California Department of Transportation
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Laser Removal of Graffiti
The GRASER Field Demonstration Unit

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Final Report

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ABSTRACT

A Field Demonstration Unit was designed, built and tested that proved it is possible to remove graffiti from high intensity highway signs in the field safely, conveniently, and quickly. The unit is called a GRASER (Graffiti Removal And Sign Electrooptic Restoration). It is self-contained, in a trailer that can be pulled behind a vehicle, with an on-board motor-generator, a Q-switched Nd:YAG laser, an optical beam delivery system, a control system, all necessary cooling and ventilation, and suitable beam containment. The GRASER worked as designed in all aspects. A videotape was prepared that demonstrates the effectiveness of the GRASER in removing graffiti from high intensity highway signs and that provides instructions for use of the GRASER. A GRASER Instruction Manual was prepared, including detailed description of components, operating instructions and specifications.

PURPOSE

The purpose of the GRASER is to provide a field demonstration unit that can demonstrate that graffiti removal using laser ablation can be successfully implemented on a mobile platform. The GRASER was specifically designed for signs located beside the roadside which are no taller than eight feet and no wider than two and one half feet. This allowed the unit to be set up and operated in the field with little to no impact on traffic patterns. In addition, this would permit roadside or parking lot demonstrations of the technology without special provisions being required for sign locations. The GRASER was designed to be compact but with enough room for an operator. All safety issues were addressed. The system was designed to be safe, easy to transport, easy to set up and easy to use.

GOALS

The design goals of the GRASER were to construct a cost efficient, effective and useful laser ablation demonstrator for graffiti removal. Size, weight, safety and ease of operation were prime considerations in the design and implementation of the GRASER. The design permits the setup and operation of the GRASER by one individual without the need of special tools or other significant hardware. The concept was of a totally self-contained system that can be opened, operated, closed and moved to the next sign with a setup and take down period of less than ½ hour.

BACKGROUND

Previous funded projects had demonstrated that lasers can be used to remove graffiti from a variety of structures. A comparative study indicated that pulse-pumped Q-switched Nd:YAG lasers are the most cost-effective for removing paint. The results of this study were published in Applied Optics ["Paint Removal using Lasers", K. Liu and E. Garmire, Appl. Opt. 34, 4409 (1995)] and reported at two optical engineering conferences. An additional funded study developed the concept of ablating paint from high intensity highway signs without damage to their retroreflection by using a grazing angle of incidence. It was also shown that any residual film after ablation could be removed by a simple polishing technique. This study made preliminary tests that indicated that automated operation would be possible using computer control. On this basis a patent was filed for and awarded.

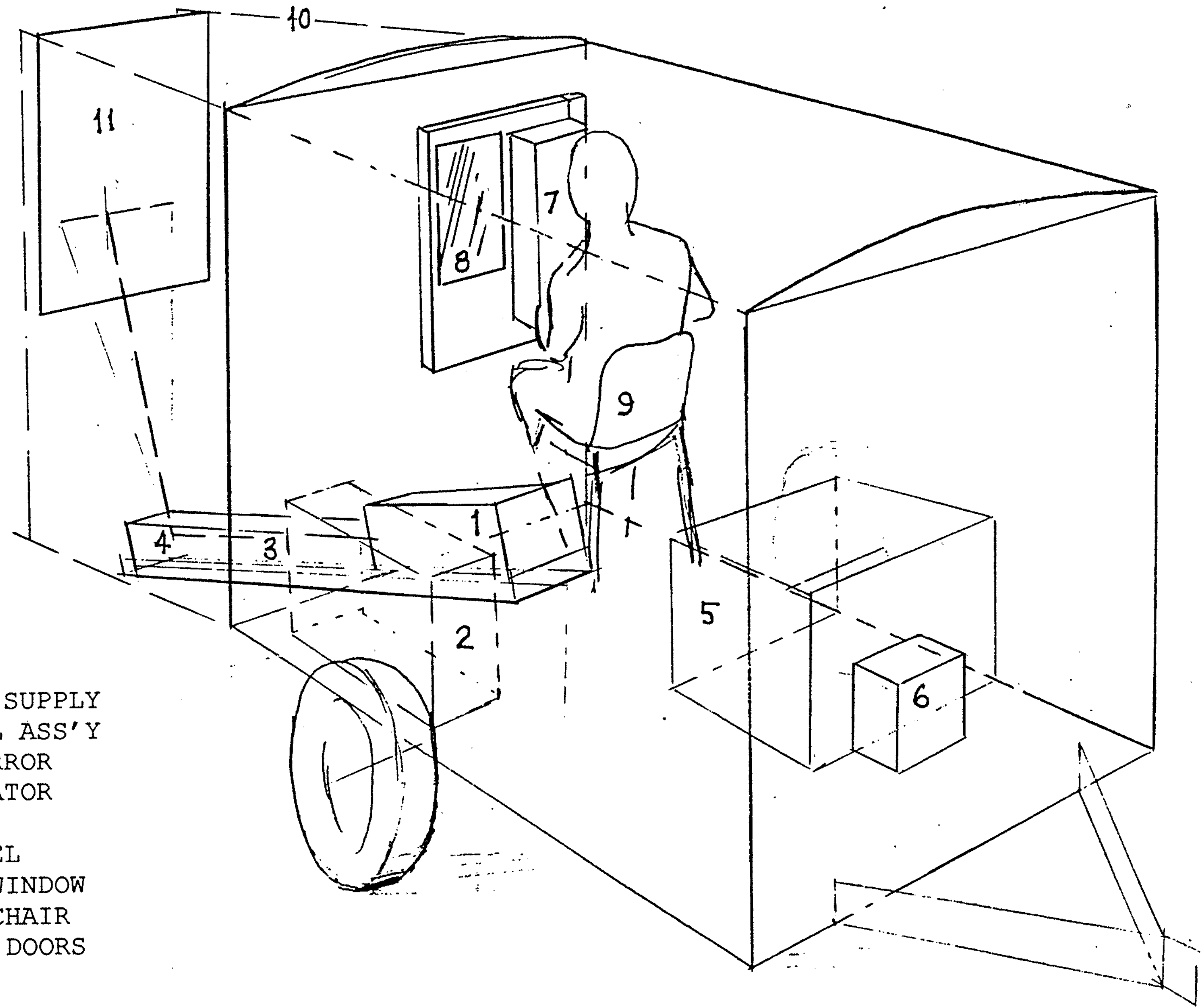
The effort that is being reported here is the development of the first field demonstratable unit. This system includes all the ideas previously generated except for the computer automation. Based on a Caltrans request, the system was designed to be operated at ground level; it was designed to remove graffiti from high intensity signs at freeway entrances.

