorant residue is vaporized with the freshly dispensed material resulting in an odor mixture rather than a pure smell.

There are several ways that incomplete evaporation can occur. If the odorant is presented to the vapor transducer faster than it can be vaporized, the odor will stiff be present after the command to create it is turned off. The easiest way to correct this is to operate the vaporization transducer a bit longer than the odor display requires to burn off any excess odorant. If desired, the extra odor can be shunted into a filter instead of to the participant's nose.

III.C.2.I. Vaporization

Another important decision is the choice of the vaporization technique in the first place. While passive evaporation assures that the odorant is turned into a vapor, the process does not necessarily produce enough odor for a vivid experience. In particular, subtle odors may not be discernible at all even if they are quite obvious in the real world. In addition, the most volatile components of the odorant will boil off first leaving the less volatile components behind and the odor will change over time.

Therefore, it is natural to consider a forced vaporization system. The most obvious way to accelerate evaporation is to use heat. However, while heat will speed the vaporization process, it does not automatically eliminate the change in the odor that occurs as ingredients with different vapor pressures are boiled off one at a time. It also does not automatically assure complete vaporization because evaporation is an extremely effective means of cooling and care must be taken to assure that the heater is not itself cooled by the evaporation, again resulting in incomplete vaporization. The solution to this problem is to use sufficient heat at a temperature somewhat above the boiling point of the least volatile component of the odorant. Enough thermal mass must be available to overwhelm the cooling effect of the vaporization process.

However, there are reasons to be wary of using heat. Some of the ingredients of an odorant may chemically react with each other when heat is applied. Some of the odorant materials have low flash points and might ignite. Finally, heated vapors will be more hazardous that cool vapors. For these safety reasons, heat was ruled out as a means of vaporizing the odorants.

Whatever the means of vaporization chosen, it is preferable that it completely vaporize the material. It is possible to dispense droplets and allow them to vaporize in the air stream. However, if the droplets are large, they may settle against the walls of the tubing. If they are smaller than 5 microns, they are considered a breathable mist and are less likely to stick to a surface.

III.C.2.m. Safety
The delivery system must be safe for the user to wear. Many of the raw chemicals used as odorants are toxic, carcinogenic, sensitizing, etc. as they are sold in neat (pure) form. At the same time, they are meant to be breathed, applied to the skin, and in many cases ingested when they are used as food flavorings. The difference is that they are typically diluted heavily before they are used. Unfortunately, the safe levels of dilution are not published anywhere. In addition, many of the traditional materials that are extracted from natural plant and animal products have never been studied for their safety.

In any of our delivery system designs, the raw chemical is diluted from by a factor of 10 to 1000 in a diluent such as water, alcohol, or mineral oil. This liquid is then further diluted by the air stream into which it is vaporized. (100 nanoliters of liquid are evaporated per millisecond into .16 milliliters of air for a maximum 1600:1 ratio. However, since the typical duty cycle of the odor delivery is likely to be around 1 millisecond on per 20 milliseconds off, another 20:1 dilution is occurring for a 32000:1 total dilution. Further dilution occurs at the nose where ambient air is mixed with the odorized air as it is breathed.

It is possible that a vaporized odorant could condense on a cool surface either on the device or on a nearby surface. It could then dry out leaving the concentrated chemical. A person touching that residue might inadvertently rub their eyes or touch their lips. While we have not experienced any such problems with the current device, earlier efforts were visited by this hazard. Therefore, it is necessary that operating the device, loading it for use, and cleaning it after use do not lead to the contamination of the device itself or to a hazard for the user.

Another safety issue arises when mounting the delivery system on the head is attempted. Doing this is attractive because the tubing can be dispensed with, eliminating the need for the pressurized air and therefore the pumps and batteries that generate it or the heavy air bottle strapped to the thigh that could contain it. The possibility of releasing toxic chemicals into the nose has been mentioned. In addition, piezo systems require special power supplies that operate at high voltages and create transients at even higher voltages. In the current climate in which people are concerned about their cell phones, the combination of high voltages and high frequencies would be sure to set off alarms whether or not the hazard was real.

III.C.3. Ease of Use

Ideallly, the hardware should be easy to turn on. The components should be easy to connect. And software should alert the user to the health of the system. The software should make odor selection, stimulus triggering, and concentration control easy for developers to specify. Test procedures should be available that allow personnel to put the device through its paces when it is on the bench so a participant is not required during the testing process.

In any setting the easier the device is to use, the more likely that it will be used In an end user site, almost no operational hassle or hazard will be tolerated. Ideally, the device would be maintenance free and no harder to reload than an ink jet printer. Unfortunately, we cannot claim that anything like that ease of use has been achieved. Ink jet printers have probably had over a billion dollars invested in their incremental improvement over a 20 year period to achieve their current level of performance.

Just purchasing the chemicals to be used as odorants was a major research project for the PI. The companies would not sell directly to him because ARC is not a chemical laboratory. After months of playing Hamlet, the University of Connecticut decided that it was completely spooked by the thought of purchasing these chemicals and did not feel that students could be asked to handle them at all or to perform the simple task of diluting them to safe concentrations. One local chemical lab was approached and after first agreeing ultimately declined. A second was finally convinced to do the work.

Ease of use implies several levels of infrastructure that do not exist. The odorants need to be diluted to a safe level. They need to be packaged into easily loadable cartridges that contain all of the odorants required for a particular virtual reality scenario. And they need to be quickly available in that form to whoever needs them without special facilities or trained personnel intervening. Given that end users will want to create their own scenarios and that standard scenarios that would be employed by huge numbers of systems are not likely to exist for some time, a programmable cartridge that can be easily loaded with the desired odorants would need to be developed first. This could be loaded by the end user or probably could be more easily done by a internet-based service with overnight delivery. That at least would permit the packaging to be less sophisticated and would centralize the facilities, skills, and chemical stocks needed to load the cartridges. Even so, a great deal of effort would have to be spent on these packaging and infrastructure needs before the delivery technology would be the limiting factor. That implies a market for such materials that is unlikely to develop for some time. More likely is that an arcade unit will be mass produced for a particular game that will have a short life, and odor delivery will then fizzle for some time before the needed technology is developed for some other purpose, e.g. drug delivery.

III.C.4. Maintainable

In addition to being easy to use, the delivery device needs to be easy to maintain or be maintenance free. The importance of this issue cannot be stressed too much. Over and over we found that miniature components could be fouled by miniature hazards and that what seemed to be sufficient precautions would be thwarted by some new level of complication.

Ink jet printers are the only examples of precision liquid handling devices that are widely available at low cost. They include a mature set of techniques and technologies for making them relatively maintenance free. The ink cartridges are carefully engineered to operate with one kind of ink which itself has been formulated by legions of PhD chemists to flow properly in that exact cartridge and that exact print head. The printer software contains elaborate procedures for clearing the ink lines and wiping the print heads before it starts to print. Even so, HP has found it expedient to make its print heads disposable rather than to keep them operating for long periods of time.

The odor delivery system in contrast must operate with a wide and unbounded range of toxic and corrosive chemicals mixed in a number of different diluents with different physical properties, including water, alcohol, and mineral oil. The physical properties of the individual chemicals are not readily available and seem to be treated as trade secrets in the industry. In addition, because of the volatility of the most of the diluents, it is likely that they will dry up inside the delivery system if it is not used for a period of time. The solid residue remaining can clog the tubing and the valves permanently. Therefore, it is necessary for the delivery system to not only be maintainable when it is in constant use, but it also must tolerate periods of disuse without complaint.

It is also desirable for the loading and unloading of odorants not to be a messy procedure. Early versions of the system could drip when odorant cartridges were inserted or removed. The current system does not have this problem.

III.D. Previous Designs

The final design was preceded by a considerable number of experiments and by several complete systems. Passive evaporation, heat-forced evaporation, electrostatically induced evaporation, micro encapsulation, odor impregnated polymers, micro venturi mixing, oscillating tubes to create droplets, ink jet print heads, and three different piezo-induced vaporization techniques were all tested. Since these approaches were described in earlier reports they do not need to be detailed here. Only the testing of the previous system which was accomplished in the final year and the earlier attempts to use piezo-induced vaporization will be elaborated upon further.

III.D.1. Micro Venturi System

The most recent complete system was also capable of wearable and wireless operation. It also provided the rapid response and ability to control the concentration needed for virtual reality experiences. Tiny amounts of liquid odorant were released into a micro venturi chamber where they were subjected to maximal turbulence and therefore maximal mixing with the air stream that was flowing through the chamber. The liquid was released through a tiny jet into the outlet of the venturi where it starts to widen. Six jets each delivering a different odorant were spaced around the outlets of each of two venturis to provide 12 odors total. [Photo 2]

The odorants were stored in syringes whose plungers had been removed and a pressurized air system substituted. The needle of each syringe was inserted into a tube which ran through a valve which controlled the flow of odorant into the venturi chamber. Using air pressure to force the odorants through the valves worked better than previous methods that had used mechanical action. While the previous techniques had worked, it was difficult to assure that the movement was uniformly smooth. Instead, the mechanism would occasionally stick slightly before continuing to move.

III.D.1.a. Venturi Operation

This system worked well for periods of time, but occasionally incomplete evaporation was observed when the venturi was overloaded, and there was a tendency for the odor vapor to condense downstream from the venturi. In addition, there was a tendency for the valves to clog from particles in the odorants or from residue from odorants that evaporated when the system was not in use. While the clogging was not the fault of the venturi design, it did necessitate a redesign of the rest of the system and the whole venturi approach was a casualty of that process.

The venturi system was quite tolerant of the changes in orientation that occurred during normal walking and stooping behavior as might be expected of a medic leaning over a battlefield casualty. However, a catastrophic problem was observed one day when it was laid on its side instead of on its base on the bench after use. In spite of the pressurized air being applied to the odor reservoirs, the liquid odorant was able to flow out of the reservoirs and back into the tubing towards the pumps that were generating the pressure. While the pumps were not damaged and the problem could be avoided by being more careful to keep the device properly oriented, the potential consequences of a mistake were sufficiently severe that the reservoirs had to be redesigned.

III.D.1.b. Clogging

The most severe problem was the clogging of the tubing and valves that could occur when a microscopic particle would become lodged in a valve requiring it to be replaced. Related to that was the tendency of the original valves to be corroded by some of the odorant chemicals. The latter problem was addressed by switching to valves with a Viton coating which were more expensive ($150) than the ones we had been using ($100).

The clogging problem was more difficult. We built an automatic flushing system which cleared the odorants from the valves by running alcohol through them after use. However, this system also used valves and there was always some odorant remaining between the fork through which the flushing material was inserted and the odor reservoirs. This material could dry up and clog the tubing if not the valves. It was finally decided to give up on automatic cleaning and instead to prevent clogging by more careful handling of the odorant materials both in and out of the system, and by completely flushing the system manually after every use. The fact that this procedure violates the ease of use requirement is not lost on the PI, but preventing the destruction of the valves was more important.

Prevention was accomplished by passing the odorants through a 2 micron filter during the loading of the reservoirs. In addition, a 10 micron filter was placed in the odorant stream before each valve. Without prefiltering through the 2 micron filter, the 10 micron filter became clogged.

Flushing was accomplished by disconnecting the odorant reservoirs and running alcohol through the system and then running air through it. This was done for each odor channel in turn. The entire procedure took only a few minutes, but would be likely to be considered a hassle by end users.

III.D.2. Piezo-Induced Vaporization

There were enough problems with the micro venturi chambers that we revisited the fundamental issue of how to transform the liquid odorant into a vapor.

III.D.2.a. Piezo Crystal

One approach that had been considered repeatedly was the use of a piezo crystal to mechanically rupture the liquid to create droplets so small that they could be considered a vapor or would evaporate as they passed through the tubing to the nose.

The initial experiments were conducted by Dr. Thomas Avedisian in the Mechanical Engineering department at Cornell. By applying a 10 Khz signal to a crystal with a drop of liquid deposited on it, he succeeded in producing droplets, but they were too large and flew off in all directions wetting everything in sight.

III.D.2.b. Piezo Film

Next, Dr. Martin Fox in the Electrical Engineering department at the University of Connecticut tested a piezo film with a 10 Khz signal. The droplets it generated were nearly invisible. The result was a faint but detectable odor that was not strong enough for our purposes. It was not clear how to apply the liquid odorant to the film. It appeared that it would be necessary to release odorant droplets onto the film. That technique would not be orientation independent because the droplets would not fall in the correct direction if the device was tilted. Moreover, the machinery required to release the droplets seemed to be as difficult as the vaporization problem.

For that reason, the venturi approach seemed attractive because no droplet formation was required and such a device would work in any orientation. (It was the reservoirs not the venturi that eventually caused problems in extreme orientations.) Initially, the piezo film seemed to offer the possibility of fabricating a number of different mechanical components out of the same material, but after initially expressing great interest, the manufacturer failed to deliver any manufacturing information beyond that included in the kit they sold us. We considered trying to wick the odorant onto the piezo film by capillary action by having second film a slight distance from it. The vibration of the film would then cause some of the material to vaporize and more liquid would fill the space it had occupied. Such wicking is used in some ink jet printers which are connected to the ink cartridges by a fine sponge. However, unless we could assure that no odorant evaporated while the piezo was not vibrating, we would need valves to prevent the vapor from escaping into the air stream. Those valves added a level of complexity and cost that appeared to nullify the advantages of the approach.

III.D.2.c. Piezo Sprayer

A third ultrasonic technique was a spray nozzle that could be used for applying paint or insecticides. In this case, a pair of piezo crystals surrounded a metal tube which was the vibrating element. The system operated at 100 Khz and generated enormous amounts of vapor. Given the exotic materials used to create this device, we did not know how well it would scale down and how to go about designing a low capacity version.

III.E. Final Approach

The final approach was to appropriate the piezo crystal from a nebulizer, which is device that sits at the bottom of a volume of water and generates water vapor at a prodigious rate. This crystal operates at 1.2 Mhz. Its principles of operation are outlined in Figure 1: Functional Flow Diagram at the end of the report.

III.E.1. Cooling the Crystal

Since it is submerged in water during its intended operation, it is cooled by the water itself. When we tested it with odorant material, it was quite successful. It vaporized the liquid rapidly and completely. But there were two problems. First, without the water to cool it, the crystal overheated and failed. Second, some of the odorant materials reacted with the crystal, discoloring it and leaving us to ponder the lethality of the newly created mystery materials.

The overheating was solved by considering the crystal as part of the larger system. The vaporized odorant wad mixed with the 5 liter per minute air stream generated by a pump or released from an air bottle that forced the odorized air through the tubing to the nose. Running this air stream over the crystal cooled it. On the bench, the crystal had failed because there was no forced air running across it. Using the air stream for cooling was initially resisted because we thought it might interfere with the operation of the crystal or it might blow unevaporated liquid down the tube, but once we overcame that prejudice it worked well.

III.E.2. Coating the Crystal

The second problem was the reaction of the crystal with some of the odorant materials. We experimented with a number of techniques including coating the crystal with Teflon. Initial coatings were too thick and damped the oscillation of the crystal. After some experimentation, we were able to determine a thickness that would protect the crystal while still allowing it to work.

III.E.3. Orientation Tolerant Vaporization

The remaining problem was presenting the liquid odorant to the crystal in a way that would work in a wide range of orientations. As pointed out earlier, droplets will not always fall onto the crystal if the apparatus has been tilted away from vertical. Another problem is that unless they are forced out of a small aperture at very high pressure, droplets will not fall from the orifice until they reach a critical mass sufficient to overcome the surface tension and viscosity of the material as they relate to the size and geometry of the orifice. If a droplet forms that is not of sufficient weight to break loose and the apparatus rotates, the liquid will flow around the orifice, perhaps falling or dripping in the wrong direction.

