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**THREE-IN-ONE  
VEHICLE OPERATOR SENSOR**

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**INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS  
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This investigation was completed as part of the ITS-IDEA Program which is one of three IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in surface transportation. It focuses on products and result for the development and deployment of intelligent transportation systems (ITS), in support of the U.S. Department of Transportation's national ITS program plan. The other two IDEA programs areas are Transit-IDEA, which focuses on products and results for transit practice in support of the Transit Cooperative Research Program (TCRP), and NCHRP-IDEA, which focuses on products and results for highway construction, operation, and maintenance in support of the National Cooperative Highway Research Program (NCHRP). The three IDEA program areas are integrated to achieve the development and testing of nontraditional and innovative concepts, methods and technologies, including conversion technologies from the defense, aerospace, computer, and communication sectors that are new to highway, transit, intelligent, and intermodal surface transportation systems.

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## EXECUTIVE SUMMARY

The Three-in-One Vehicle Operator Sensor envisioned by Northrop Grumman uses non-intrusive eye tracking and image analysis to perform the following functions: (1) Drowsy Driver Recognition, (2) Anti-Theft Protection, and (3) Alcohol Impaired Driver Recognition. This sensor could have a significant impact on safety by decreasing the number of accidents caused by either drowsy drivers or intoxicated drivers. In addition, the sensor could help prevent vehicle theft by verifying the identity of authorized vehicle operators based on physical characteristics of their eyes (iris verification). Various schemes for application of the identity verification feature may even prove to be a deterrent to vehicle hijacking.

Northrop Grumman initially intends to develop and deploy a drowsy driver recognition sensor for application to commercial trucking. Wider application to passenger automobiles will follow closely. A sensor that performs both drowsy driver recognition and anti-theft protection is envisioned next. If market interest in alcohol-impaired driver recognition becomes evident, development of that function will follow. This staged approach to development will facilitate earlier introduction of a sensor performing the functions that the marketplace desires most.

The investigators successfully demonstrated drowsy driver recognition algorithms during the execution of this ITS-IDEA contract. Development and initial testing was accomplished with the use of data gathered in the Northrop Grumman driving simulator. The algorithms were further tested and demonstrated using imagery of drowsy drivers obtained from a major domestic automobile manufacturer. The fact that the algorithms correctly identified signs of drowsiness in the automobile manufacturer's imagery is especially significant because: (1) the drowsiness recognition algorithms were not altered

before they were applied to the imagery, (2) the simulator that was used to gather the imagery had a different camera and lighting scheme, and (3) the subject in the video was wearing eyeglasses (with significant reflections). The feasibility of alcohol impaired driver recognition was also demonstrated, using Northrop Grumman Independent Research and Development funds.

While independently working on anti-theft protection, Northrop Grumman became aware of an iris verification system developed at Los Alamos National Laboratory. The investigators visited Los Alamos and witnessed successful demonstrations of their system. Discussions indicated that their approach could facilitate vehicle anti-theft protection. Northrop Grumman subsequently funded Los Alamos National Laboratory, using Independent Research and Development funds, to examine issues specifically related to the performance of iris verification for anti-theft protection of vehicles.

The investigators intend to further test the robustness of the sensor system by using imagery data from planned sleep studies at the Walter Reed Army Institute of Research. The studies are scheduled to begin in the fall of 1995 and will employ a large number of truck drivers as subjects. This imagery and associated data will be used to further validate and, if necessary, reline the drowsiness recognition algorithms.

A prototype sensor will be constructed, based on the results of this ITS-IDEA project, for testing in both simulation facilities and in vehicles. The investigators will work with representatives of the user community, such as the American Trucking Association' (ATA) Foundation, as well as major domestic automobile manufacturers and their suppliers in the ongoing development and deployment of the Three-In-One Vehicle Operator Sensor.