This final report describes the GRASER, the choices made it in its design, the results of tests of the operation of the completed system, conclusions from the work and recommendations for further developments. The laser beam delivery system was designed and constructed by a Dartmouth student for his Bachelors of Engineering project. The overall GRASER was designed, constructed and tested by Gregory Burke and Robert Russell, Research Engineers at Thayer School of Engineering, with oversight by Professor Elsa Garmire.

SECTION I: SYSTEM DESIGN OVERVIEW

Figure 1 sketches the GRASER deployed for operation and Figure 2 presents simplified engineering drawings. The operator sits in a trailer to operate the unit. A motor generator is located behind and the laser power supply is beside him/her. Previous to operation, after securing the trailer close to the sign, the operator has pulled the optical rail assembly out from its stowed position to extend beyond the trailer to the base of the sign. This rail holds the scanning mirror that steers the ablating laser beam upon the sign.

The operator control panel is attached to a laser safety protective window, both of which must be unlocked from their storage position at the side of the trailer and swung into place before operation can begin. This safety mechanism makes it impossible for the laser to be operated unless the protective window in place. This window, the same as used factories that employ laser cutting, absorbs all YAG laser radiation and makes it possible for the operator to safely observe the sign during ablation.



1 LASER HEAD
2 LASER POWER SUPPLY
3 OPTICAL RAIL ASS'Y
4 SCANNING MIRROR
5 MOTOR/GENERATOR
6 BATTERY BOX
7 CONTROL PANEL
8 PROTECTING WINDOW
9 OPERATOR'S CHAIR
10 CONTAINMENT DOORS
11 SIGN