The solution to this problem was to use the viscosity and surface tension of the liquid odorant to our advantage. The tendency of a partial droplet to form at the end of the tubing was such that it would bulge out from the end of the tubing little by little and until it reached a critical mass it was held in place protruding from the tube without any tendency to be shifted out of that orientation by tilting of the apparatus. Rather than forcing a complete droplet out of the orifice to fall onto the crystal by gravity, the bulging of the partial droplet was allowed to expand until it bridged the tiny gap between the orifice and the crystal. When the bulge made contact with the crystal, the material touching the crystal was vaporized instantaneously.

By this means a partial droplet much smaller that what would be required to break loose by gravity can be delivered over a wide range of orientations. It is conceivable that the bulge would flow down the outside of the tube if the device is completely inverted, but participants are not expected to do hand stands or other gymnastics in virtual reality.

III.E.4. Orientation Tolerant Reservoirs

As mentioned earlier, the potential consequences of laying the delivery device down incorrectly when it was not in use were so great that, even though the worst never happened, we felt that that hazard should be diminished. In addition, the usefulness of the device would be increased if the range of operating orientations could be increased. Finally, the fact that there was a change in shape and dimension from the reservoir to the tubing meant that it was possible for the air to get past some of the odorant, thereby stranding it.

The solution we chose was to use the tubing itself as the reservoir. When the liquid is in the tubing with no air pressure being applied, it stays in place by capillary action or by surface tension regardless of how the orientation is changed. In addition, since the tubing used as reservoir and the tubing used as a conduit look the same to the liquid odorant, its behavior is the same throughout the system. As before, pressurized air is applied to each reservoir and when the valve in the corresponding channel opens, the liquid is propelled through the tubing onto the piezo crystal which vaporizes it.

III.E.5. Delivery System Elements

Now that the requirements have been discussed and the principles of operation of the final device have been detailed, we can run through the device itself and the procedures for operating it.

III.E.6. Functional

The device delivers from 1 to 10 odors with a 10 millisecond data transmission time, a 1 millisecond electromechanical response time, and a 40 millisecond air transport time to the nose. It provides control of concentration over a 100:1 range. It provides up to 600 seconds of continuous odor delivery. However, since people quickly habituate to odors and no longer smell them after a few seconds, it is possible and preferable from a safety point of view to turn off an odor which is supposed to be present but is no longer perceived without the participant noticing its withdrawal. Therefore, the 600 seconds is more than sufficient to support a 1/2 hour to 1 hour experience.

III.E.7. Physical

The device is contained in a clear plastic cylinder 6.5 inches in diameter and 11 inches high weighing 7.5 pounds. [Photo 1] The unit comprises the following components:

- a 7 liter per minute air pump for driving the main air stream through the tubing
- a 10 psi air pump for driving the liquid odorants through the 10 odor delivery channels
  - * alternatively, there can be a 17 pound air bottle with 1/2 hour of air strapped to the participant's thigh. It is silent and with
  - * two miniature regulators can replace both pumps and their batteries.
- three external 12 volt batteries worn on a belt (for weight distribution)

which provide 36 volts for running the piezo as well as power to non odor delivery devices such as the HMD and the tracking target. These weigh 6 pounds.

- one surface-mount printed-circuit board with the following subsystems
  *RF transceiver
  *RF address decoding and error checking
  *RF antenna for receiving from and transmitting to the host PC
  *a 40 Mhz 8051 micro controller with the following software:
    -wireless packet control software
    -10 channels of pulse width modulation for the valves
    -cleaning procedure software
    -wireless status software for reporting back to the PC
  * a high voltage piezo drive circuit
  * 10 channels of valve control electronics
  * an air reservoir pressure sensor
  * an air reservoir inlet valve
- 10 each 2 cc odorant reservoirs
- an air manifold for distributing the air pressure to the 10 reservoirs
- 10 odorant channels terminating a small distance from the piezo crystal
- a 1.2 Mhz piezo crystal for vaporizing the odorant
- a tube for delivering the odorized air to the nose
- an external PC controls the device and communicates with it through a serial port and a wireless transceiver. high speed ethernet link. The simulation machine could directly control the delivery system, but it is best not give too many real time functions to the same computer. Currently, the delivery system is running under Windows, the tracking under LINUX, and the graphics under IRIX. None of these operating systems are ideal or good or even acceptable for this kind of function. The ideal would be to strip LINUX of functionality to the point where it had an old fashioned Load-and-Go capability so that there was no runtime operating system at all, just the application code. This way the developer could work with hard timing of the kind that you have with hardware, not the probabilistic timing so beloved of academics that is foisted on developers by priority interrupt systems. The PI's own systems have always worked been based on hard timing but it is harder and harder to get past the operating systems that are bundled with computers to look at what it takes to drive the underlying hardware and to write the software to do it. LINUX at least provides the source code.

III.E.8. Flow Through the Odorant System

The pressurized air from the reservoir pump is distributed to each of the reservoirs through the air manifold at the top of the delivery system. Each reservoir is a 2" cylinder with 20 inches of 1/8" ID tubing coiled inside of it and plugs into the manifold from below. Special fittings connect the reservoir to the manifold and prevent odorant from dripping from either the reservoir or the manifold when the former is unplugged from the latter. When pressure is applied to the reservoir, the liquid odorant is driven from the reservoir up through the connecting fitting in the manifold and from there through a 10 micron filter that protects the miniature valves from any particles that may have gotten into the odorant. The filtered odorant is forced against the valve input at 10 psi. When the valve opens for as little as a millisecond, a tiny amount of odorant is forced through rigid tubing that is positioned so that its end is a tiny distance from the piezo crystal.

The manifold is round and the reservoirs are evenly spaced around it. The valves are also arranged in a ring and the rigid tubing ends in a circle of orifices that are spaced around the circular piezo crystal. It is the shape of the crystal that dictates the shape for the rest of the system.

The 5 liter per minute air flow is blowing continuously over the Teflon coated crystal simultaneously keeping it cool and removing the odorant vapor to be delivered to the nose. 5 liters per minute is also the amount of air required for sedentary human breathing if the system provides all of the air the participant is breathing. However, since additional ambient air is breathed along with the odorized air, there is enough air to support the exertion of walking as opposed to sitting.

III.E.9. Control

Control is currently assumed to originate from the host processor which keeps track of the participant's current location, the participant's current action, and the location and of odors and potential odor sources in the simulated environment. The host computer then directs the PC to command the delivery device to release the appropriate odor when the participant is near the virtual odor source.

Actually, several steps are being glossed over here. The host machine sends a high speed ethernet message directing the PC. The PC in turn directs its RF software to transmit a command to the delivery device. The RF software builds a packet that is sent three times at 50 Khz. This packet contains an address of the the receiver to keep it from responding to spurious transmissions at the same frequency. The packet is sent three times so that successive messages can be compared to see if what has been received is indeed a valid message. Once the packets have been built, they are sent through the serial interface through the RF transmitter to the receiver on the delivery device.

The delivery device has its own microcontroller which is running the packet decoding software which decides if the received packet is indeed a valid message. If it is, the microcontroller interprets it to see which valves are being addressed. It then determines the duty cycle of the pulse width modulation that has been specified to control the concentration of the odor. This is specified in terms of milliseconds on versus milliseconds off. Then, the number of on/off cycles before the odor burst is terminated is specified. Since the length of period can be any number of milliseconds and the ratio of on time to off time is completely programmable within that, there are many more possible intensities beyond the 100:1 range that the requirement specified.

There is additional software in the microcontroller to report the status of the delivery device back to the PC. This is not done on a regular basis because it was discovered that transmission was unreliable when both the transmitter and receiver were turned on. In fact, it was necessary for the microcontroller to turn off the receiver and to wait a noticeable amount of time for the transmitter to power up before a return packet could be sent reliably. After much experimentation and frustration, the normal ack/nack handshake that might be expected to accompany such a communication was abandoned during runtime operation because it was far too slow for real-time interactive performance. Besides, there was not much the system could do if a particular packet was missed and an odor was not displayed on time. Elaborate error recovery routines could not repair the past and might jeopardize the future. So, elaborate error handling was abandoned in favor of status lights indicating valves being activated and relying on the user to report that the odors do not seem to be working. If a problem is suspected, the system can be sent packets which put it into checkout mode during which it does report what it is doing back to the PC at the slower rate at which the RF system can handle bidirectional communication. Or, the RF link can be bypassed by a direct electrical connection for testing.

III.E.10. Odorant Loading

In the requirements, the ability to easily load and reload multiple odors in a single effortless action was cited as a desirable feature. That has not been achieved. However, it is easy to plug an individual reservoir into the delivery device or to unplug it. There are two connectors at the top of the reservoir. One plugs into the air manifold and the other plugs into the odorant delivery channel. The user pushes the connectors on the top of the reservoir into the fittings on the manifold and the job is done in a second. The process is no longer accompanied by dripping odorant as it once was, which would leave the investigators with powerful odors on their hands that might take days to wear off. However, there is no mechanism for simultaneously loading multiple odors and loading the reservoirs themselves is a somewhat cumbersome process.

To load a reservoir, one loads a syringe with 2 cc's of the liquid odorant from the container in which it is stored. Then, the syringe is fitted into the end of a tube which constitutes one end of a fixture that has been created for this purpose. The tube carries the odorant through a 2 micron filter and then through some more tubing which terminates in a fitting that mates with the input of the reservoir. Hand pressure on the syringe forces the 2 cc's of material into the tubing which is used in the reservoir. Then, the loading fixture is disconnected and the reservoir is either inserted into the delivery device or plastic caps are placed over its inlet and outlet fittings to prevent contamination during storage. Then, the loading fixture is flushed and back flushed with pure grain alcohol. This prefiltering of the odorants with a 2 micron filter prevents the 10 micron in-line filters in the delivery device from becoming clogged through extended use. When 2 micron filters were used in the delivery device, they quickly became clogged and slowed down the odor delivery.

III.E.11. Flaws in Final Design

There were several flaws in the final delivery system. They have not been observed to cause a problem with its operation but nevertheless raised concerns. Some of these have been addressed and others will await the next generation of design.

III.E.11.a. Bubbles in the Reservoirs

First, using pressurized air to drive the odorant from the reservoirs through the valves and onto the piezo crystal assumed that the air was unable to get past the odorant. If perfectly continuous pressure were maintained on the odorant that would probably be what happened. However, when the unit turned on, there was an abrupt increase in pressure as the pump brought the pressure on the odorant reservoirs up to 10 psi. Then, during normal operation, that air pressure was monitored by a sensor which tripped whenever the pressure dropped below 9.5 psi causing the the pump to turn on until the pressure was back at 10 psi. During the time that the pressure was declining from 10 psi to 9.5 psi, the odorant could move backwards in the tubing. Whenever the pump turned on, there was a very abrupt increase in pressure resulting in mixing of the air and liquid, which forced air bubbles into the odorant in the reservoir tubing.

Fortunately, the air bubbles did not impair the functioning of the system. When they reached the valves, the pressure was so high that they were driven through almost instantaneously. So, while there was probably some delay in the onset of an odor when a bubble is in the odorant line, it was not noticeable to the user. Nevertheless, we were offended by this and sought to eliminate abrupt changes in the pressure both during startup and during normal operation of the feedback loop. Now when the device is powered up, the pressure builds gradually. And when the device is turned off, the pressure bleeds off gradually. During normal operation, we have set the sensor to detect a .1 psi drop in pressure so that the pump turns on when the pressure falls to 9.9 psi. Because the correction that needs to be made is less dramatic, far fewer much smaller bubbles appear in the odorant lines.

The negative consequence of this strategy is that the pump is turned on more often using more power. Minimizing power use was the reason for the larger acceptable range of pressure in the first place. Using proportional valves instead of solenoid valves would probably allow the pressure to be controlled more smoothly but would result in even greater power use. In general, higher speed pressure regulators with much finer control and faster response times than those we found on the market would be desirable. A MEMS device with many parallel valves possibly of logarithmically related diameters would be ideal for this purpose.

III.E.11.b. Stranded Odorant

Another issue was that the check valves that prevented odorant from dripping out of the delivery tubing in the manifold had an unexpected side effect. Something about the internal geometry of the check valves permitted the air to get past some of the odorant, stranding it there. Thus, while most of the odorant was available for display, a small amount was not. This was only noticed during the flushing procedure. After the delivery tubing was flushed with pure alcohol and then with air, a small amount of liquid flowed out of the check valve when the pressure was removed, indicating that this liquid was not blown out of the system through the valve.

III.E.11.c. Priming Material

Related to this issue is the fact that the amount of odorant required to prime the delivery channel is a noticeable fraction of the total reservoir. (The delivery channel consists of the check valve, the tubing to the 10 micron filter and its fittings, and the flexible tubing that leads to the rigid tubing, and the rigid tubing itself.) This fact is not a problem if the odorant is all consumed in a single use. The problem arises if only a small fraction of the odorant that was originally loaded into the reservoir was needed in a particular session. When the reservoir is removed for storage, a non-trivial amount of material is still left in the delivery channel from which it will be flushed to keep it from drying out and clogging the valves. This material is wasted. The length of the delivery channel is equivalent to 4 inches of tubing which is 20% of the length of the tubing in the reservoir.

For a material that is used only infrequently in any single session, over a number of sessions most of it will be flushed out of the system rather than being used for odor display. During current laboratory operation with easily acquired odorant materials, wasting some of the odorant is not much of a problem. However if custom odors are created, they may include very expensive raw materials as well as being the result of a very expensive synthesis process. In this case, wasting a significant fraction of the material would be unacceptable. To some extent, further miniaturization involving the machining or micro-machining of custom valves and fittings will reduce the lengths and diameters of all channels cutting down on the amount of stranded material. In addition, it would help if the valves could be flushed without removing the odorant from the system. In general, minimizing lost material is a future design requirement.

III.E.11.d. Cannibalized Components

Another issue that does not affect the operation of the system is that the piezo crystal was taken from a commercially available nebulizer. Its manufacturer buys the crystal and drive circuit module from Japan and has been unable to get specifications on the crystal itself, a schematic of the circuit, or sources for the analog components in the drive circuit. Since the nebulizer costs only $15 assembled and finding out further information seemed impossible, it was necessary to cannibalize the components from the nebulizer circuit and to place them in the drive circuit on the PC board in the delivery device. While this procedure is inelegant and labor intensive, it is almost certainly cheaper to take advantage of the costs of a mass produced device than to reverse engineer the circuit and to try to find equivalent components which would have to be purchased in small quantities.

III.E.12. Delivery System Summary

The final delivery system can be used in the three major virtual reality formats: desktop, CAVE, and HMD. It is portable, wearable, and wireless. it can display one or more of ten odors with a 50 millisecond lag time which is fast enough for most immersive training applications.

III.F. Delivery System Deliverable

The system described above is the deliverable for the project. The device with its own documentation is being sent separately to the contracting authority. That documentation comprises:

- mechanical design
- electronic design
- micro controller software
- PC odor control and RF packet software
- operating procedures

IV. Wireless Operation

The second major area of effort was in tracking the participant's head movements in an immersive virtual environment.

This effort is premised on the belief that odor display and indeed visual and auditory display in virtual environments would be most effective if these virtual sensations were encountered exactly as they would be in the real world. The naturalness standard implies unencumbered behavior with complete freedom of movement. Current virtual reality technology offers tethered movement to a significantly encumbered participant wearing an HMD or complete visual immersion to a stationary and much less encumbered participant in a CAVE. So far, at least 65 $1M CAVEs have been built which is almost certainly more than the number of $1M HMD-based immersive virtual reality systems. This might indicate that the CAVE is superior to the HMD, but the comparison is not fair because most HMD systems forego the greatest advantage that their approach has to offer, namely the ability to walk around in the virtual world thereby making use of the lifetime investment we all have made in interpreting the world in terms of the height of our eyes above the ground and the length of our stride. Tethered operation does not answer the need, because the most important object in the space—the wire—is invisible.