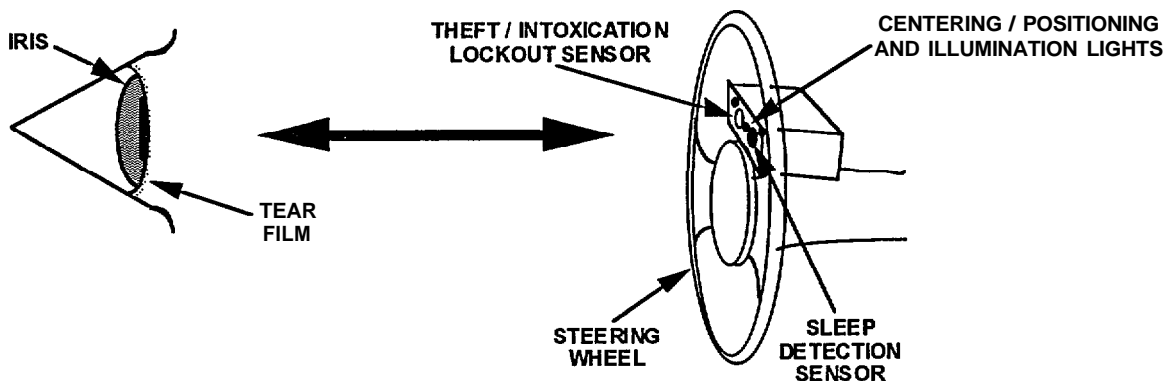


FIGURE 1 Three-In-One Vehicle Operator Sensor

## **IDEA PRODUCT**

The Three-in-One Vehicle Operator Sensor envisioned by Northrop Grumman uses non-intrusive eye tracking and image analysis to perform drowsy driver recognition, anti-theft protection, and alcohol impaired driver recognition. The sensor could have a significant impact on safety by decreasing the number of accidents caused by either drowsy drivers or intoxicated drivers. Additionally, the sensor will help prevent vehicle theft by verifying the identity of authorized vehicle operators based on physical characteristics of their eyes (iris verification). This feature could reduce asset losses of individual owners and, collectively, the insurance industry. Various schemes for application of the identity verification feature may even prove to be a deterrent to vehicle hijacking. Based on the results of the research, the investigators will concentrate future development on drowsy driver recognition and anti-theft protection.

## **CONCEPT AND INNOVATION**

The Three-in-One Vehicle Operator Sensor is unique in that it will non-intrusively perform its three functions in a single, integrated package. This is accomplished by processing the outputs of a single electro-optical sensor.

### **DROWSY DRIVER RECOGNITION FUNCTION**

The drowsy driver recognition subsystem will continuously monitor the driver's state of alertness and will trigger an alarm and/or another form of stimulation when there is a decline in the state of alertness of the driver beyond a predetermined threshold. The drowsy driver recognition subsystem uses innovative algorithms that can optically track facial features, including the eyes and the eyelids. The algorithms accumulate evidence of drowsiness over time. The algorithms have been developed so that they can also use other information concerning the state of alertness of the driver, such as steering wheel motion information, to enhance subsystem performance. Northrop Grumman's current implementation of the drowsy driver recognition function relies on facial imagery for primary determinants of drowsiness, with steering wheel motion data used as a corroboratory indicator.

### **ANTI-THEFT PROTECTION FUNCTION**

The anti-theft subsystem will optically monitor the vehicle operator's iris (of the eye) during the engine start sequence and disable the start if there is not a match against a stored set of authorized operator iris patterns.

Iris patterns are unique for each individual, just as fingerprints are. The uniqueness is based on color and markings including striations, color flecks, contraction furrows, pigmentation variations, freckles, and defects known as nevi. The combination of features used for vehicle anti-theft protection will be determined by carefully weighing subsystem costs against the level of protection required.

### **ALCOHOL IMPAIRED DRIVER RECOGNITION FUNCTION**

The alcohol impaired driver recognition subsystem will illuminate and optically monitor the vehicle operator's eye during the engine start sequence, concurrent with the driver identification process described above, and disable the start if signs of alcohol consumption in excess of predetermined thresholds are detected. This configuration eliminates many of the deficiencies of the current technology, including the possibility of a non-intoxicated passenger providing the critical breath input.

## **INVESTIGATION**

The primary goal of the Three-in-One Vehicle Operator Sensor Project was to demonstrate the feasibility of non-intrusively performing the three functions proposed for the sensor. The investigators successfully demonstrated drowsy driver recognition algorithms in the execution of this ITS-IDEA contract. The basic feasibility of alcohol-impaired driver recognition was also demonstrated, using Northrop Grumman Independent Research and Development funds.

While independently working on anti-theft protection, Northrop Grumman became aware of an iris verification system that had been developed at Los Alamos National Laboratory. The investigators visited Los Alamos and witnessed successful demonstrations of their system, which was developed under the sponsorship of an agency of the U.S. government. Discussions indicated that their approach could facilitate vehicle anti-theft protection.