Figure 1. GRASER Deployed for Ablating a Sign

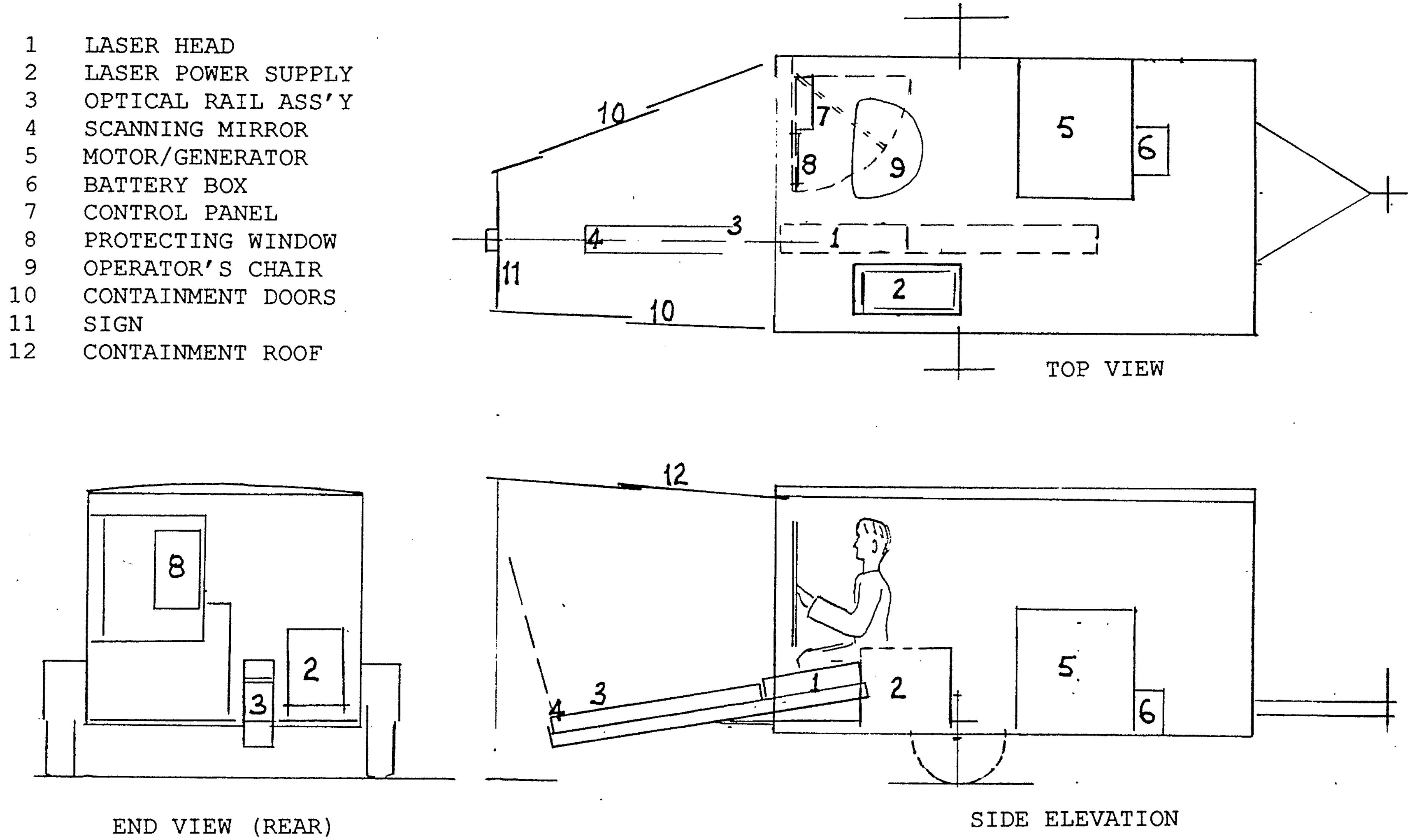


Figure 2. Simplified Engineering Drawings of GRASER

Beam containment screens enclose the sign for the safety of passersby. These screens are hinged extensions on the trailor doors. The operator must unfold them from their stowed positions and place them around the sign before the optical rail assembly can be extended from the trailer.

The laser beam is projected from the laser source down the optical rail assembly to a turning mirror that deflects the beam up at grazing incidence to the sign. Scanning of the laser beam across the sign is achieved by moving this turning mirror. Two stepper motors are employed, one that rotates the scanning mirror through an arc, providing lateral motion on the sign, and the other translates linearly back and forth along the optical rail assembly, providing up-and-down motion on the sign after the beam is reflected from the turning mirror.

Mechanical considerations were a forefront issue in a field-demonstratable unit. The challenge was to get a graffiti removal system out of the laboratory and into the field. The GRASER was designed with the knowledge that the unit was to be transported and demonstrated in many locations. The system needed to be well secured and cleverly disguised to discourage vandalism. To maintain low weight and easy repair the internal structures are constructed of plywood and two-by-fours. Plywood is inexpensive, rugged and easily installed within the trailer. The GRASER was designed as a feasibility demonstration unit and not for commercial purposes. It was intended that most if not all the components of the GRASER including the trailer would be reusable on the next generation of graffiti laser ablation equipment. Thus, as few modifications were made as possible to any of the equipment. This includes the trailer, motor/generator and laser.

The design approach was successful. The GRASER sat outside in the sub-freezing weather of Hanover, NH, with no moth-balling except for removal of water from the laser and removal of the automotive battery. It was put back into operation after moth-balling and it operated in an identical manner. It didn't even require optical realignment.

The main system components of the GRASER system are:

- Trailer
- Operator Controls
- Motor Generator
- Laser system
- Cooling and Ventilation
- The Optical Rail Assembly
- Laser Beam Delivery and Steering Optics
- Beam Containment
- Safety

These will be detailed next in this report.

Trailer

The GRASER is mounted within a lightweight trailer. A common low cost trailer was chosen which would fully enclose, protect and conceal all of the GRASER components. The trailer contains a motor generator, laser power supply, and additional support electronics. The motor generator is positioned as close to the center of gravity as possible maintaining a modest 'tongue weight'. Fans and floor vents provide ventilation such that excess heat and any fumes are removed from inside of the trailer. The laser power supply is centrally mounted to provide easy access, to assist in maintaining a well balanced trailer. No major modifications other than the floor vents were made to the trailer.

Operator Controls

The operator controls are located in a central panel located just on the inside of the operator's viewing window. The controls are attached to the safety viewing window. To access the controls the operator must swing the viewing window in place along with the control panel. This automatically places the operator behind the protective laser viewing window. The controls are rugged and extremely simple. Electro-mechanical relays were chosen as being inexpensive, easily serviced and highly reliable in operation. The control panel also houses the stepper motor driver electronics. The panel is designed as a 'module' that can be removed and opened for service. Most importantly, the operator controls can be interlocked to ensure operator safety.

The Motor Generator

The motor generator contains a 5 kW, gasoline powered, two-phase alternator. The unit is capable of two phase 240 VAC, single phase 115 VAC and 12 VDC. The unit is totally self-contained and mounted upon its own cart. Operation and maintenance instructions are contained in the GRASER Instruction Manual. The Motor Generator is intended to be used on this and any future development on this project. The laser requires 240 VAC two-phase; the cooling and ventilation fan requires 115 VAC. Both are plugged into the motor generator. A battery provides starting power and runs the lights.