IV.A. Wireless Video and Olfactory Display

Therefore, completely wireless operation was seen as the most realistic way for olfactory stimuli to be encountered in immersive virtual reality scenarios. The odor delivery system described earlier is wireless. The virtual image is also transmitted wirelessly. This was not a matter of simply using commercial wireless units for transmitting a video signal from a stationary transmitter to a stationary receiver. These units are susceptible to multipath transmission problems which are caused by reflections of the signal from nearby objects leading to multiple copies of the signal arriving at the receiver slightly displaced in time. In a stationary setup, this problem can be dealt with by adjusting the receiving antenna. In immersive virtual reality where the person is wearing the antenna and is likely to be turning often, these systems lose synch constantly and often lose the signal completely. The solution is a diversity receiver which selects the best signal from multiple antennas.

IV.B. Wireless Tracking

The final component of a completely wireless system is wireless head tracking. There are two large-area tracking systems that have been described in the literature, the Hiball system at the University of North Carolina in which the participant wears 7 position-sensing diodes on his head and the Constellation™ system developed by InterSense Corporation which uses a combination of inertial and ultrasonic time-of-flight measurements. [Welch][Foxlin] Both of these systems require significant instrumentation of the environment: an array of LEDs in the the University of North Carolina case and a grid of ultrasonic transmitters in the InterSense system. Both of these systems are tethered. InterSense does point out the possibility of wearing a modem (suggested to them by the PI) to transmit information back to the computer to achieve wireless operation but doing so slows down the operation of the system because the data must be formed into packets and transmitted serially.

Whereas these two systems are inside out in the sense that the participant wears the sensors, the approach taken in this project has been outside in with the participant wearing a target which is detected by stationary sensors positioned around him in the environment. Such a system is inherently suitable to wireless operation because the sensors that determine the participants location are mounted in the environment where they can be connected to the computer.

IV.B.1. Overhead Tracking Approach

Early in the program, a wireless head tracking system was developed based on 8 ceiling-mounted video cameras positioned along a 40 foot path. This system did provide 1/30 second x-y position and gaze direction (yaw) determination. Pitch and roll had to be averaged over several sample periods to provide stable values. If that system were reimplemented today with the fast framing cameras that are now available, it would easily be fast enough and accurate enough to compete with other systems. In fact, the sensors that we are using in the final approach would provide very high speed data and twice the accuracy of the original system. Recently introduced sensors would combine very high speed with four times the resolution of the original system.

However, the original approach had several disadvantages. First, a 16 foot ceiling was required to allow the cameras to cover a sufficient area. This requirement would prevent the technique from being used in many laboratory settings. Second, the cellular approach required the installation of a large number of cameras (64) to cover the desired 40'x40' area. While the cost of the components would be significant, the cost of the installation itself might be more so. Any system requiring a significant installation is likely to face significant resistance. On the other hand, this system did have the advantage that it could handle multiple participants. The University of North Carolina system which involves dynamic patterns in the ceiling LEDs might run into conflicts if multiple people were present. The InterSense system would seem to have even more trouble with multiple participants because multiplexing the ultrasonic channel would slow the system down further.

IV.B.2. Virtual Camera Approach

While we felt that our original approach had basically solved the problem, we had a second idea that had a number of advantages over that approach as well as those mentioned above.

IV.B.2.a. Virtual Camera Specifications

This approach had an array of wonderful advantages:

- it would allow coverage of a 40 foot square area with sensors mounted in the corners of that space, so minimal installation would be required.
- it would provide very high speed operation—over 1000 samples per second. (10 thousand samples per second was possible.) The sensor circuit was built and operated at speed. The software algorithms were implemented and ran up to 30 thousands samples per second, so the hardware was the limiting factor.
- it would be very accurate—one millimeter accuracy throughout the working volume.
- it would work in a typical office space with an 8 foot ceiling.

The speed is important to the accuracy. All of the analyses of tracking systems discuss accuracy in terms of a stationary target. None consider the fact that the target is moving. A walking person is moving about 2 millimeters per millisecond on the average. The instantaneous rate of movement may be considerably higher. If the tracking technique depends on sequential querying of multiple sensors, then the person may have moved enough between samples from the different sensors that the values from the respective sensors do not constitute an instantaneous sample in any sense at all. By speeding the sample rate, this source of error is minimized. In addition, a high sample rate permits successive samples to be averaged if there is any instability in the data. Finally, the faster the sampling, the more time is available for computing the system's reaction to the participant's behavior and generating the graphic, auditory, and olfactory responses.

This approach involved creating a virtual camera with 6000x6000 pixels to be positioned in each corner of the room. This feat was accomplished by using two line sensors—one for the horizontal coordinate and the other for the vertical. The 6K resolution of the line scan sensors explains the resolution of the approach.

IV.B.2.b. Virtual Camera Optics

The trick is to map the rectangular image produced by normal camera optics onto each line scan sensor in a way that preserves the coordinate information in the dimension of the line while collapsing all of the information in the other coordinate onto a single pixel. An optical system based on cylindrical lenses was used for this purpose. For this system to cover a square area from the corners, it was necessary to have the equivalent of a wide-angle lens in front of the rectangular to linear conversion system.

IV.B.2.b.i. Anamorphic Optics

In addition, it was noted that while the person's head could be located within a 90° field of view horizontally, it would be confined to a 30° field of view vertically. The result would be that two thirds of the resolution of the line scan sensor would be outside of this range in a conventional optical system. Optical systems which have an asymmetric field of view are termed *anamorphic*. There was no mention in the literature of anamorphic fish-eye lenses. Further complicating the design was the fact that both the line scan sensors and the brightest LEDs operate in the infrared part of the spectrum which meant that conventional optics could not have been used even if we had been willing to settle for symmetric optics.

Dr. Jannick Rolland of the Center for Research and Education in Optics and Lasers (CREOL) at the University of Central Florida in Orlando developed a complete design for this optical system. Unfortunately, the cost of actually fabricating these custom lenses turned out to be $320K for the eight optical systems, to which we would need to add the cost of the optical assembly and the printed circuit boards for the line scan sensors which had only been prototyped at that point. In addition, the optical assembly was very large—almost 2 meters in length. The cost was deemed too high and the size seemed to be quite unwieldy. Therefore, considerable effort was expended in the last year to find design compromises that would lower the cost and decrease the size.

IV.B.2.b.ii. Optical Alternatives

One of the expensive aspects of the design was the fact that the line scan sensor had 10 micron pixels and was therefore 60 mm long. The large size of the sensor necessitated very large lenses in the front end of the fish eye. Therefore, we looked at using a 4K sensor from a different vendor with 7 micron pixels and therefore only 28 mm length.

We also abandoned the anamorphic approach and decided to live with the loss of vertical resolution. To accommodate the reduced resolution, we reduced the working volume to 20 feet square. Since the new sensor was sensitive in the visible rather than the IR region, we could also use a conventional fish eye lens design. Indeed, we could use an off-the-shelf consumer product if we could get the complete optical characterization of the device from the manufacturer. Unfortunately, none of the lens manufacturers were willing to provide this information which forced us into designing a custom fish eye that would work with the second stage of the system. The cost of the resulting system was $80K for the optics rather than the $40K that might otherwise have been achieved.

IV.B.2.b.iii. Non Optical Alternatives

We then looked at a variety of ways of performing the rectangular-to-linear conversion of the second stage of the system by non-traditional means. The PI tried getting a number of firms to fabricate a two-dimensional version of fiber optics in which planar elements would be laminated together separated by optical cladding and shaped so as to reflect light entering from a thin rectangular cross section at one end to a point on the line scan sensor at the other.

He worked with several sensor manufacturers to get them to fabricate a device in which all of the pixels in each column were joined to create a single elongated sensor. While such a device would contain much more silicon, it would eliminate the half of the optics dedicated to the function of collapsing a rectangular image onto a linear sensor to get the horizontal or vertical coordinate of the currently illuminated LED on the tracking target.

Dr. Rolland developed a theoretical technique using a retroreflective screen as an element in an assembly that would perform the desired transformation. When off-the-shelf screens were found not to be precise enough, 3M was convinced to create special retroreflective screens whose performance was closer to ideal. Unfortunately, these materials were still not good enough to make the design work in a practical sense.

Another approach was to use an even smaller 2K sensor and to steer its field of view by means of a mirror mounted on the shaft of a stepper motor. This approach would apply the reduced resolution over a much smaller field of view to provide even greater resolution. Since the person could move out of this narrow field of view, it would be necessary to move the mirror to keep him in view. While it would be possible to make measurements while the mirror was being steered, it would be more prudent for the system to dynamically decide which pair of cameras had the best view of the participant and to direct the remaining pair to make the mechanical adjustments needed to improve theirs.

IV.B.3. Fall Back System

While we were trying to salvage the line scan approach, we were looking at a fall back position based on a new kind of sensor that had recently become available. One of the frustrations of image processing has always been that one is a prisoner of the raster scan, forced to read out the entire image even when only interested in a small fraction of it. There have always been analog video cameras with steerable scanning, but they were too expensive for experimental use. However, the recent advent of CMOS sensors has finally made such a capability affordable. These devices permit the user to read out individual pixels randomly with horizontal sequences being faster than those that require a new line to be set. Given that single LEDs are being tracked and that these can only move a small distance from one sample to the next, it is only necessary to scan the window of possible locations rather than the entire image. Thus, we can track a 3 or 4 LED target at around 1000 samples per second. It should be noted that this speed can be maintained only if the target has been initially captured and is not lost during operation. If it is, the participant may be asked to hold still for a second while the sensors scan the entire space looking for the target.

IV.B.3.a. Cameras

The cameras we purchased were only 512x512 resolution but the vendor listed a 2Kx2K device based on the same principles of operation that they said was available. Our thought was to use the inexpensive device for proving the concept and then to substitute the higher resolution device once we were convinced that the approach would work. With the first device, we felt that we could cover a 10 foot square CAVE-like area with better speed and resolution that the tracking system currently used in the CAVE which has a very noticeable lag.

Proving the concept turned out to be difficult not because of the problem but because of the state of the products with which we had to solve it. What had been presented as off-the-shelf products over time revealed themselves to be evaluation boards with many unnecessary quirks that could have been eliminated with little effort by the vendor. For instance, the lenses were mounted slightly off center and at a slight angle to the camera board. When screwed all the way into the lens holder, the lens was out of focus. It was necessary to stop somewhat short of the end of the threads. Each camera was different from the others necessitating a characterization process and correction algorithm unique to each one.

In addition, the drivers on the camera boards would work with only 3 feet of cable which was enough for us to test with a pair of cameras hooked up to one computer but which prevented us from arranging four cameras in the corners of the space as required by the design. Plus, for some reason the cameras came with only two device addresses which meant that more could not be interfaced to a single computer. The fact that we only had two PCI slots in our PC also forced to look at more than one computer.

IV.B.3.b. Software

The software also presented problems. The software that was sold with the cameras was written in GNU C and was not designed to run on Microsoft systems. Not all of the code could be accessed. However, we were able to get it running under DOS which was acceptable because it is faster than Windows for low-level real-time work. It was necessary to get 32 bit DOS Extender software to handle the large arrays that were needed by the camera test software and the desire to create diagnostic graphic software.

Only when we added the third and fourth cameras, requiring additional PCs to control them, did we discover that there was no ethernet software with sockets available on the market that would run under DOS operating in this mode. Rather than trying to convert code that was not designed to operate under WIndows™ to run under that regime, we decided to move the system to LINUX. There were several reasons for this. Whereas Windows™ is basically unknowable except through long experience, LINUX is theoretically transparent since its source code is available. Also, we have over 20 years of experience working with UNIX systems. Finally, it is likely that a real-time version of LINUX will be developed which strips away all the overhead of being ready to handle every possible option that any of 100 million users in the world might want at any given moment. What is desirable is an old-fashioned Load-and-Go operating system which provides services during the programming process but which disappears when the real-time application takes over the machine and only uses those operating system functions that the application requires.

IV.B.3.c. Multiprocessing

Given the problem of installing more than two cameras in a single computer and the 3 foot limitation on the cabling, we resolved to dedicate a PC to controlling each camera, to correcting for the idiosyncrasies of each camera and for the distortions of the wide angle lenses, and to computing the rays along which the target LEDs were found. A fifth computer then integrates the information from the four cameras to determine the location and orientation of the target in three dimensions. This machine also controls the smart target. A sixth computer displays diagnostic information in graphic form.

Having been forced into a multiprocessor system and into learning LINUX has taken an unexpected investment in time but has the advantage in that it is a competent system and will not be subject to the capricious upgrades that jeopardize every effort done on PC operating systems. On the other hand, we have still not found any way to initialize the cameras under LINUX so the system is brought up under DOS first.

The major hurdle to implementing this computer-as-a-component system was getting the ethernet to operate in the consistent way that we needed for our real time application. Under its default settings, the ethernet is treated like a resource to be utilized. The goal is maximum total traffic, not rapid response. Messages sent one moment are not guaranteed to be received at the destination the next. Instead, they may be queued for some time on the originating computer before they are sent or may not be reported to the application that is to use the data the moment they are received.

This default is not consistent with the needs of a real-time application operating across an ethernet that it dedicated to it. In this case, what is required is consistent behavior characterized by instantaneous response. The lower levels of the ethernet protocols contain mechanisms for enabling such communications. Messages are not sent from computer to computer so much as from part of a process running on one computer to another part of that process running on another. The sockets that enable such communication also speed up the transmission by eliminating much of the overhead that is unnecessary in such a dedicated network.

The resulting communication over a 100 MB ethernet line is fast enough not to represent a bottleneck in the tracking application, and the entire process of camera handling, interprocessor communication, and data integration takes place faster than 500 times a second.

IV.B.3.d. Status

The current status is that this third wireless tracking system does control the tracking of head-worn LED targets by four cameras and integrates the results to produce 3D coordinates and orientations. It does so 500 times a second and produces stable output values. However, it currently handles only benign orientations. The hand off from pairs of cameras to select the pair with the best view of the target has not been done nor has the smart target function been implemented. Nor has head movement modelling been done. This is not necessary, but it would allow us to decrease the size of the windows that we are currently scanning and to increase the sample rate even further. Since the current sample rate is much faster than the graphic generation rate, this is not a priority.

IV.B.3.d.i. Smart Targets

Currently, the system operates with three or four targets facing opposite directions, each consisting of three LEDs. These targets are easily viewable from all directions as long as the head is tilted no more than 45° in any direction. Greater tilting can probably be tolerated, but possibly not in all locations in the environment. To accommodate a greater range of angles and positions, we will implement a smart targeting system. With this approach, a larger number of LEDs will be distributed around the head and the system will dynamically select a subset of them to create a target which can be easily viewed by at least one pair of cameras. With this technique the system will be able to handle the problems that arise when the LEDs on a fixed target would have to be viewed at very oblique angles. The detection of the LEDs is difficult at such angles and the possibility that two LEDs will line up merging into a single spot of light becomes real. The smart targets will permit the person's head to tilt much further from the vertical,. It will not permit them to lie down wherever they want facing in any direction. However, a medic should be able to bend over a casualty and an infantryman will be able to lie down in the center of the working volume.

IV.B.3.d.ii. Recapture of Lost Target

We have also not dealt with the issue of what to do when the tracking system loses lock on the target. Currently, the person stands still for a moment while the system finds him. In the small working volume the current system can handle, we do not expect that the user will outrun the system. However, it is possible that they will raise their hand or even both hands, momentarily occluding the targets from the view of any sensor pairs. In this case, the system will face the more daunting task of trying to find a person as they are moving around.

This requires searching a larger window which will slow the system down considerably. The brute force solution is to have every camera scan its entire field of view which can be accomplished at no more than 3 samples per second. While it might seem that capture would be guaranteed within 1/3 second, this is not so. At this glacial scanning rate, it is quite possible for a person to outrun the scan so they remain invisible for a considerably longer period of time. A perverse individual could thwart recapture indefinitely. A more likely scenario is that one of the cameras will detect at least one of the LEDs on the first scan. The location of that

LED in the scan will constrain where the person can be enough to shrink the search window on all cameras on the next scan. Each scan will improve the information so that by the end of a second or two, the system will be locked onto the participant. Since all of the cameras will see a given target at the same vertical elevation, they can each be given a vertical quadrant to search, cutting the capture time by a factor of four.