The motor/generator is contained within a plywood cabinet. The cabinet is designed to be opened for easy access and removal of the motor/generator. The purpose of the cabinet is to assist in directing ventilating air from the fan into and around the motor/generator and for noise reduction. Air is drawn in through the operator compartment and exits through louvers in the floor directly below the motor generator. Exhausts from the gasoline motor are ducted out through the floor, back and forward towards the 'tongue' of the trailer, where the exhaust exit port is located. This assures that no exhaust gases are present inside the trailer at any time. Fresh air is pulled in through the open doors of the rear of the trailer, while hot air exits below the trailer; exhaust gases exit at the front near the tongue or hitch of the trailer.

Laser System

The laser system was chosen based on experimental results obtained in the first and second phases of this project. It was determined that a short intense laser pulse would ablate the graffiti with minimal damage to the retro-reflective qualities of the highway sign. A Nd:YAG laser pulse-pumped by a flashlamp operating at 20 Hz was demonstrated to be the best approach. The least expensive laser that met the required output power (650 mJ per pulse in a pulse 4-6 nsec wide) and optical beam quality (0.6 mrad) was chosen. It was model Surelite I-20, purchased from Continuum, Inc.

The laser is provided with its own power supply from the manufacturer. Details on this power supply, its operation, maintenance and safety issues are contained in the manufacturer's manual provided in the GRASER Instruction Manual.

Cooling and Ventilation

Motor/generator

As previously described in the motor/generator section, cooling air is drawn in by the fan and passed over and through the motor generator area. The hot air is ducted down and out through louvers located beneath the motor generator. The louvers also allow for any spills of oil or overfilling of gasoline to safely exit the motor generator cabinet. The motor/generator has plenty of ventilation so that no additional venting prior to starting is needed; this is an importance consideration where gasoline is stored in enclosed areas. Fresh air is drawn in by the fan by way of the open rear doors of the trailer and out through the floor of the trailer.

Optical Rail Assembly

Two 'muffin' fans are located on the optical rail within the beam delivery system. The purpose of these two fans is to maintain a slight positive pressure inside of the optical beam and across the internal optics. This includes the output mirror. The purpose is to attempt to keep these components clear of dust and other atmospheric contaminants, which may be present during the ablation process. A cover is provided which effectively closes this area when the system is being transported.

Optical Rail Assembly

The optical rail assembly houses a HeNe laser pointer, optical shutter, YAG laser and the laser beam steering assembly. The optical rail assembly approach was chosen after much deliberation as a safe, rugged and reliable method to direct the laser beam onto the sign. Safety interlocks assure the operator must be behind a protective partition before the laser beam can be projected onto the sign. The optics, laser head, and steering optics are mounted upon a single, rectangular aluminum rail that is 4" X 6" X 6' long. The rail is provided with Teflon slides which enable sliding of the rail into and out from the trailer (along a base that is attached to the trailer). The unit is completely self contained with air piston lift, hold assist, as well as provision for locking and tilting of the rail at the correct angle.

The design decision to use the rail approach was made after much deliberation. The problem was how to allow the operator to view and ablate a sign significantly higher than the trailer itself. The solution was to position the operator near or at the rear of the trailer and allow for the laser beam to reach up to the top of the sign. However, to achieve this, the laser must also be projected from some point outside and beyond the rear of the trailer. This meant that the laser beam and beam steering optics needed to be positioned somewhere several feet beyond and at an angle to the sign itself. We wished to avoid setting optics upon the ground, and also wished to avoid or discourage people 'stepping over' such optics for safety reasons. Additionally the laser beam steering optics needed to be coupled and accurately aligned to the output of the laser head. The solution was to mount the laser head, aiming beam, and steering optics onto a single rigid rail. The use of the rail solved the alignment problem.

A major innovation to the optical rail assembly was the base slider. This allowed the optical rail to be withdrawn and re-inserted into the trailer. The first method considered would have used linear Ball bearings. This method seemed environmentally unsuitable (due to dirt, etc.) and the use of Teflon guides/slides was deemed more suitable. The aluminum base is rigid, stable and allows for shock mounting to the trailer floor. This was a more desirable solution in light of a somewhat flexible trailer floor. The aluminum base, Teflon slides, and aluminum rail have proved to be an ideal solution. The Teflon sides are provided with a locking clamp which can hold the rail in any position along the base.

The base also provides a method for using gas springs to assist the operator in tilting the rail. The gas springs push upward, lifting the laser head. This allows the user to release and position the rail at exactly the desired 10 degree angle. The force of the gas springs holds this position, yet allows some flexibility should the rail accidentally get 'bumped'. Internal to the rail is a simple latch mechanism, which is released by a small 'pull ring' at the front of the assembly. The latch securely holds the rail in place during transport.

To extend the rail the operator unlocks the Teflon guide/slider and withdraws the assembly from the trailer and re-clamps the slider. Once removed the user can pull the release ring. This allows for the rail to be tilted at the fixed angle of 10 degrees. The rail assembly is re-installed into the trailer in the reverse fashion.