However, what is the graphics doing during this time and what is the participant doing? In the absence of up-to-date tracking information, the system can decide to use a predicted location for the graphics or it can simply freeze the graphics on the most recent correctly computed frame. When the participant experiences the loss of optical flow, he is unlikely to continue moving as if nothing has happened. Instead, he is likely to pause, possibly for enough time for the recapture to take place.

IV.B.3.d.iii. Accuracy

We have not measured the absolute accuracy of the system and are not as concerned about that as with the relative accuracy and monotonicity. At any moment, an HMD wearer thinks he is where his eyes tell him he is in the virtual world. It is not important where he actually is in the real environment unless he is about to bump into something in the real environment. What is most important is that the image does not jitter. Of next importance is that if he moves his head, the resulting changes in what he sees are the ones that he expects.

Absolute accuracy is most important in augmented reality system in which the user can compare virtual objects with physical objects and is quite offended by obvious discrepancies between their positions. The current system would provide such accuracy only in a small working volume as might be involved in an assembly task.

The original plan was to substitute 2Kx2K cameras for the 512x512 cameras as soon as the system was working properly with the lower resolution devices. With the high-resolution cameras, the tracking system would have provided satisfactory accuracy at high sample rates over a 20'x20' area. This would have been a large enough area to support many useful simulations of emergency medical scenarios for dismounted personnel. Unfortunately, the vendor removed the 2Kx2K devices from the market because it felt that they were not living up to the performance specifications that the company had claimed for them. Very fast framing 1Kx1K sensors are now available and offer another alternative.

V. Odor Representation

Representing the odors needed for virtual reality simulations turned out to be the greatest barrier to using odors in virtual reality training simulations, especially for medical training applications. While our initial collaborators at Monell Chemical Senses Center assured us that getting many of the odors we would need would be no problem, it turned out that getting any of the appropriate odors was a challenge. Of the odors that could be acquired, very few were dead-on duplicates for the real thing. Most of the medical odors that Monell was able to produce were completely unconvincing. This was also the case for the two odors that were provided by International Flavors and Fragrances Corporation. Only Monell's sweat smell could be judged as a complete success. However, that formulation was not developed under this project. Instead, it was the single result of a multiyear research project itself costing hundreds of thousands of dollars.

V.A. Fragrance Industry Practice

On the one hand, the odor duplication process is very sophisticated and on the other it seems very primitive. The world's 200 perfumers—each making $200K per year—are all associated with large corporations. Those who purport to be free lance agents need the facilities of the big firms to ply their trade. Access to those facilities requires a clear business opportunity representing tens of millions of dollars in sales in which the large firm expects to participate.

The facilities of a fragrance lab include elaborate analytical equipment supported by PhD chemists and laboratory technicians. The equipment typically includes a gas chromatograph connected to a mass spectrometer. The gas chromatograph separates the ingredients of a vapor sample and the mass spectrometer breaks its molecules into fragments which can be identified and from which the original complex molecules can be inferred. Since any naturally occurring odorous compound may contain hundreds of components many of which do not contribute to the odor at all, fragrance labs have what is called a sniffer port between the gas chromatograph and the mass spectrometer which the perfumer can use to smell the constituents that are output from the chromatograph to see if they are important to the overall odor.

However, the human nose is more sensitive to a wider range of odors than any instrument and there are likely to be components that are observed that cannot be detected or identified experimentally. In this case, the perfumer may be able to identify it by smell from the sniffer port and it may be possible to substitute a material with a similar scent. Since there are many different types of instruments each with different strengths and weaknesses, the PI is not sure whether it is simply the case that no single instrument has the sensitivity of the human nose or whether there odors for which no instrument can duplicate human performance.

On the one hand, duplicating real world smells is not a priority of the fragrance industry. On the other, analyzing and duplicating the smell of competitors' products is probably its primary activity. It resembles the fashion industry in the sense that new fragrance ideas appear in high-end perfumes which are then imitated at lower cost by competitors and are in turn imitated by other competitors in other categories until detergent manufacturers may be influenced to add aspects of the scent to their products.

V.B. State of Odor Synthesis

However, there are a number of biases operating in the fragrance industry which is in the business of pleasing people. Therefore, they have almost no interest in unpleasant odors. There are two exceptions. First, some unpleasant ingredients can contribute to a pleasant result when used in small quantities. Second, manufacturers of products designed to eliminate or at least mask unpleasant odors may develop synthetic versions of the unpleasant odor material they are working against. For example, corporations have developed analogs of sweat, baby vomit, human urine, cat urine, feces, etc. The PI has talked to individuals in the industry that have spent their entire careers imitating just one of those odors. However, these formulations are closely guarded trade secrets. They are not available for virtual reality research.

If you look at the odors that have been developed, there is an emphasis on fruits and flowers which by and large have pleasant odors. Vegetable smells are much less developed, although there are many ingredients described as herbaceous or grassy. It is likely that food flavorists work with these odors, but they create materials that are ingested not smelled through the air. The PI serves the Fragrance Foundation on the jury for the technological innovation of the year award. At the 1998 meeting, Takasago had several very good examples of smells for organically grown vegetables such as tomatoes and cucumbers.

Meats and therefore human tissues are much less studied. The fine fragrance industry would have no interest, but one would think that manufacturers of canned foods and frozen meals would. Many of the odors associated with medical procedures come from cleaners and antiseptics. Some of these such as alcohol can be used directly. Others have ingredients that have been added to give them a smell. For instance, anesthesia is sometimes given an odor even though it typically has no smell of its own.

Man-made materials and the odors associated with emergency medical scenarios have a number of additional problems. First, existing fragrance customers have no interest in such odors. Second, they are terrified of the ingredients and do not want the liability of handling them or of foisting them on the public. Third, odors such as gasoline, diesel fuel, and motor oil as well as their combustion products often include particles and droplets as well as vapors which adds a completely new issue to the problem of duplicating them. Some of these ingredients are changing chemically as they are being smelled and so would be impossible to duplicate with stable ingredients. Smoky smells exist for wood and meat but burning fuels and electrical insulation are not available. Explosives have not been touched.

Even if the complete analysis of every ingredient in a real world smell was possible with current instrumentation, a perfect simulation is often not possible. Some of the ingredients may never have been synthesized. Some may not be available commercially or may be too expensive. In no case is duplicating the hundreds or thousands of ingredients in a natural odor considered practical. Instead, it is a matter of identifying those which are most important in giving the odor its characteristic bouquet. In many cases of common odors like coffee, the imitation is a pale representation of the real thing.

V.C. Odor Experience

Compounding the problem is that we do not know very much about everyday odor experience. On the one hand, we know that humans are capable of extremely sophisticated discriminations and on the other we know very little about what people smell during the day and whether they notice it and if they do not are they nevertheless subconsciously affected by it. Only a few studies have been done in which people record what they smell. In at least one case, an alarm has been used to remind the subject to record what they were smelling at that moment. It seems that smelling is a little like dreaming. Everybody does it, but most people do not remember doing it most of the time.

This ignorance may imply that odors are not very important to 20th Century Man. Consciously, this may be true. On the other hand, there is evidence that subconscious perception of odors can have significant effects on our behavior. The most familiar example of this is the fact that women living together tend to synchronize their menstrual periods. In addition, one odor researcher who is also a marriage counselor reports that if one of the partners does not like the smell of the other, the union cannot be saved. Do such distastes operate among men who must work together in military units? Do differences in diet lead to differences in body odor that cause friction in multinational peace keeping forces? Are there other profound influences that remain to be discovered?

Similarly, we know that people have very great differences in their abilities to detect odors. Two orders of magnitude difference in sensitivity is common. In addition, specific anosmias—blindnesses to particular odors—are common. However, the only large population study that has been done was in the pages of National Geographic. We know that there are a thousand genes that code for the olfactory receptors and assume that there are as many different kinds of receptor cells.[Glausiusz] We further know that as many as 30% of them appear to be too damaged to function. We do not yet know what chemicals or chemical characteristics these genes code for. We do not know whether there is a universal set of 1000 or whether there is a much larger pool of which we each get no more than a thousand.

We also do not know how odors are encountered in the real world. All of our efforts to display odors are based on the certainly misguided assumption that odors occur in neat gradients emanating from their sources. It is almost certainly the case that odors are mixed non uniformly in the real world and that instead of a consistent odor intensity we experience rapidly changing sensations as we move in and out of odor plumes and are buffeted by complex air flows. Evidence for this would include the fact that one of the popular heroes of the olfactory world, the moth, cannot follow gradients as has long been assumed.[Taylor] Instead, moths fly into an odor plume and turn upwind. When they fly out of it, they reverse course and either fly back into it or they wander around randomly until they do. Placed in a carefully constructed gradient, they are lost. This behavior suggests not only that moths cannot follow gradients but also that gradients may not be an important aspect of odors in the real world. If they were, you would expect moths to follow them much as lobsters do in the sea.

Not only are we likely to encounter ever changing concentrations of any given odor, but since these odors have many different components each with different physical properties, the proportions of the ingredients that we associate with a given smell is likewise changing moment by moment. For sure, odors coming from any given source are likely to change through time as the more volatile components evaporate, as heavier components sink to the ground, and as bacteria act on what remains to produce new ingredients. Sweat certainly changes in this way. Thus, what we have been treating as single odors composed of fixed ratios of components are almost certainly more complex than that. We do not know how smelling interacts with physical behavior. (We do not even know how vision interacts with physical behavior.) We know nothing of these issues. No one does.

V.D. Past odor efforts

The original efforts at odor representation were undertaken by Monell. IFF also contributed a few candidate odors. A number of other fragrance firms were approached and a professional perfumer worked with us for a while hoping to get one of the big firms to support this part of our project. After considerable effort, we were unable to garner any interest from the industry. We also approached universities that might have some of the capabilities including the Flavors Laboratory at Cornell. To our surprise, they had little interest.

Therefore, we attempted to get the odorant chemicals for ourselves and to see if any of the raw chemicals could be made to serve our purposes. The chemical firms did not want to sell directly to us because we were not a chemistry laboratory and universities did not want to ask their students to handle the raw materials which are toxic in neat form which is how they are sold. After many attempts, we were able to get a local lab to purchase the chemicals and to dilute them down to a concentration that was safe to handle. This solution backfired when we discovered that the concentrations while seemingly correct for smelling in the bottle were too weak when displayed through our delivery device.

This convinced us of the need to make the dilutions with respect to the odor delivery system itself. Since the laboratory we were dealing with charged $175 per hour for its services, it was not practical to take the delivery device to their premises to work out the concentrations.

Instead, we found that we could get the chemical suppliers to ship us one or two chemicals at a time without complaint. We diluted these materials in a very well ventilated out building while wearing special clothing, gloves, and a mask. In this way, we were able to test approximately 50 chemicals with the delivery system.

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V.E. Odor Mixing

While only a few of these were ready for prime time by themselves, the process of readying them for use was worked out and we were able to begin what would be the next step, the use of the odor delivery system itself to mix together composite odors from individual chemicals. Given that most odors are complex mixtures of many ingredients and that in almost no cases are all of the ingredients represented in a simulated odor, mixtures of the 10 most prominent ingredients would be the practical limit in many cases. In cases, where the 10 most prominent ingredients are known, the delivery system could be used to vary the proportions of these under the control of a trained perfumer.

Why would professionals be interested in mixing chemicals with our delivery device when they have expressed no interest in coming up with the same formulations using their traditional techniques? The answer lies in the way that odor mixtures are formulated. The perfumer sits in a laboratory surrounded by 5000 odorant chemicals all in liquid form. From this inventory she has chosen a small subset of from 10 to 50 ingredients which she is planning to work with. Then, she adds one of the ingredients

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to a beaker, then another and so on. After observing this process for a few minutes, I was struck by the fact that the perfumer could not back up. If she had too much of one ingredient, it was almost impossible to reduce its contribution without tediously computing new amounts for each of the other ingredients. If she decided that the new ingredient did not work at all, she was out of luck. She had to start over.

While the perfumer typically starts with a good idea of the kind of scent she is looking to create, the process is laborious and costly because the ingredients that the perfumer works with are often expensive formulations in their own right.

It would seem infinitely easier not to work with liquids at all. Instead, one could mix vapors. If the vapors can be mixed in the proper proportions, the perfumer has no investment in those proportions. Only a tiny amount of material is involved at any moment. And the effort required to achieve those proportions is infinitesimal. Proportions can be changed in seconds. The experimentation with odor mixtures can be speeded up by orders of magnitude, saving money and more importantly time.

While the perfuming process is undoubtably much more complex than it was just described to be and the 10 odor delivery system that the PI has developed may not handle enough chemicals or offer sufficiently fine control, it is possible that the ability to speed up exploratory experimentation would change the fragrance development process itself.

For instance, consider the genetic algorithms developed by Karl Sims when he was at Thinking Machines.[Sims] He created insanely complex equations in two variables to assign color values to each pixel in a two-dimensional image. By randomly varying the coefficients of these equations, he produced four variations on the first image. The user selected the one that pleased him the most. Then, four variations on the new image were created and the process continued until the user was satisfied with the final image that resulted from repeated applications of the basic process. The interesting thing is that often a user with no artistic training or talent was able to produce a very pleasing image that he would have been incapable of generating with conventional artistic tools. Applying the same idea to fragrance development suggests that if the most salient

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components of a particular smell were loaded into the delivery system, a non-perfumer might be able to do as well as the professional. (Remember that the professionally produced materials were often not convincing.)

While we did not implement genetic algorithms for this purpose, we did try the idea with basic pine smells which are made up of three primary ingredients. We were able to acquire two of the three ingredients and to vary their proportions at will with the delivery system. While it is impossible to claim that we were producing perfect simulations of any given variety of pine tree, it is possible that we were and just did not know it. What we were doing was producing a variety of evergreen-like smells that could be used to provide texture to an outdoor scene which contained a variety of unidentifiable evergreen plants.
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V.F. Impressionistic Odors

This raises a question about odor display in general. Is the goal to perfectly represent the odors that are present in particular real world situations? Given that the state of our knowledge of our own odor experience and the fact that that the modern world almost never requires us to identify unknown odors or to correctly track natural odors to their sources, it is not unreasonable to ask whether the goal is to represent a particular reality that smells in a very exact way or whether it is simply to create a simulated world that smells believable, even though no real world smells exactly like it. Such an impressionistic approach to odor representation is probably necessary if we are to avoid the extreme expense of proceeding the way the fragrance industry traditionally does.

By extension, such an approach may be necessary if we are to represent the odors of hazardous materials. For instance while diesel fuel is a common smell, a number of its components including benzene are hazardous. When the EPA had an interest in determining the effects of exposure to the smell of diesel fuel as opposed to its hazardous ingredients, Dr. Amos Turk created a formulation which duplicated the qualities of diesel fuel without using those ingredients.[Turk] His mixture contained chemicals which stood for the perceived qualities of this material, i.e. burnt, oily, pungent, aldehydic. Although the resulting mixture did not smell like diesel fuel, it was deemed successful in determining how an odor like diesel fuel would affect people's performance. While odor duplication was explicitly not the goal of Turk's work, it is likely that a similar approach could be taken to odor representation. Indeed, it is almost certainly part of the approach that professional perfumers employ when they try to create a knock off of an expensive fragrance with inexpensive ingredients.

For odors to be an important part of virtual reality, it is not enough to simply take readily available odorants and to present them at the appropriate moments in simulations. A library of odors that smell convincingly real needs to be gathered. We thought that we would be able to do that, but found that we were unable to get the interest of those with the skills and unable to buy their services with mere money. Ironically, we are confident that there is a commercial opportunity for the fragrance house that takes on this challenge. Indeed, the fragrance industry is already plagued with mature markets and overcapacity. Unless they broaden their definition of the business that they are in, they all recognize that there will be a shakeout.

V.G. Hazardous Materials

A final concern about odor representation is that it is greatly complicated by the fact that many of the materials are listed as hazardous in neat form. However, there is little indication in these listings of the degree of hazard or the level of exposure for which there is no hazard. The mere possibility that circumstances exist under which a material can present a hazard is not very enlightening. 89 people drowned in molasses in downtown Boston a hundred years ago. Would listing it as a hazardous substance be appropriate? Many odorant materials are clearly dangerous. Some are sensitizers in that the effects of successive exposures are more severe. However, many everyday substances to which people are routinely exposed such as diesel fuel and diesel exhaust fumes contain toxic materials. It would be nice to be able to distinguish materials which are instantly lethal from those which require long term exposure in high concentration to cause harm.

In general, the issue of odor design and odor representation are perceived to be of small significance to the larger community and of interest to those in the business only in so far as there is an immediate payoff. Recent research suggests that particular odorants have real effects on performance. However, these results are based on short term studies. The possibility that any stimulus confers permanent benefits seems to defy basic evolutionary principles. If a stimulus is always present, there seems to be no possible reason for an organism to continue to respond preferentially to it. It seems much more likely that sequences of odors might function together to create an olfactory analog of music or at least of Muzak.

Very little will happen to change the cost structure of the fragrance industry in the near future because while better and cheaper instrumentation is on its way, the cost of the skilled professionals and other facilities is not likely to go down in the big companies. These firms are limited by the number of fragrances they can market and promote as much as by the number they can invent. In today's world, military simulation is perceived to be a minuscule market. Other kinds of virtual reality training, theme parks, arcades, and home entertainment systems suggest a much larger market but history is littered with flash-in-the-pan odor inventions.

The only bright spot is the fact that the industry is moving past fragrances and odorized products such as detergents to a expansion of the category of products intended to make our olfactory environment richer. Room and car odorizing products are now standard fare in grocery stores. Many of these products are representations of fruits or woods. While many are poorly done, they represent an appetite on the part of the public that has not yet been sated. However, given the difficulty of adding odors to existing entertainment systems, it is not likely that any major investment will be made in the private sector in the near term. Perhaps, as large screen projection television on a chip invades the home in the next few years, theaters and arcades will feel the pressure to improve the sense of presence that their experiences provide.

VI. Simulation

This category of effort was expected to be a major activity of the PI since it is the area in which he has the most experience. However, the difficulties in getting the odor delivery, odor representation, and tracking problems solved led to much more focus on those areas.

VI. Odor Cue Environment

Three odor scenarios where modelled. The first was a bare virtual environment furnished with objects that might be expected to smell. The user's movements toward and away from any of these objects led to an increasing or decreasing concentration of the expected odor stimulus. This test was done with wireless video and wireless olfactory display but the head-tracking was done by conventional magnetic tracking. Thus, the participant was tethered to the computer. This ability to explore the odor environment physically was much more effective than when the odors were presented to a seated user looking at the same visual stimulus. Voluntary physical movement with respect to the odor-producing objects not only connected the odor to the visual stimulus but it also seemed to make the odor itself seem more real. It was also interesting that when a strong odor was encountered, it was quite unpleasant for people if they could not reduce it by moving their heads away since that was their first instinct. If it did not decrease when they moved their heads away, they felt trapped and tore off the mask.

VI.B. Traffic Accident Scenario

The second situation that was modelled was an urban accident scene in which we tried to determine how many odors would be required to simulate a realistic emergency medical situation. In this scenario, one car operated by a drunken driver runs a stop light, hits another car and a pedestrian, comes to a stop after knocking over some garbage cans, and catches fire. The driver staggers out and falls on the pavement. An ambulance arrives and a paramedic performs triage on the three victims: the drunken driver, the driver of the other car, and the pedestrian.

As she approaches the car that was struck, she smells the exhaust from the still running vehicle. She sees that the driver is bleeding profusely from a superficial head wound. She smells the blood and the sweat from the workout he had before the accident. She also smells the gasoline from a ruptured gas tank flowing away from the car. Since this individual is conscious and not in immediate danger and the fuel appears unlikely to ignite, she tells the driver to turn off the car and moves on to the next victim.

As she approaches the injured pedestrian lying on the street, she passes a pizzeria and is momentarily immersed in the aroma that is wafting from it. She can see that the injured woman's abdomen has been penetrated and smells that her bowel has been ruptured. While this person's injury is severe, she will be OK for a few minutes.

The paramedic then moves quickly on to the drunken driver lying on the pavement near his car. He is surrounded by a pool of blood which is coming from arterial bleeding in his leg. She smells the blood as well as alcohol on his breath. She might notice the smell of the garbage from the overturned trash cans and will definitely observe the stench of the smoke being blown her way intermittently from his burning vehicle. But since this individual has lost a lot of blood, she applies pressure until the bleeding stops and quickly dresses the wound before returning to the person with the abdominal injury who while more severely injured could afford to wait the few minutes required to save this man's life.

This accident is a realistic training scenario for a civilian paramedic. It involves 10 odors and could therefore be supported by the current delivery system.

VI.C. Battlefield Scenario

The final scenario that was modelled was a battlefield casualty situation in a rural setting. There are two vehicles beside a country road, one of which is burning and the other is still running. The scene is a grassy setting at the edge of a pine forest with a variety of low lying evergreen bushes at the margin.

Again there are three casualties. The medic must decide which of the casualties to treat first. One has stepped on a land mine and had his foot blown off. He is lying on his back with his foot elevated near the overturned earth from the explosion. He smells of blood and sweat from weeks in the field. A second soldier has a sucking chest wound from a sniper's bullet. A third is lying on his stomach. His back is badly burned.

The smell of burnt flesh is very pronounced near him.

Again, the odors required fit within the capabilities of the current delivery system. Of course, it would be possible to construe scenarios in which many more odors would appear to be necessary. However, given the current doctrine of stabilize and transport, the medic will not do as much cleaning of wounds as he might have done 50 years ago.

VI.D. Simulation Summary

These scenarios are representative of the kinds of situations that might need to be simulated. The importance of the odors to simulated environments has been observed. It is possible to design formal experiments that would prove or disprove the value of the odors on the training itself. However, until the odors needed are truly convincing, such critical experiments would be premature. All that would be tested for sure would be the quality of the odorants themselves and we would be willing to stipulate that so far they are not very good.

VII. Odor Studies

There are three applications of odors that are of interest in medical practice and training. The first is the use of odors to increase the realism of a virtual reality simulation for training purposes. The second is the more speculative use of odors in telesurgery. The third is the use of non representational odors as part of the human interface during medical procedures.

VII.A. Simulation

The importance of the odors to simulated environments has been demonstrated during this project for the odors that are available. However, the effect of odors is much more valuable when coupled with head movement in an immersive system than in a desktop environment. It may be that this is because the desktop user is grounded in the reality of the office environment rather than the one depicted on the screen. A visually immersive but sedentary environment might benefit from odors. However, when driving in a car, not knowing whether an odor is coming from inside or outside the vehicle is a common confusion in real life, especially in those cases when the odor might signal an immediately life threatening situation.

VII.B. Telesmell

Olfactory telepresence is a very interesting possibility. While odor is not always important in surgical procedures, there are situations when it is vital. In these cases, a remote surgeon would lack diagnostic information that would be obvious if he was at the scene. For instance, the smells of feces, urine, or stomach acid could instantly tell the remote surgeon what organs had been ruptured by a bullet wound. The smell of infection would instantly tell him that an appendix had burst.

During this project, the PI spent considerable time working out the technology of a telesmell demonstration first with Dr. Paul Keller of Pacific Northwest Labs and the with Dr. Brian Andreesen at Lawrence Livermore Laboratory.

Telesmell depends on two technologies which are in their infancies. The first is odor delivery which was addressed in this project. The second is artificial nose technology as has been developed by the two individuals above.

VII.B.1. Remote Odor Display

The odor delivery system developed in this project is sufficient for a preliminary demonstration in that it can be loaded with a set of odors which are deemed to be significant for the purposes of the demonstration or even in a particular practical application such as telesurgery. Then it could display odors from that repertoire that have been detected in the remote location. The only problems would be the inadequacy of the available odorant materials pointed to throughout this report. However, if an unexpected odor appeared at the remote site, the system would be helpless. There would be no way it could ad lib an unknown odor. For instance if a soldier had suffered a chemical burn and that eventuality had not been anticipated, the system would not be able to display it.

VII.B.2. Artificial Nose Technology

Detecting the odors in the remote site is the job of artificial nose technology which is a trendy topic. The instrumentation that is used to identify unknown odors in the laboratory is being miniaturized. Dr. Andreeson had a portable Time-of-Flight mass spectrometer that was originally mounted on an airplane to look for evidence of underground Iraqi cities. We thought we could use this device to identify a small set of odors in real time. In addition, there are many research projects and even a few products that are using neural nets to analyze the responses of a number of sensors used in concert. These sensors are often based on polymers with different coatings that respond differentially to different odorant compounds. The sensors change their resistance or their resonant frequency in ways that are characteristic of each odor and their signals are fed into a neural net (already trained with known odors) that then outputs the identification.

At the time the PI was evaluating this technology, these sensors took a minute and a half to respond, far too slow for telepresence. However, the PI's conversations with Nate Lewis of Cal Tech about his technology may have influenced the latter to emphasize the speed of his sensors which Cyrano Systems, the company which was formed to commercialize his technology, now proudly proclaims are capable of sub-second response. This performance suggests that a telesmell system based on these sensors would be feasible.

Aromascan Corporation has a system based on similar sensors. It works like a laboratory device. The instrument takes 1.5 minutes to identify a sample once it has been introduced, it is likely that the entire process of preparing the sample and removing it after the analysis would take considerably longer. The Cyrano Systems devices are new and are being marketed as single purpose sensors. They have no general purpose device that could continuously sample the ambient air and be trained to simultaneously detect a wide range of odorants so there is no way to predict how large such a system might be.

The problem with these chemical sensors in general is that they are analog devices that are likely to be affected by the materials that they are sensing. Drift, aging, temperature sensitivity, contamination, fouling, etc. are all likely to be problems. Similarly, the issue of continuously sampling the ambient air is a new one. A sensor array based on these devices may be affected by what it was smelling immediately before as well as what it is smelling now.

Lawrence Livermore's approach was to use a Time-of-Flight Mass Spectrometer. This device was bulky and would only be suitable for a proof of concept demonstration rather than practical device. However, the miniaturization of mass spectrometers continues apace and there is currently a device 2"x2"x1" that suggests that a portable system based on this approach is thinkable.[Design]

VII.B.3. Proposed Telesmell Demonstration

It should be noted that telesmell should probably start with a project that demonstrates the idea as part of a system before the ultimate miniaturization and the detection of subtle odors is attempted. The project the PI devised with Paul Keller was to select a group of odors for which sensors could developed with certainty of success. Household cleaners were chosen as fitting within the guaranteed capabilities of the sensors that Dr. Keller was already working with. Then, two environments would be created: the odor environment and the remote sensing environment. The remote environment would be an empty space containing only a wide area wireless tracking system with wireless audio and video image transmission to a participant wearing an HMD and an odor delivery system.

As the participant walked around the remote sensing environment, his position, head orientation, and direction of gaze would be tracked optically. That information would be transmitted to the odor environment in which a second person would act as a robotic cameraman and nose for the individual in the remote sensing environment. As the remote participant moved, the robotic cameraman would move accordingly and look in the same direction. Audio cues would tell the robotic cameraman how to move his head to duplicate the actions of the remote participant. The video image seen by the robotic camera would be transmitted to the remote sensing environment and displayed on the remote participant's HMD.

To stabilize the image and to minimize lag, the robotic camera would have much higher resolution than a standard video camera as well as a wide-angle lens. Only the NTSC-resolution window needed by the remote participant would be transmitted. While this remote control setup would be a little awkward, it would probably be sufficient for the task and would definitely be cheaper than a true robotic camera capable of slewing at the rates of human movement. In addition, this master/slave arrangement might be of use in a variety of teleoperation applications where an expert in one location wants to direct the actions of a non-expert in another.

As the remote participant navigated the remote environment, he would not only see the odor environment through his HMD, he would smell the odors as well. The robotic cameraman would wear an artificial nose system that would inhale the ambient air, identify one or more of a set of ten prearranged odors, note the concentration, and transmit this information to the remote participant who would perceive it through the wireless odor delivery system that he is wearing. (It is not critical that the artificial nose be comfortably wearable to test the concept. It would be sufficient to mount it on an IV stand on wheels of the type that patients commonly push around hospitals.)

VII.B.4. Future Telesmell

If this preliminary demonstration provides a convincing experience of smelling the remote odors, then the problems of miniaturizing the artificial nose and odor delivery technologies can be addressed. And even more challenging, the development of the A-nose components needed for particular applications can be perfected.

Another motivation for the telesmell capability described can found by collapsing the distance down to zero. It is commonly assumed that at least some soldiers will wear special suits that protect them from biological, chemical, and radiological weapons. In these cases, they cannot breathe the ambient air unless it is heavily filtered. Odors will be removed along with the CBR agents. Denying a soldier one of his senses will not only make him uncomfortable but will also cut him off from the immediate battlefield. To increase his battlefield awareness, it will be necessary to have A-nose technology sense the odors in his surroundings and an odor delivery capability in the suit to reconstitute those odors for him. When going to all this trouble, it would be useful to provide him with a magnified odor sense that will allow him to detect and track the odors of enemy soldiers, enemy campfires, and enemy vehicles.

VII.C. Odor at the Human Interface

There is a body of science that suggests that odors have an effect on human performance independent of their power for realistically representing real world environments. These studies show that odors elevate mood, improve memory, and heighten vigilance. If these results stand up, there would seem to be many situations in which such effects would offer practical benefits.

VII.C.1. Odor Science

These studies were originally motivated by a desire to subject the age-old claims of aroma therapy to scientific scrutiny. And while the studies have been done by scientists, they should be received as suggestive rather than authoritative. The reason is that few of the studies involve the large numbers of subjects needed to overwhelm the large individual differences in odor sensitivity in the population. Even fewer have been replicated by other investigators. Standards on what is meant by "peppermint" have not been established since this term can be applied to a variety of materials produced by different means.

A few of the studies have experimental flaws which may taint their results. For instance, a study at the University of Cincinnati by Joel Warm and William Dembers, reports that odors improved vigilance.[Warm]

However, the odor was introduced intermittently by a fan that was only turned on when the odor was being displayed. Thus, the sound of the fan and the movement of the air always accompanied the odor cue confusing the issue of which stimulus actually caused the improved vigilance. When this issue was pointed out to the researchers, they cited the fact that it was the best instrumentation they could come up with since they had no expertise in electronics.

VII.C.2. Odor Studies in This Project

This project made two contributions to this literature. Both studies involved 90 subjects, enough to make them unassailable from a standpoint of experimental design.

The first tested the hypothesis that odors could improve the spatial reasoning ability of a surgeon while he was operating. This study was conducted by Dr. Susan Knasco at the Monell Chemical Senses Center in Philadelphia.[Knasco96] Her study showed a 10% improvement in performance on standard tasks for spatial reasoning at the .001 significance level when subjects were exposed to peppermint. There was a smaller effect with lavender and none with the other odors tested. This effect in large enough to be of practical as well as of scientific significance. The report on this study was delivered earlier in the program.

A second study tested the related supposition that odors might improve manual dexterity as well.[Knasco97] In this case, no effect was noted. That two studies on such closely related tasks would have such different results suggests either that the studies just happened to find an important boundary between odor effects or that the strong result of the first study should be subjected to further scrutiny. Since these studies while involving a large number of subjects did so only for a few hours apiece, it is reasonable to be skeptical about whether there will be long term benefits of such exposure. Nevertheless, even a one-shot improvement might provide potential warfighting advantage, if the performance of a MASH unit could be improved for just the 24 hour period surrounding a single battle. The report on this study was delivered earlier in the program.