Laser Beam Delivery and Steering Optics

The output from the YAG laser is directly projected onto the sign to be ablated. The laser beam has a divergence of less than 2 mrad at full power which results in an approximate 6.0 mm spot size on the sign, which is typically positioned about 2 meters from the laser output aperture. This spot size is nearly ideal for the ablation process. The laser output is directed along the beam through the steering system and reflected by a high reflectivity dielectric turning mirror up and onto the sign. The location of the turning mirror, a meter from the output aperture of the laser head, allows for some divergence, prolonging the life of this mirror.

Beam blocks and safety shutters

There are four safety blocks to the laser beam in the ablation laser system. Two are mechanical and two electronic:

1. A shutter inside the laser cavity, provided by the manufacturer. This intercavity shutter is controlled through various electrical connections internal and external to the laser. This intercavity shutter is integral to the laser system and is also controlled by the on-board computer. Other important functions such as low water level, laser over-heat and low flow are under the control of the laser power supply. The manufacturer's manual, included in the GRASER Instruction Manual, contains more information with respect to water flow and water temperature interlocks.

2. An external interlock (designed in this project) activated by the operator's 'ablate' button. When the operator presses the 'ablate' button, a solenoid removes the laser pointer turning mirror that usually blocks the YAG beam. This motion activates a micro-switch that sends the signal that fires the laser.

3. A manual mechanical shutter located at the output of the laser head. When transported for long distances, or stored for several months, we recommend that this shutter be 'closed' to prevent dust and dirt from entering this area.

4. A physical block to the ablating beam by means of the laser pointer turning mirror. This turning mirror must be fully withdrawn from the laser beam path before the YAG laser can be fired and in doing so closes a micro-switch which allows the intercavity shutter to open. This prevents the intercavity shutter from opening while the laser pointer is in use and adds a small delay, allowing time for the laser pointer turning mirror to be fully withdrawn from the beam path.

These four beam blocks assure that only the operator can operate the main ablation laser.

The laser pointer

A small low power HeNe laser pointer is mounted on the optical rail system. This provides the operator a visible spot which indicates where the invisible ablation laser beam will hit the sign. The laser pointer and the ablation laser light beams are co-axial. This laser pointer is operated using a switch located on the operator's control panel. The two turning mirrors can be adjusted to aim the pointer's beam co-axially. One mirror is fixed while the other is mounted upon a swing mount, which contacts a micro-switch when fully withdrawn from the laser beam path. This solenoid-operated swing mount is activated using the 'ablate' button on the users control panel. There is also a switch located on the body of the laser pointer itself.

In the future a green colored visible laser pointer would be preferable to the red HeNe laser. A green laser spot would be would provide better visibility. The cost for these lasers was prohibitive at the time that the demonstration GRASER system was designed. Their cost has come down dramatically and such a green laser pointer will be used in the future.

The Steering Optics (common to both lasers)

The beam steering optics is designed to steer the ablating YAG laser and the laser pointer beams in the X and Y axis. The system contains two small stepper motors. The motors are driven through a series of electrical pulses. The pulse driver electronics are contained within the operator's panel. The beam steering unit was designed to be simple, robust and reliable.

The first motor controls the lateral sweep of the beam from left to right and in doing so determines the 'dwell' or overlap of the ablation laser light pulse on the sign. The sweep speed indirectly dictates the amount of energy delivered to the area covered by graffiti. The slower the sweep, the longer and more of the laser beam is delivered to a designated area. The user can adjust the sweep through a small potentiometer located on the bottom of the operator's control panel. The dielectric laser turning mirror is mounted directly to the shaft of the first stepper motor. There are small projections from either side of the mirror mount which contact micro-switches which limit the distance traveled. When the 'ablate' button is pushed only the first stepper motor is operated. All other functions are locked out.

The second motor moves the beam up and down the sign using a polymer coated drive chain system. The speed for this motion is fixed and is only adjustable by opening and adjusting a potentiometer within the operator's control panel. In most cases there is no need to adjust the speed of this motor.

Both the laser pointer and the high power ablate laser beams impinge on the dielectric turning mirror.

Beam Containment System

A major obstacle in the design of the GRASER was the laser beam containment system. This was overcome through a series of extensions on the trailer doors. These extend from each of the trailer doors, unfold and reach around the sign to be ablated. A top containment roof is lifted and placed at the top of the sign and is linked to the top of the trailer. These three containment doors prevent any laser light from exiting the ablation region and reduces the amount of sunlight present. A reduction of sunlight is necessary for the operator to properly view the sign, the progress of the ablation and restoration of the sign retro-reflective qualities. Canvas curtains serve to further protect and isolate the sign from sunlight and to discourage the general public from attempting to view the ablation operation. While the diffuse scattered light from the sign is within eyesafe limits, it remains a good policy to keep non-qualified personnel away from the ablation process.

There is no need for the doors to extend to the ground; in addition, air for cooling and ventilation is needed and is pulled from under the doors.