The very high cost of these studies, the equivocal nature of the results, and the realization that other parts of the program needed additional resources led us to curtail further studies in this program. The most useful study in terms of this program would have been one which showed whether odors improved the efficacy of virtual reality based training. However, given the difficulty in getting realistic odorants produced, such a study would be premature. It would be impossible to separate the quality of the odor from the effect of the odor on the training. Furthermore, such testing would require investing considerable effort in the development of training scenarios. While it would have been possible to test whether odors had an effect on the participants' sense of presence, that concept is so poorly defined that the study would be reduced to asking people if they thought the odors enhanced the experience. The evidence provided by such an opinion poll seems strictly cosmetic and far too weak to use as an argument for or against using odors in any given application.

VIII. Recommendations

VIII.A. Introduction

The purpose of this project was to add olfactory stimuli to virtual reality simulations. However, the project exposed the researchers to the current state of both olfactory science and technology as well as to the deficits and opportunities in these fields. In the process, I will argue that there are significant benefits that would accrue from defining and meeting the following grand challenge: the invention of an Olfactory Super Sense which is as superior to our natural sense of smell as the microscope and telescope are to our natural vision. Finally, we will comment on some other weaknesses of current technology in other areas that were confronted during this project.

VIII.B. Olfactory Science

The chemical senses of smell and taste are the oldest in evolutionary terms and represent a significant fraction of both our genetic code and our brain mass. And yet, the scientific understanding of olfaction is crude compared to our knowledge of vision and hearing. Given the extent to which animal behavior can be ruled by smell and the evidence that we are also subject to unconscious odor influences, it is simply good science to redress this imbalance by raising our level of understanding of these senses to that of vision and hearing.

We should know how we smell, what we smell, how to duplicate smells, and how to deliver them. While there is a considerable amount of study going on, it is fragmented, preliminary, narrowly focused, and seldom asks the questions that immediately arise when considering practical applications. Odor scientists have dwelled upon behavioral responses to a small set of simple odors in the laboratory. They test odor thresholds against a background of no odor even though in real life we are typically confronted with ever changing concentrations of smells against an indeterminant background.

VIII.B.1. Human Olfactory Capabilities

Children and adults are routinely given eye exams which give us very good information about the performance of the population on the vision abilities needed for reading and driving. Hearing tests are also common, especially when any deficit in understanding language is observed.

However, olfaction is not thought to be critical to everyday life and is only measured when a complete deficit is noticed after an illness or injury or when a person complains of a persistent malodor not perceptible to those around him. As a consequence, our knowledge of how well people can smell is much more poorly developed. We know that women are more sensitive than men and young people are more capable than the elderly. We also know that there are enormous differences (up to two orders of magnitude) among individuals of both sexes.

The problem is aggravated by the fact that we do not understand the fundamental mechanisms of smell and the possibility that olfaction is not based on a neat organizing principle such as the spectra of light or sound. In vision, we can easily understand myopia in terms of optics, color blindness in terms of the cones, and poor contrast perception in terms of aging rods. In hearing, we can understand selective frequency deficits in terms of broken cilia in the inner ear.

We know that people can perform remarkably sophisticated feats of odor discrimination. For instance, woman living together use their sense of smell to synchronize their menstrual periods. Women can identify their husbands' laundry by smell alone. Women can measure genetic distance and find the scent of unrelated men more pleasant than that of kin, except when they are pregnant and the preference is reversed.[Richardson] Similarly, both sexes can determine the physical attractiveness of a member of the opposite sex by smell alone.[Mundell] Men find the scent of attractive women pleasant whereas women find the scent of attractive men unpleasant.

The fact that we are not often aware of such perceptions makes it even more important to understand them because we do not know how often such subconscious factors may be influencing our behavior. It may determine who we get along with and why certain people instinctively dislike each other. This could be significant in team building. Given that different ethnic groups certainly have different odor characteristics based on their diets and possibly because of different genetic makeups, unconscious odor judgments should be considered a possible factor in any situation where different nationalities and ethnic groups must cooperate such as in peace keeping missions or diplomacy.

These observations suggest that our sense of smell is more powerful than we often assume and that we may have capabilities that we do not use. We need to understand how well the population can smell things. We need to know what odors each individual is blind to and why. We need to settle the issue of nature versus nurture. To what extent is the ability to smell fixed at birth and to what extent is it learned through experience? It is further important to understand how much that learning can be improved with training. We know that some people are super smellers. But is that because they have more receptors, more sensitive receptors, additional types of receptors, or do they have more processing in the olfactory bulb? We believe that people are very poor at recognizing the ingredients in mixtures. Is that just because we are seldom asked to do so or is it a fundamental consequence of how olfaction works?

We see it written that humans can distinguish 10,000 different odors, but it is not clear what that means. Many people can identify only a few odors reliably. They often will be stumped by even the most familiar smells. Furthermore, they can be convinced that one smell is another quite easily. While professional perfumers indeed have a working knowledge of many odorous chemicals, they do not report that their everyday olfactory experience is that different than anyone else's. It would be useful to see how many odors ordinary people can identify in isolation and how many they can correctly identify from a small set of candidate odors.

This information may reveal diseases and genetic conditions that heretofore escaped notice. It may also explain occupational preferences and performance. For instance, a surgeon may miss a clue because he is unable to smell it. We know for instance that older people lose their ability to smell mercaptans that are added to give natural gas an odor. Clearly, a new alarm odor is needed given the aging population.

Given that we live in a society in which identifying odors is almost never a matter of survival and seldom of any practical significance whatsoever, it would be valuable to study the sensorium of primitive people such as the natives of Papua New Guinea who often smell things before they see them in the rain forest and whose culture is based much more on smell than ours. It is possible that they have more intact odor sensing systems because they use them, just as the wild creatures from which house cats are thought to have originated have larger brains than their domesticated descendants.

VIII.B.2. Genetic Information

In the past, we knew little about the genetic basis for odor perception other than it constituted a surprisingly large proportion of our genetic endowment. During the period of this project, that knowledge has been greatly expanded by the identification of 1000 genes that appear to code for the different kinds of receptors.[Glausiusz] Of these, about 30% appear to be defective—probably because olfaction no longer figures strongly in human survival. In fact, they may have started to atrophy the moment we walked upright because we get much less information from our nose in the air than we did when we kept it close to the ground.

It is now possible to think about identifying the function of these receptors. Initially, we may well find that there is a genetic basis for some specific anosmias (odor blindnesses). When there is not, we can look for environmental or experiential factors that may explain such a selective loss of function.

We will want to identify the odor function of each gene and therefore each type of receptor. What odors can the receptor detect. How does it function? Does it react to a particular chemical, to the size and shape of a molecule, to the strength of different bonds, etc? How does each receptor react to each chemical? Does a single chemical as opposed to a complex odor affect more than one receptor? How does each receptor react to each complex odor? This information will help us determine which ingredients of complex odors are most significant in the odor sensation they evoke. It may also alert us to olfactory homonyms, chemically different substances that smell alike. In fact even if there are not primary odors, there may be an odor alphabet from which many complex odors can be formed.

We will want to screen the population to see how the different receptors are distributed among us. How much do we differ in our ability to smell different things? How much of that distribution is based on heritage and how much on random variation? In particular, we will want to find out what genetic traits distinguish the super smellers from the rest of us. We may want to screen for super smellers and to see if there are tasks for which their capabilities uniquely suit them such as tracking.

Understanding these mechanisms may lead us to strategies that we can use to improve our instrumentation which still lags natural technology. It will also help us in identifying strategies that can be employed in future delivery system design and odorant synthesis.

VIII.B.3. Animal Capabilities

At the same time, we have to understand animal olfactory capabilities much better than we do. We need to know whether animals are more sensitive because they have their noses to the ground, because odors are needed for their survival, because they have more receptors, because the have more surface area in their olfactory epithelia, or because they have types of receptors that humans do not. Something is known about which creatures have the best sense of smell, but it would be useful to anyone studying them to know what they can smell, how sensitive they are to it, and how each odor is presented in their environments. This information could lead to the identification of unique capabilities in some animals and perhaps motivate us to try to duplicate them.

An evaluation should also be performed on different techniques that some creatures employ for acquiring chemical information about their environments. For instance, kiwi birds have their nostrils near the tips of their beaks so they smell what is under the leaves in the forest or the sand on the beach. Snakes use forked tongues to sample the air and the detritus on the ground. They then place the tips in a special receptacle in rear of their mouths where the actual chemical sensors are located. The two prongs provide a kind of stereo perception which helps snakes follow odor trails.[Schwenk] Similarly, moths have elaborate antennae which are likely involved in tracking pheromone plumes to their sources.[Taylor] In these and similar cases, natural strategies may suggest techniques that can be employed by human technology. In general, every animal sensory modality should be identified and evaluated for duplication for practical as well as scientific reasons.

VIII.B.4. Odor Environment

In order to understand the sense of smell in humans and animals, we need to analyze the odor environment they inhabit. Surprisingly, little is known about our everyday olfactory world. We do not know what odors we encounter and what odors we notice as we go about our lives. As mentioned earlier, smelling is like dreaming; everybody does it but most people do not remember doing it. In extreme situations when there are complaints, environmental firms will be brought in to measure the extent of noxious odors emanating from a hog farm or some other olfactory nuisance. However, we know little about how odors are distributed through the work-a-day world. Do odors change throughout the day? Do odors vary with altitude, weather, humidity, season, etc. How is our ability to smell affected by the wind? On the one hand, we would quickly habituate to any odors present in stagnant air and breezes bring us new smells. On the other hand, high winds may make it difficult to smell at all.

What is known about the sense of smell has primarily been learned in the laboratory. Odors are presented and evacuated. In some cases, the investigators rule out any background odor by prefiltering the air before it is odorized. However, in most real environments there is a background. How does our perception of odors vary with the background? We know that one odor can mask another; however, if the masking odor was part of the background we would already be habituated to it and only smell the odor that would ordinarily be masked resulting in a totally different experience.

We need to be able to measure the odor background much better than we can now. We need to determine whether people are aware of the presence or absence of background odors. Special forces people that the PI has spoken with report following the absence of a smell when they are tracking a person. This actually makes sense if in becoming habituated to person's scent, the tracker's perception of other odors that he encounters is altered from what he expects. This deviation would tell him that he is still on the trail. When he leaves it, his perception will return to normal and he will notice that previously masked elements are now observable. Such sophisticated olfactory perception is totally foreign to most of us. However, if such a capability exists we should study and understand it.

We know that sensory deprivation can be disturbing. The PI has long believed that selective sensory deprivation is also possible. We have sensory deprivation environments and we have anechoic chambers which eliminate background sounds. Clean rooms used for semiconductor manufacture are probably odorless although their designers are more concerned with particles than with vapors.

However, we have not systematically studied the effects of olfactory deprivation except in those who have completely lost their sense of smell. One anecdote that suggests that odor deprivation can be a source of discomfort was given to the PI by a reporter for a biology magazine who had spent several months in Antarctica. (Because of the cold, the air carries almost no odors. The local fauna do not smell as creatures elsewhere do because there is no point.) When she returned, she was starved for olfactory stimulation and just lay on the ground smelling the vegetation. It is likely that there are many situations in modern life where we have so successfully eliminated smells that one could argue that the addition of odors would increase comfort and performance without claiming that odors have magical powers.

In addition, we can only understand animal behavior if we understand the odor environments that they inhabit. It is not enough to simply say they have a better sense of smell than we do. What smells do they encounter, where do they run into them, and how do they affect their behavior? Because most mammals are quadrupeds, their noses are close to the ground. If they are tracking another animal, its tracks, its droppings, and its urine are all on or close to the ground. Some of the food of animals such as pigs and skunks is under the ground. Heavier molecules from odors that are released in the air settle to the ground and those from material on the ground never rise much above it. How do these odors behave over time? In general, what do animals have available to smell? What are the signals and what is the noise?

VIII.C. Olfactory Super Sense

In addition to accomplishing the scientific goals just laid out, we also need to set and reach a corresponding technological goal. Progress in science, technology, and industry has repeatedly been sparked by advances in our ability to perceive natural and artificial phenomena. To accomplish that goal, we have created a series of technological senses that far exceed our human endowment. We can see the very small and the very distant. We can see in the infrared and the ultraviolet. Our instruments can detect infrasound and ultrasound in amplitudes far below our human hearing and at distances far beyond it. Thus, all that is being proposed is to create an olfactory supersense that is akin to our other technological senses. At the very least, we should be able to smell as well as any human or any animal. If we could do as well at detection as natural creatures, we might do far better at identification because unlike them we would not have to learn from experience. The entire repertoire of identified compounds would be instantly available.

When there is a void in science and technology, it is possible to argue as a matter of faith that filling the void will lead to practical benefits. However, in this case it is also possible to identify a number of very specific problems which might be addressed by the fruits of such a scientific and technological endeavor. For the moment, we will confine ourselves to the areas of interest from which this project itself would have benefited.

VIII.B.1. Medical Benefits

Odors have a long association with medicine. At one time, odors were thought to be the cause of disease and noblemen had a servant carrying a device to perfume the air walk in front of them. As recently as a hundred years ago, the nose was the only diagnostic instrument available to the physician. A number of common ailments were known to have characteristic odors. Measles, ectopic pregnancy, schizophrenia, and sometimes cancer could be diagnosed just by smelling. Diabetes was detected by tasting the urine. In addition, the body's reaction to poisons produces odors which indicate what has been ingested.

Today, we would assume that these diagnoses are done in laboratory tests. However even there, technicians are taught to recognize the different bacteria that are being cultured by smell.

We also know that animals and instruments can make diagnoses of diseases from odor alone. When the PI gave his first talk on odors in virtual reality at Medicine Meets Virtual Reality in 1995, he asked that any doctors in the audience who had specific experiences in which odors had been diagnostic in their practice report those anecdotes to him. One individual (a urologist) described an incident in which a woman complained to him that her dog kept sniffing her left breast. Upon examination, he discovered that she indeed had a lump which was later determined to be malignant. Subsequent to that, a doctor in Florida trained a dog to detect skin cancer.[Higgins] In another study, rats were able to detect the presence of a cancer-producing retrovirus which had not yet been expressed as a cancer in another individual by smell alone.[Beauchamp]

Similar results have been achieved with instrumentation analyzing a patient's breath. Dr. Barry Marshall of Australia has developed a test to detect the ulcer causing Helicobacter Pylori from a patient's breath.[Marshall] The bacteria produce an enzyme called *urease*. Carbon 14 reacts with urease in the stomach and can be detected in CO2 that is exhaled. Another doctor was able to detect Pneumocystic Carni, a complication of AIDS, from exhaled breath.

These results suggest that odors contain a wealth about infections and the functioning of a person's body. It is possible that a wide range of conditions could be identified by smell. If so, and if a technological device could be miniaturized and made disposable, such tests could be done in the doctor's office in a single visit. This would eliminate the second visit to get the results, the handling, the elapsed time, and the anguish of people who are waiting for results. Many women spend a significant fraction of their lives anxiously waiting for false positives from one test to be overruled by more sophisticated follow-up tests and biopsies.

It is also possible that the health of the body's organs and systems is revealed in the person's body odor. Given that body odor is affected by diet and especially by fat intake, cholesterol and triglyceride levels may be evident as well.

In addition to medically significant odors, it is likely that emotional states also modulate a person's body odor. Such cues might be valuable in psychiatric diagnosis and therapy. They might help measure the emotional state of patients whose pulse and blood pressure react to the stress of the doctor's office.

Even before embarking on a technological development, it would be worthwhile to use animals to determine what conditions inside the body are signaled by smells that are easily available outside of it. While rats and dogs are not likely to be welcomed on hospital staffs any time soon, their capabilities would demonstrate what is possible and motivate the development of artificial technologies which duplicate or surpass them.

VIII.C.2. Military Super Sense Applications

There are also a number of uses that the military and law enforcement officials could make of an artificial nose that exceeded our own. The obvious ones would be in the detection of chemical and biological warfare agents. It would also be possible to detect the presence of remote vehicles and campfires as well as the paths used by enemy patrols.