Safety

The GRASER system was designed from its early conception with safety being first and foremost in mind. The ablation laser emits an extremely powerful invisible light beam which can cause serious eye damage. Every precaution was made to ensure that the operator MUST be behind the protective observation window before the ablation procedure can begin. In addition, the ablation shields provide for an enclosed region which would limit access to persons who are not protected, yet provides proper ventilation. The operator has complete visibility of the ablation region while operating the laser thus ensuring that no persons can enter the area unseen.

SECTION II: SYNOPSIS OF CRITICAL PERFORMANCE TESTS

A series of tests were completed on the GRASER to evaluate its performance. What follows is a short synopsis of three major tests confirming proof of concept and operation.

Test 1

1. Goal: Evaluation of Controls and Safety Interlocks

The purpose of this test was to ensure operator safety and safety to all persons in or around the GRASER while in operation.

The motor/generator and laser controls were operated without the laser lasing to insure that they were in working order. The coaxial laser pointer was directed to simulate the ablation laser to ensure that no light from the laser would exit the ablation area. The controls were checked for reliable performance and the position of the operator was evaluated to be sure any risk of exposure was minimized.

2. Results

The controls worked perfectly. The operator has full visibility without incurring any risk of exposure. The laser pointer confirmed that no laser light could exit the enclosure.

3. Conclusions

The system worked as intended with no major form/fit design suggestions.

Test 2.

1. Goal: Overall performance

The first test involved the optics, steering and controls. No serious attempt to ablate graffiti was made in this first test.

The laser beam was swept across a non retro-reflective ‘stop’ sign. The sign had regions that both were and were not covered in graffiti. The purpose of this test was as follows:

- Evaluate sweep speed control
- Evaluate beam overlap
- Evaluate beam size (between the top and bottom of the sign)
- Evaluate ablation/beam range and adjust limits
- Evaluate operator controls and ergonomics

2. Results

The sweep speed control worked well. No changes appeared necessary. The operator WILL have to adjust sweep rate to increase overlap in regions that are more heavily covered in graffiti. Also, the operator will have to increase the sweep rate at the bottom of the sign and decrease the sweep rate at the top of the sign to compensate for spreading of the beam. The spot size was approximately 6.5 mm at the bottom and 8 mm at the top of the sign. Spot sizes smaller than 6 mm can cause permanent damage to the sign media. Beam spots of greater than 9 mm do not ablate the graffiti evenly. The range or coverage was set by adjusting the limit tabs and micro-switch position.

3. Conclusions:

The overall performance of the optics, steering system and controls was satisfactory. The operator could view the entire sign and could exercise full control over the laser sweep speed. A minor suggestion may be to add a slight delay in opening the intercavity shutter at the beginning of the sweep function. A slight delay was noted between movement of the sweep motor and initiation of the first few ablation pulses. This resulted in a slightly greater overlap at the beginning of the sweep/ablate function.

Test 3.

1. Goal: Ablation of graffiti covered substrate

We had possession of several small sections of retro-reflective high intensity sign material. These were placed at three different locations of our 'mock sign': top, middle and bottom. The purpose was to evaluate the GRASER's performance in removing paint from these small sections.

2. Results

The GRASER successfully ablated the graffiti from all three samples. The samples at the top of the sign did require a 'second' pass as the operator neglected to slow the sweep rate for the first pass. The samples at the bottom of the sign were 'cleaned' the best and samples located in the central region were adequately cleaned on the first pass.

3. Conclusions

- The GRASER as envisioned effectively ablates graffiti from sample retro-reflective highway signs.
- The ablation process does leave a slight residue which needs to be removed before the retro-reflective qualities of the sign are restored. However the residue is light and easily cleaned.
- The operator MUST adjust the sweep controls to ensure even ablation between the top and bottom of the sign.

Note: Further ablation tests were conducted; however these tests were limited due to not having several 'full size signs' to work with. Sign sections were strategically located to emulate a much larger sign.

SECTION III: PROVIDING DELIVERABLES

A videotape of the process of graffiti removal was recorded, edited and sent to Caltrans. This video was made using the GRASER on a sign that was set up on-location at Dartmouth. The GRASER was positioned in place and was used to remove sunlight-cured paint, mimicking graffiti that has been in the field for a long time. The video demonstrates that the GRASER operated as expected; graffiti was successfully removed. Retro-reflection of the sign was then restored by polishing. Thus the video also proves that graffiti can be removed with the GRASER without damage to the retro-reflecting properties of the sign. The videotape also gives instruction on how to operate the GRASER and records the movements of the operator during the procedure.

A GRASER instruction manual for was put together and provided to Caltrans. The manual includes photographs and text outlining the Specifications, Field Operating Instructions, Maintenance, and Theory Of Operation. The appendices include electrical and mechanical schematics and the manufacturers' Users Manuals. The Field Operating Instructions include: Setting Up, Safety, Cold Start, Warm Start, Ablatingthe Sign, Cleaning the Sign, Shutting Down, Extended Shutdown, Electronics and Electrical, Motor Generator, Laser System, and Laser Optics. A copy of the manual is kept with the GRASER at all times.

The GRASER system was moth-balled after the completion of funded contract. The laser and motor-generator are being stored at Dartmouth Thayer School of Engineering, for safe-keeping. The trailer is stored safely in a parking lot. The GRASER is being stored pending a further follow-on research program, or an expression of interest from a private company. The moth-balling has been designed so that the system can be put together at a moment's notice. It can also be shipped to Caltrans if requested. The system has been taken out of moth-balls once, put together and run successfully without even any additional optical alignment.

SECTION IV: CONCLUSIONS AND RECOMMENDATIONS

The GRASER as designed will clearly demonstrate the effectiveness of using laser ablation to remove graffiti from highway road signs. The unit is self contained, lightweight, reliable and easily set up in the field to demonstrate its capabilities.

A demonstration videotape was created and has been provided to Caltrans. The GRASER is designed to be brought to California and demonstrated there. However, if follow-on work toward a second-generation GRASER will use the same laser, it would be better to keep the GRASER in New Hampshire. The videotape documents its performance.

Several recommendations are offered here for further studies which would enhance a second generation GRASER unit:

1. Improved Mechanisms for Removal of Residual Film

The GRASER is completely successful at ablation of graffiti. However, when used on high intensity highway signs, it requires a subsequent cleaning operation to fully restore the retro-reflection. A light abrasive or cleanser such as " Bon-Ami" has been shown to work well with hand-polishing. If post-ablation cleaning could be eliminated entirely, there would be a significant reduction in time, labor, and materials. There is need for further study to investigate whether suction or a gas jet during ablation could successfully remove the residual film.

The alternative is to design an automated clean-up system, in the form of a roller-buffer, or to adapt a small hand-operated electric polisher to automated operation by following the laser around as it moves across the sign removing graffiti.

2. Ablation reproducibility and reliability

The GRASER needs to be validated as providing a reproducible and reliable means of graffiti removal. (This is the "Dem/Val" process.) While the GRASER has been proven to remove graffiti successfully, many questions remain with respect to the uniformity of the ablation process over large areas and the ability to consistently remove various types and thickness of graffiti. There are additional questions as to successful ablation over sign regions having various background coloring as well as different graffiti media, depth, and pigmentation. The GRASER can be used to gather and process this data. For example, is it better to move the laser beam slowly over the surface, being sure to remove the entire paint layer in a single pass? Or is it more cost-effective to make several rapid passes, each one removing only some fraction of the paint layer? This needs to be investigated and will provide further understanding of laser light interaction with surface materials such as paint. The demonstration that laser ablation can provide reproducible results is imperative to a fully operational system and necessary for a full cost-effectiveness analysis.

3. Re-evaluation of cost effectiveness

The cost effectiveness of laser ablation was theoretically evaluated in the original contract and it was projected that, with a successfully designed system, laser ablation would save time, materials, lower labor costs, and conserve resources. Most importantly, it provides workers with a safer work environment by elimination of harsh chemical cleaners and the risks associated with overhead sign work.

The implementation of the field demonstration unit clearly established the ability to use laser ablation in the field. Using the GRASER to obtain further data will enable a re-examination of the cost-benefit equations using data on reproducibility and reliability from a working system. Such experiments using the presently constructed GRASER will allow predictions as to what improvements can be made to further enhance the current system.

4. Evaluate the 'Latest Generation of Optical Fiber Technology'

The GRASER directs the laser light using a single mirror system onto a retro-reflective sign. This technique has distinct advantages as well as several disadvantages. The main advantage is its simplicity. The GRASER uses two separate stepper motor servos and one highly reflective mirror. The delivery system is extremely efficient and nearly 99% or more of the laser light is delivered on the targeted region. The system is robust, efficient and inexpensive.

The main disadvantage of the single-mirror system is the limited spatial region of effective ablation. This results from the characteristics of the laser source in combination with geometric considerations relevant to the projection of light over a wide two dimensional surface at a shallow angle. Variations in spot size, translation speed and fluence potentially affect the reproducibility and repeatability of the ablation process.

The laser source has a finite divergence angle; the laser's divergent beam results in an ever-increasing spot size as the distance increases from the laser aperture, resulting in a weaker interaction with the graffiti. Nearer the laser, where its spot size is smaller and the light is more intense, graffiti may be easily removed. Farther away it is more difficult and takes longer. This effect is most pronounced at the extreme ranges of the GRASER's range, i.e., near the top and far edges.

During the initial stages of the design process the use of optical fiber to guide the laser light to the sign was considered and discarded, because of concern over damage to the end of the fiber. Since the initial optical design, however, there have been considerable advances in high power optical fiber technology. It is appropriate to re-evaluate the use of high power optical fibers to deliver the laser beam, in light of the drawbacks of the GRASER optical listed above and the potential improvements in optical fiber technology. A moving optical fiber feed would remove the main disadvantage of the single-mirror system. It would make possible uniform illumination everywhere over the sign. An alternative to overcome this disadvantage is a computer automated system, discussed below.

5. Optical Delivery Optimization for Graffiti Removal on Overhead Signs

It is of interest to consider adapting the GRASER to operate on overhead highway signs and bridges. It would be appropriate to investigate achieving a laser graffiti removal system compatible with being mounted on a "Cherry Picker".