Of even greater currency is the detection of mines, booby traps, and enemy personnel in current and past battlefields as well as the interdiction of terrorists' explosives and illegal substances. Many approaches to these problems are being considered. One of the most effective of these is the use of dogs which are known for their keen sense of smell and which were used to good effect in Viet Nam where they completely shut down the infiltration of the Viet Cong in the Delta region. (The dogs could detect the breath exhaled by VC who were submerged in the water and breathing through tubes. They could also hear the ultrasonic sounds generated by the wind vibrating trip wires for booby traps.)

The problem with dogs in mine detection is that they fatigue easily. They can only work for 15 minutes at a time before they need a rest. In general, they are trained to recognize a single odor. They can track one person but not look for any one of ten. They cannot look for mines one day and narcotics the next. Even when just searching for mines, dogs have to be trained to each particular type of soil and require two days to adapt to it.[Mine]

There would be a tremendous appetite for a technology that could duplicate canine olfactory performance which would not have these performance issues. For instance, a dog can track a person given a sample of that person's odor, but in the case where a sniper is known to have shot from a particular location, the dog may not understand that you want him to follow the human scent that he perceives there. A synthetic instrument might be able to detect the presence of a human scent and possibly even recognize the most recent of several scents. Unlike the dog, an instrument could record what it had detected and transmit that information anywhere in the world to be tested against suspects found years later.

Such a capability would be extremely valuable in guerrilla conflicts, peacekeeping missions, and civilian law enforcement. Given that identity and genetic distance can be inferred from odors, it may be possible to correlate odors with blood samples, to recognize blood types and hereditary conditions. Odor prints could become a powerful forensic tool. If emotional states are revealed in a person's body odor, they may be useful when interrogating prisoners of war and criminal suspects. Emotional states revealed by odors might also provide an edge in negotiations and diplomacy.

Once miniaturized, such devices could be worn on the feet where the signal is strongest and be used for tracking enemy personnel and for warning of land mines. They could be mounted on airplanes and surveillance drones. A number of devices worn by different individuals could be used in concert to improve tracking performance just as a snake uses the stereo information provided by its forked tongue to follow the trail of its prey.

A more speculative application is based on the fact that homing pigeons apparently memorize the smells of the terrain they pass through when they are transported blindfolded to a remote location and play back the odor sequence in reverse to find their way home. This implies that there are sufficient odor cues to guide a missile to a remote site.[Able]

VIII.C.2. Civilian Super Sense Applications

There are also many industrial processes and consumer applications that would be found for an improved ability to detect and analyze odors. Food and beverage quality and freshness control are obvious possibilities that are already being addressed with today's mediocre technology. The reason is that the human noses that have controlled these processes in the past are getting old and younger people have not shown any interest in picking up the skills. In addition, the right instrument would be more repeatable and not be affected by colds and vacations.

VIII.D. Odor Synthesis

The premise of this project was that odors would be a necessary ingredient in simulating real situations. However, the state of current odor synthesis technology and commerce is such that realistic odor representation should not even be attempted without a budget for odor synthesis twice as great as that for this entire project. Even then, many of the odors that the PI has been shown as serious efforts by those in the big leagues of the fragrance industry have been completely unconvincing.

Such an effort would require a professional perfumer full time, an analytical laboratory, and an inventory of odorous chemicals. Even with these resources dedicated to such a project, it is clear that today's instruments are not as good as the human nose that must be satisfied with the results and that such an effort may be doomed to failure. Therefore, odor simulation is another motivation for the Olfactory Super Sense described above as well as for the scientific effort required to have a much better understanding of our olfactory sense than we have today.

However, rather than being motivated by commercial considerations, experimental odor synthesis should not confine itself to the most predominant peaks in the analysis but should attempt an exhaustive duplication of the original material. To be repeatable over a long period of time, it should start from pure chemical feedstocks.

It may be that such an approach is doomed to failure just as sound synthesis abandoned purely digital synthesis in favor of sampling techniques that started with rich real world sounds. Or it might be that some of the ingredients are not commercially available or have not been analyzed or synthesized at all. It would be useful to know.

One alternative would be an artistic approach which developed a repertoire of stock odors that could substitute for some of the exotic materials. People are not very good at naming odors and can be fooled into believing that one odor is another. However, they may have an acute sense of what does not smell like any real odor at all. It is that reaction that the PI has had to some of the professionally produced materials he has been shown.

Another approach would be an extension of the oldest one. Elsewhere in this report, it was mentioned that the most convincing simulation would be accomplished by using real materials. While this is not very appealing in the case of medical odors and not very practical because the raw materials lose their odor quickly, the fundamental processes of traditional perfumery capture the odorous compounds from natural materials. For instance in effleurage, flower petals are mixed in heated liquid lard which takes up their odor producing oils. Then, the lard is heated to the point where these oils vaporize. After they boil off, the vapor is fed through a distillation coil which is cooled to condense the oils at its output. It is possible that this process can be used to produce some of the odors needed for realistic simulations. We experimented with this process without great success, but it is likely that real chemists would have more luck. However, it may be that many of the odors do not lend themselves to this kind of processing.

VIII.D.1. Odor Language

One benefit of a better understanding of the olfactory sense and how it interacts with specific chemicals is a more rigorous odor vocabulary. Currently, there are a number of adjectives that odor professionals use in describing the qualities of a particular odor: fruity, woody, floral, pungent, musty, etc. However, when the PI showed some of the chemicals that had been developed for him to other people in the industry, they trotted out subsets of these descriptors seemingly at random. There are certainly no rigorous standards by which these terms are applied and as a result much conversation about the subject is almost meaningless.

While those in the industry would disagree with this characterization and attribute it to the PI's ignorance and frustration, there is no doubt that this vocabulary is not grounded in scientific objectivity and until it is, scientific and technological progress are going to be stymied. It would be a real contribution to the science, technology, and business of olfaction if these words could be given an unambiguous scientific footing or if new vocabulary based on scientific knowledge of the olfactory sense can be created. Indeed, it would be reasonable for the National Bureau of Standards to undertake a preliminary study of this issue.

If such concrete vocabulary can be arrived at, it would also benefit the odor simulation process because combinations of attributes may be duplicated rather than exact odors. In particular, the trigeminal sense needs to be better understood to see to what extent trigeminal sensation differs from one odorous compound to the next. This could be done by involving those who have lost their sense of smell. Since the trigeminal sense is connected to the brain through a completely different cranial nerve, it is likely to still be intact and functioning in isolation from olfaction. We can then test these individuals to see what odors they can distinguish from their trigeminal components alone. This will tell us how many kinds of trigeminal sensation there are. Ideally, we could find safe odorless compounds that would trigger every discriminable trigeminal sensation. This would allow us to substitute one trigeminal stimulus for another when formulating odorants with the confidence that we know what we are doing. Such substitution would be particularly welcome when the material being simulated is toxic.

The concern about toxicity also has to be put on a rational footing. Military training and military operations accept a higher level of risk than civilian life. Current cautions about hazardous substances seem to have been created by insurance companies wanting to avoid all risk on the one hand and trial lawyers wanting to call any risk actionable on the other. Certainly, guidelines that declare the exposure experienced from standing on a street corner in any city an unacceptable risk are irrational, especially when the exposure times are very brief. Declaring everything toxic makes it difficult to distinguish the merely unpleasant from the truly lethal.

VIII.E. Odor Delivery

This project focused on the development of odor delivery systems for virtual reality simulations and the system developed is a reasonable contribution towards that goal, especially because it is designed to be compatible with the three major virtual reality formats: desktop, ambulatory, and CAVE. However, it does not deal with all aspects of odor perception. Real odor sensation is often associated with particles, droplets, humidity, moisture, and temperature when these occur in the real world. Simulating these aspects of odor perception has to be tested to determine their importance and they must be included in the delivery system if they prove to be valuable.

Similarly, new science will continue to shed light on odor perception and possibly add new requirements to the delivery system. For instance throughout the program, the PI was told that odors could not be lateralized between the two nostrils. A very recent result shows that the two nostrils actually provide different sensations from complex mixtures of odors. Earlier studies that use simple odors had failed to notice this effect.[Lemonick]

VIII.E.1. Types of Delivery Systems

However, there are other kinds of delivery system that would be needed for other applications which are worth pointing out here. In addition, meeting their requirements would improve the performance of the simulation system.

VIII.E.1.a. Psychophysics System

The current system is intended to provide odors during simulations. It is not intended to measure the participant's sense of smell. It makes benign assumptions about how many levels of intensity people can discriminate and about their sensitivity in general. However, we know that people vary enormously in their ability to detect odors. It would be useful to have a device that could present any odor in precise amounts from below the threshold than can be detected by the most sensitive person to above the threshold of maximum perceived intensity by the least sensitive person. In between these minimum and maximum concentrations, it should be able to vary the concentration more finely than any individual's ability to discriminate in their personal range of sensitivity. This device could be used for screening the population for various kinds of odor blindness, for testing people's ability to improve their sense of smell, and for testing people's awareness of odor textures as opposed to static odor concentrations.

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VIII.E.1.b. Odor Organ

Currently, odorants are mixed as liquids which is cumbersome and makes it difficult for the perfumer to back up. There would be an important place for a device that would contain a large number of odorous compounds on line, be able to vaporize precise amounts of those materials, and to mix the vapors in carefully controlled proportions. It would further be desirable to be able to vary the settings very rapidly to allow the perfumer to consider many more combinations than she typically can using traditional techniques.

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A related device would have a more limited but still appealing application. Deaf-blind individuals are missing the two most important sources of experience and might be very interested in a technology that addressed their sense of smell. An odor organ played with a keyboard might be a source of pleasure for these individuals. Given their lack of other stimulation, they might devote themselves to creating a new art form based on it. In the past, the idea of a temporal art form based on odors has always failed because there was no way to evacuate odors once they had been introduced. If individual delivery devices were placed in the seats in a theater as they have been for one simulation ride in Puroland (a theme park outside Tokyo) and evacuated through a ceiling exhaust system, it would be possible for compositions created by deaf-blind individuals to be performed for large audiences.

VIII.E.1.c. Human Interface Device

The current system is a multipurpose device which can be used in several different virtual reality formats. It contains attributes such as portability and wireless operation which are not necessary in static applications. In addition, it provides an odor repertoire that may be overly large for some applications. In particular, there is evidence that certain odors may improve performance in tasks unrelated to simulation. For instance, odors are believed to improve memory, mood, vigilance, spatial reasoning, etc. These uses of odor in the traditional computer interface and indeed in any environment where operator performance is important should be investigated.

In many cases, a single odor such as peppermint is believed to provide a benefit. While it seems unlikely that peppermint would make the world a better place indefinitely, it seems that it might be a useful performance enhancer when used in particularly important situations for short periods. It is also possible that the duration of the effect might be increased by introducing it sporadically or according to a complex reinforcement schedule. It is also possible that a number of odors could be introduced in patterns that would vary over time just as Muzak is played in department stores to keep the staff motivated.

A device targeting this application might deliver a single odor under computer control. Or it might deliver preprogrammed sequences of odors. In this case, a single tube could contain a series of different odorants separated by bubbles that would be fed to a single transducer.

As more complex control is desired and as the odors are tied to particular tasks and scenarios, a stripped down version of the current device would be desired. For instance, during training an operator might learn to associate particular odors with particular tasks. Possibly if the appropriate odor is presented when a particular task is to be performed, it will activate the memory of the training more effectively. Similarly, if a person is presented with a complex interface with many tasks to perform and many contingencies to consider, using odors to enhance the user's sense of context might help him organize his thinking.

For instance, today's desktop metaphor claims to be spatially organized, but it is a fraud unless you would be content with a desk the size of an airline seatback tray. A real desk is much larger. You do not just move your eyes around it, you also move your hands, you turn your head, you refocus your eyes. All of this participation strengthens the sense of context that you can create and exploit on your desk. Instead of overlapping windows which simulate a pile of papers not a desktop, you could turn your head to activate the window or tool bar required for a certain task. You could enhance that proprioceptive cue with an odor that was unique to the window. Alternatively, odors could be used as signals or alarms that would alert the user to the need to perform a certain set of tasks on a specific set of inputs.

VIII.E.1.d. Odor Entertainment Systems

Low cost systems are need for arcades, movies, home entertainment, cars, personal space fragrancing, and body adornment. Such systems will need to be easily reloadable and ideally disposable.

VIII.E.2 Future Delivery Technology

In many ways odor delivery would seem to be a perfect problem for MEMS technology. This was the reaction of Ken Gabriel who headed the MEMS effort at DARPA when he was told of the PI's interest in such a device by Anne Marie Alanzillotto of Sarnoff Labs. (after he returned to CMU) At the time, the project was too far along and a MEMS effort would have required at least an additional year to produce a chip. In addition, the fact that the medical odors were not available and their physical properties therefore unknown meant that the requirements could not be stated with certainty. However, the project was of sufficient interest that Sarnoff was interested in sharing half the cost of the effort.

However, there are many ways that technology can be brought to bear on the odor delivery problem short of creating the complete system. First, low power methods for pumping and selecting small volumes of liquid odorants are needed. Separately constructed valves are obviously too expensive, too large, and too power hungry.

Better methods for ejecting odorants from the dispenser are also needed. The current system's 100 nanoliter bursts are probably too large. Even the 25 micron droplets produced by ink jet printheads are too large to inhale and a separate transducer would still be required to vaporize them. (Ink jet print heads were seriously considered for this project, but required information from the printer manufacturers that they were unwilling to provide.)

Ideally, the dispenser chip would produce vapor directly instead of releasing droplets to be vaporized by an external transducer. A possible problem is that a residue might build up that would render the chip inoperable. Finer control of the output volume would also be desirable. Tolerance of a wide variety of materials and antifouling mechanisms would be needed.

Also important is the issue of getting odorant to the chip. Current technology seems to permit only nine liquid input channels to be interfaced to the chip. This is at the edge of what is considered a minimal odor repertoire. There are many applications that might require more.

In general, odor delivery is a perfect application for MEMS technology in that it involves very small amounts of material and addresses a completely new application, one that will be created by the technology rather than simply being met by it. However, it should be recognized that since better instrumentation is required in order to understand the needs of the application, any advanced delivery system is going to require iterative design and testing rather than detailed specification followed by a do-it-right-the-first-time implementation.

VIII.F. Telesmell

This application is quite speculative but should at least be demonstrated to the level described earlier. For research purposes, remote surgery like simulation should assume that odors are necessary until proven otherwise. Until the odors needed to simulate surgery itself are available and until sensors can detect them as well as the human nose, telesmell for that application cannot be meaningfully demonstrated. On the other hand, there are sensors that detect some odors well enough for a proof of concept to be performed for telesmell in general.

In addition, olfactory telepresence could be valuable in other contexts. The most ubiquitous is telecommunication. The fantasy of teleconferencing systems is to be able to provide a sense of being with a remote person that is so strong that there is no desire to visit him in order to communicate better. One step was the concept of a shared virtual telecommunication space which both participants enter for the purpose of the conversation. This idea which the PI invented is now considered one of the fundamental axioms of virtual reality. While remote individuals are able to share information in virtual reality, no one would claim that they really feel like they are together. Persuasion or trust building will require a much more powerful sense of presence.

Possibly, being able to smell the other person would give you a better sense that you were with them. It is known that babies react physiologically to their mother's scent. Maybe adults have similar reactions to each other's body odor. Some people keep clothing and other articles that contain a loved one's scent, especially when they are deceased. This idea could be easily tested by putting people in teleconferencing systems that were close enough together that the odors from each space could be circulated to the other. The test should be done with both intimates and strangers. It is possible that the idea should also be tested for phone conversations between phone booths. If a measurable effect is found, it might improve both informal and personal telecommunication. In cases where two people contact each other often, their scents could be concentrated and simply transported for display during their conversations. For instance, soldiers deployed in remote locations might have an enhanced sense of connection with their families if personal odors were displayed during their televisits.