There are three concepts for getting the ablation laser light to an overhead sign. The first implements direct beam delivery, using the laser system designed in the GRASER with minor modifications and mounting it on a "Cherry Picker". The second concept uses a mirror system "articulated arm" attached to the "Cherry Picker" with the laser mounted remotely at the truck, and the third system considers using optical fibers to transport the laser light from the truck to the "Cherry Picker" (and the sign). All three possibilities need to be evaluated to decide on the optimal design for a laser ablation system compatible with overhead high intensity highway signs and other overhead structures such as bridges. Preliminary considerations are outlined here:

A. Direct beam delivery

This implements the GRASER optical system with the laser head mounted locally on a "Cherry Picker" for overhead operation. In this concept the current optical system as developed for the GRASER would be utilized. The major change is that the laser beam would travel at a shallow angle down rather than up (to avoid damaging the retro-reflection seen from below by cars). This modification can be made replacing only a few of the present components. Minor modifications/improvements based upon more experience with the GRASER should be included, such as those that would guarantee a uniform ablation path of 4' x 8' or more.

Putting the laser as close as possible to the ablation target conserves useful light as much as possible and it would make use of the lessons learned from the previously designed GRASER. However, the "Cherry Picker" would have to account for the extra weight of the laser, power supply and supporting structural components. This would increase the basic weight of the overhead ablation system by an estimated 400 lb. The motor-generator would remain in the vehicle and electrical power (220 VAC) would be transported up through the arm of the "Cherry Picker" to power the laser system. The alternative of keeping the laser power supply in the vehicle and placing only the laser head on the "Cherry Picker" would be evaluated as a back-up. This latter approach provides somewhat more security to the system against theft and would place less weight on the "Cherry Picker", but requires water and high voltage to travel long distances up the arm of the "Cherry Picker".

B. Articulated arm delivery

In an effort conserve space, weight and size; consideration has been given to mounting the complete laser remotely within the vehicle. The motor-generator, laser and power supply would be permanently mounted within the vehicle and the light would be directed through a series of mirrors up through the articulating arm to the overhead sign. Such systems are commonly used in manufacturing environments and also for medical applications. The mirror system would be identical in design to those that transport infrared laser light (which cannot be efficiently conducted through optical fibers) to targets. The articulated arm saves weight and places the laser system in a protected and controlled environment (by including a sleeve to protect against contaminants). The result is an articulating arm ablation package that is considerably lighter and more compact than mode A. above. The weight reduction is important when the "Cherry Picker" needs to be lifted to the overhead sign. The disadvantage is that there is more opportunity for mirror misalignment (which can be controlled with servomotors, however), the need for ruggedization, and the possibility of increased energy losses through the long optical transmission system.

C. Optical fiber delivery

Delivery of the laser light through an optical fiber could prove to be the most effective and efficient overall method. The motor-generator would remain stationary in the vehicle along with the laser power supply and laser head. The laser light would be coupled into a large core silica fiber and transmitted remotely through the articulating arm to the overhead ablation system. At the overhead ablation site the laser light would be re-collimated, refocused and directed onto the sign. This system would overcome many of the problems associated with the current system, as the distances and angles of the projected laser light would be consistently maintained. This system would be low loss, rugged, reliable and offer repeatable ablation energy. There are several unanswered questions, however, about the success of coupling the high laser energies necessary to remove graffiti. Most importantly, can we obtain sufficient intensity to ensure graffiti ablation without damaging the ends of the fiber? This option should be evaluated by investigating a variety of applicable fiber types.

6. Remote operation using computer assisted automation and imaging

A result of the research outlined in this final report is the concept to acquire and process images using computer assisted image processing techniques. Ideally, NO workmen would need to be at or near the overhead sign. All imaging and ablation would be done from the ground. This would improve the safety of workmen and fully protect them from accidental exposure to laser radiation or injury from falls. A project is needed to develop such an imaging system. Several similar successful systems have been used in space exploration and in hazardous material handling environments. This would be the first implementation of this technology to laser ablation of graffiti. A fully automated system would depend on several achievements:

- Development of methods for remote evaluation of the graffiti (preferably automated identification) using high resolution cameras and computer imaging techniques.
- Development of computer software which can predict with high accuracy regions of the sign where the laser light needs to be directed.
- Elimination or automated removal of the film caused by laser ablation (such as automated mechanical polishing).

Several steps are needed to achieve the required automation development:

a. Improved operator interface

At present the GRASER operates manually with the controls introduced by the laser manufacturer. The computer must be interfaced to the equipment to allow remote operation.

b. Computer assisted diagnostics of regions requiring ablation

Camera systems can be used in conjunction with a high speed computer capable of rapidly processing complex images and performing rapid image analysis. The high intensity highway signs are particularly valuable for this operation because retro-reflection is "blackand-white". That is, the regions in which there is no retro-reflection stand out very clearly when properly illuminated.

c. Remote operation

Computer assisted diagnostics may make it possible to completely eliminate the operator from the "Cherry Picker's" operator station. This will further reduce weight and size of the overhead ablation system.

d. Safety interlocks

One advantage of a computer-operated imaging system is the potential to automatically detect movement in the image (such as a person coming into the field of view) and to turn off the laser through an interlock. This provides the ultimate safety for using a laser ablation system remotely in areas where people (or animals) might have access.