Body odor is based on complex chemicals, but it is the opinion of George Preti, a chemist at the Monell Chemical Senses Center that there are about 20 compounds which when mixed together in the proper proportions define a person's signature scent.[Preti] This hypothesis should be tested. If it is true, then an artificial nose coupled with a remote odor delivery system would be sufficient to connect any two people together with olfactory telepresence.

VIII.G. Tracking & HMD Display

The project considered three optical techniques for wireless tracking of HMD participants. It also briefly considered some HMD design approaches that it had examined in more detail in the time between the notification of the award and when the funding was received. These efforts were performed in collaboration with Dr Jannick Rolland of CREOL, the Center for Research and Education in Optics and Lasers, at the University of Central Florida. The PI was struck by the degree to which optical design is still based on the techniques of a hundred years ago and the extent to which prototyping with these techniques is prohibitively expensive. As a result, HMD design has not progressed markedly and will not with traditional methods. The fact that SONY's recent contribution is based on the same techniques is further evidence of this fact.

Dr. Rolland and the PI considered a number of out-of-the-box ideas that would accomplish optical functions by nontraditional means. But real breakthroughs are needed in this area and such an effort is appropriate for DARPA to fund. In fact, it is possible that DARPA has already funded projects and caused technology that has not yet been brought to bear. If not, such an effort is due.

One difficulty was the interface of an asymmetric wide field of view to a large high-resolution sensor. The PI has recently become aware of two related techniques which offer alternative approaches to this problem. The first is the use of switchable LCDs with different refractive indices to steer a laser beam being considered for funding by the Army. The second is electronically switchable diffractive optics being commercialized by DigiLens which has recently received $12M in investment. The implications of this technology are profound to a wide range of everyday as well as sophisticated problems. DARPA is encouraged to seriously consider spurring uses of this technology and to take a bow if it had a hand in causing it to be created. The PI has several projects in mind that can be accomplished with this technology and is sure that there are many military projects that would benefit from it.

VIII.H Recommendation Summary

Significant efforts in all of the following areas have been recommended. These efforts should not be pure science for science sake. Such purely scientific work has led to a pattern of omissions that will persist unless practical priorities are taken into account. Instead, there should be a systematic effort to look the olfactory sense from a applied point of view even when fundamental scientific work is required.

Human Olfactory Science
Animal Olfactory Science
    Medical diagnosis by animals and instruments
Olfactory Super Sense
Odor Analysis
    odors for simulation
    odor environments
    human body odors
Odor Delivery
Odor Simulation
Odors at the Human Interface Research
Olfactory Telepresence
Optics Techniques

IX. Conclusion

The overall conclusion to be drawn from this project is that it is easy to do olfactory display badly and hard to do it a little bit better. Advances are required in the practical psychophysics of human perception, the chemical analysis of odors, and the synthesis of odors before it is possible to determine whether current micro mechanical technology can be used to create the ultimate odor simulation. The experience with the current system is that the best odors definitely enhance ambulatory simulation now but that odors are less convincing in screen-based simulators.

A significant effort is required in each of these areas to bring this technology to the level where it should be, given the state of our other technologies. However, in light of our societal prejudice that odors are not important and that making use of them was not as easy as we had hoped, it is not unlikely that they will continue to be neglected. At the same time, given the fact that what is missing is knowledge of fundamental human machinery and that many applications can be contemplated, the large effort required might lead to a large payoff if it was undertaken.

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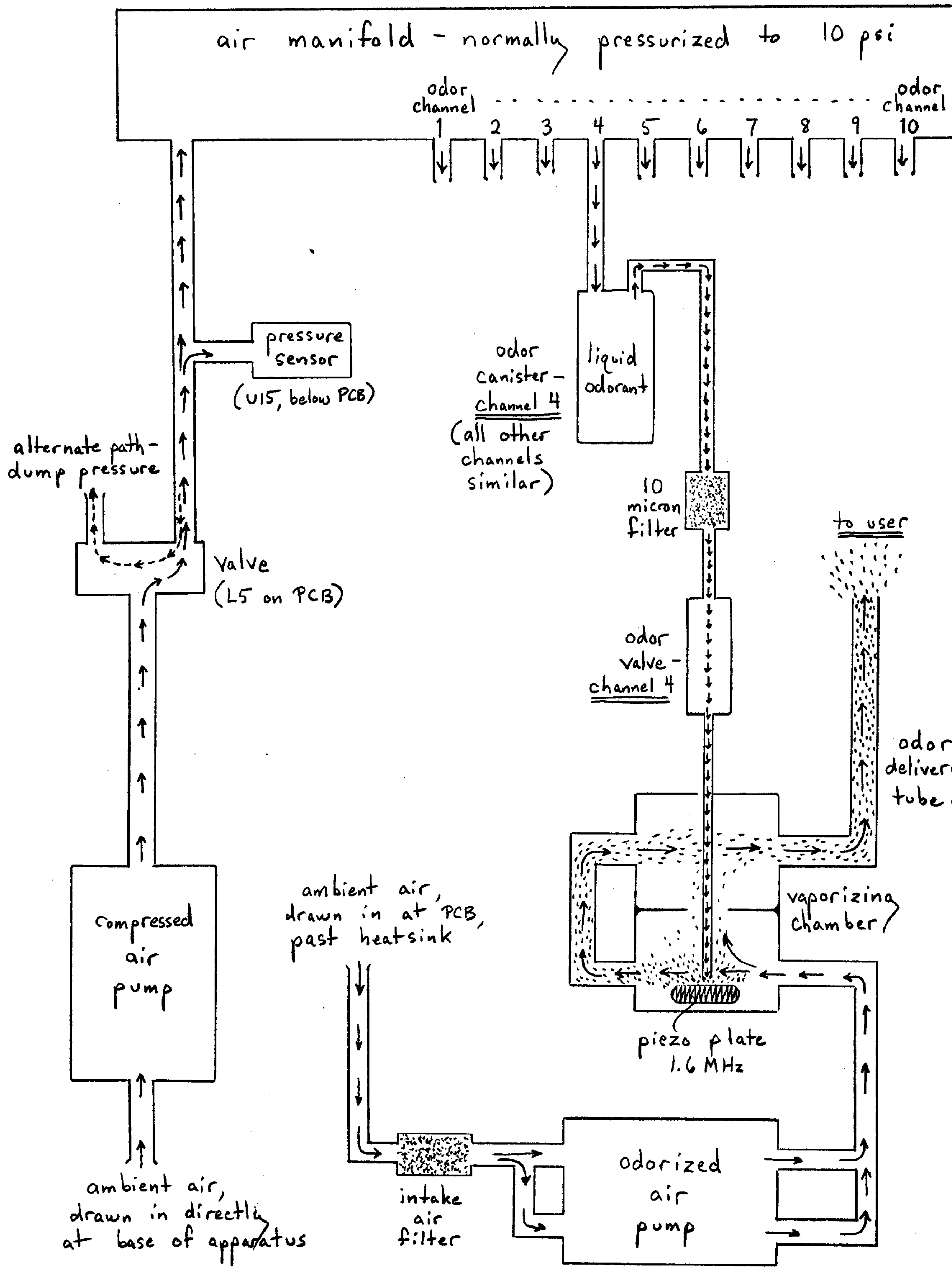

Functional Flow Diagram

Figure 1

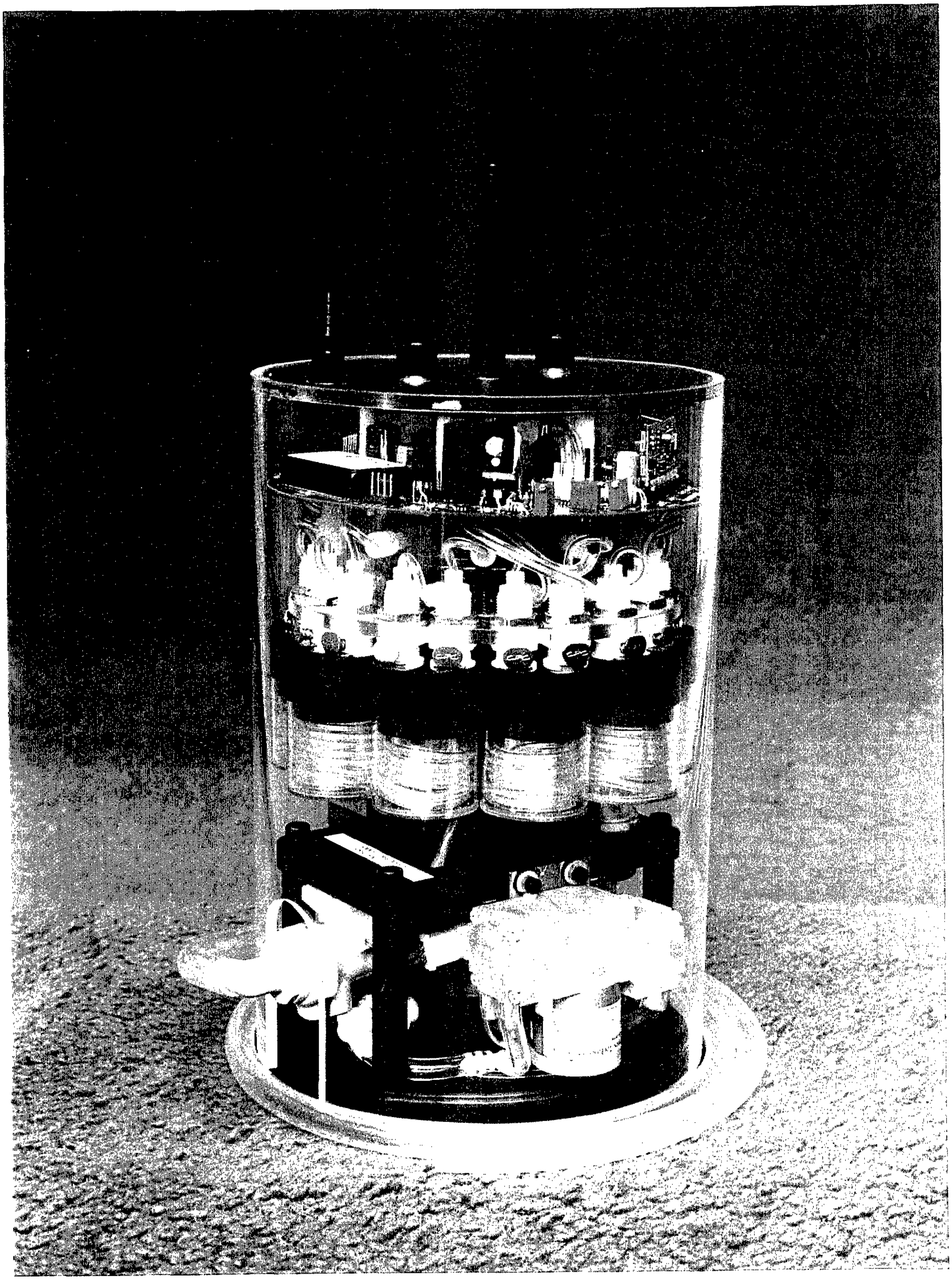

Photo 1

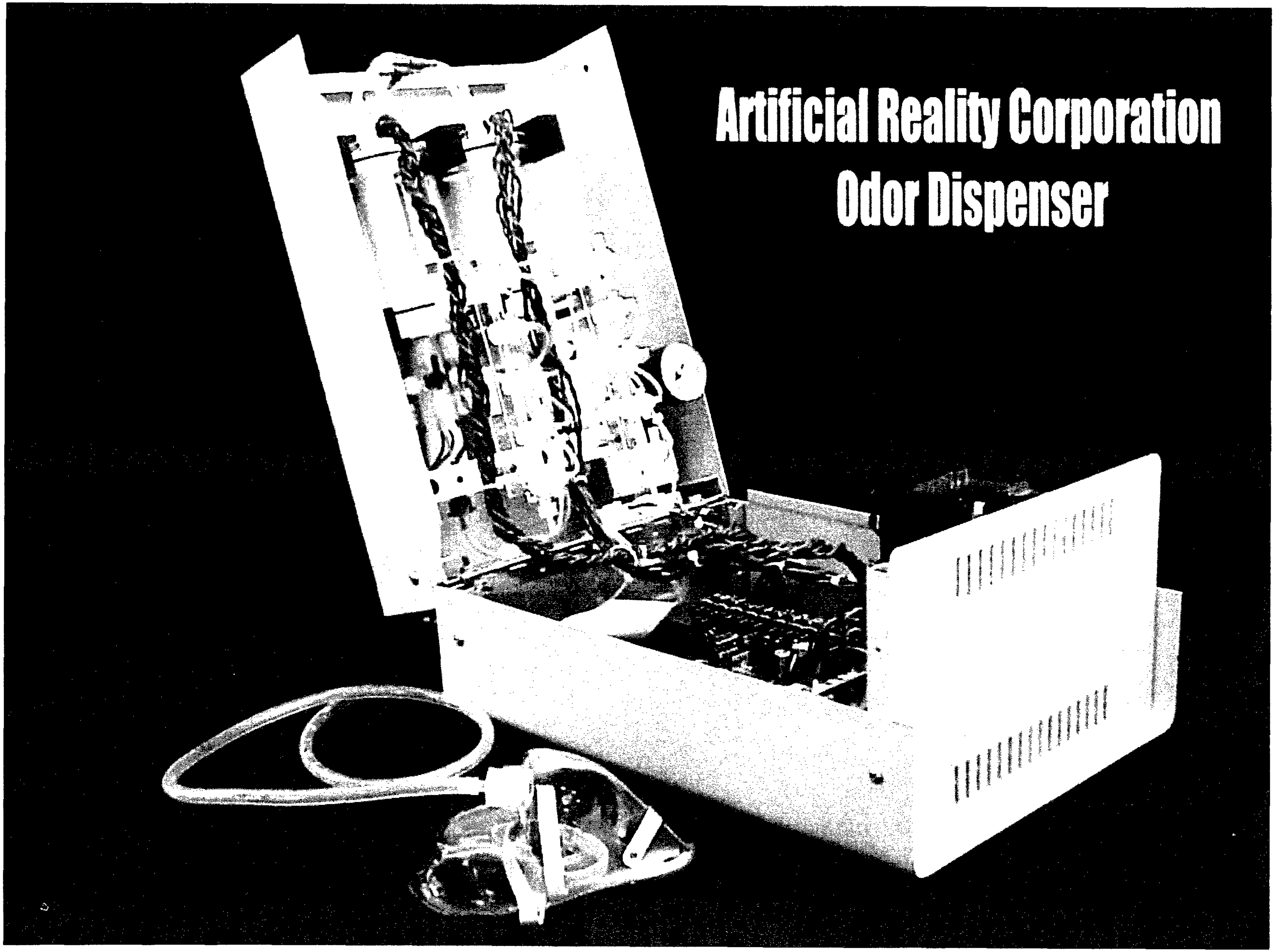

Photo 2

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ATTENTION OF:

MCMR-RMI-S (70-1y) 2 Feb 01

MEMORANDUM FOR Administrator, Defense Technical Information Center, ATTN: DTIC-OCA, 8725 John J. Kingman Road, Fort Belvoir, VA 22060-6218

SUBJECT: Request Change in Distribution Statements

1. The U.S. Army Medical Research and Materiel Command has reexamined the need for the limitation assigned to technical reports written for the following grant numbers:

96-C-6117	ADB233743, ADB243030, ADB259960
94-J-4113	ADB251394, ADB241076, ADB220530

Request the limited distribution statement for Accession Document Numbers listed be changed to "Approved for public release; distribution unlimited." These reports should be released to the National Technical Information Service.

2. Point of contact for this request is Ms. Judy Pawlus at DSN 343-7322 or by email at judy.pawlus@det.amedd.army.mil.

FOR THE COMMANDER:

Phylis Rinehart

PHYLIS M. RINEHART
Deputy Chief of Staff for
Information Management