### **DROWSY DRIVER RECOGNITION**

The investigators successfully demonstrated drowsy driver recognition algorithms as part of this project. Development and initial testing was accomplished with the use of data gathered in the Northrop Grumman driving simulator. The algorithms were further tested and demonstrated using imagery of drowsy drivers obtained from a major domestic automobile manufacturer.

## Imminent Sleep Studies

A review of the literature failed to uncover any study that directly attempted to induce sleep in an operator while on duty. The literature indicated that the impact of drowsiness was most likely to be manifested in operator EEG, eye blinks/eye closures, and a loss of tonus of the anti-gravity muscles. It was therefore decided that an imminent sleep study should be performed to gather video imagery and determine if the imagery could be used to differentiate between drowsiness/imminent sleep onset and alertness.

The test apparatus consisted of an available laboratory simulator, modified for the purposes of this study. The car simulator consisted of three key elements: a networked computer system, custom software to model vehicle handling characteristics and to provide simulated roadway imagery, and a suitably modified automobile with a 21 inch monitor placed in front of the driver to provide the out-the-window view. The steering wheel and foot pedals were interfaced with the computer system for control purposes. The steering wheel inputs resulting from this interface were downloaded and analyzed.

Two adult male volunteers served as test subject drivers. They "drove" the simulator on two occasions each. For the alert condition tests, the subjects had obtained a normal night's sleep the previous night. For the drowsy condition tests, the subjects had gone without sleep the previous night and had taken two sleeping pills to accentuate the feeling of drowsiness.

The test procedure involved having the drivers drive repeatedly around the simulated track, an egg-shaped loop three lanes wide. This necessitated that the driver make small steering wheel corrections continuously throughout the tests. Each lap around the loop took a little more than seven minutes, which constituted one trial. The vehicle was placed in automatic cruise control, so that the apparent speed was 40 mph. By simplifying the driver's task so that he never needed to use the foot pedals, the driving task was rendered more boring.

To determine the impact of drowsiness on driver performance, several performance measures were taken. Since the purpose of the study was to explore whether features of a driver's facial morphology can be used to automatically detect drowsiness, a video recording was made of the front view of the driver's head and neck. Driver deviation from track centerline and steering wheel control movements were measured, recorded, and analyzed to corroborate the impact of drowsiness on driving performance.

The analyses of the corroboratory data showed clear differences in driver performance between the alert and drowsy trials. Both drivers showed the same pattern of performance deterioration with drowsiness. Although the mathematical mean of centerline deviation for both alert

and drowsy conditions was similar, the statistical measures of distribution indicate that the absolute deviations of the drowsy drivers were much greater. Steering wheel control movements also showed clear differences between the alert states and the drowsy states. These steering wheel movements are easy to obtain in actual vehicles, using proven technology. The investigators now consider certain patterns of steering wheel movement to be strong corroboratory indicators of drowsiness.

## Drowsiness Recognition Algorithm Development and Demonstration

There are two critical issues that any drowsy driver recognition system must address. The first is the question of how to accurately detect drowsiness at the initial stage. The second is the issue of how to alert, stimulate or refresh the driver when drowsiness is detected. For this task, effort was focused on addressing the first issue, detecting the drowsiness as early as possible using innovative detection algorithms. Once drowsiness is detected, some form of alert or stimulation will be initiated.

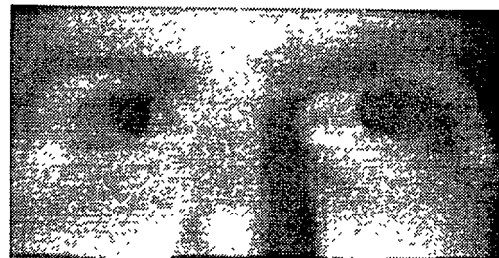
In the process of developing the algorithms, the investigators developed the capability to convert analog videotape imagery directly into digital images hosted on a VAX mainframe computer. Once the digital images were uploaded to the VAX, they were analyzed with an array of existing tools and became an integral part of algorithm development. A representative database of digitized imagery from the imminent sleep studies, in both the alert and the drowsy conditions, was uploaded. From this digitized database six segments were selected (three alert and three drowsy segments) for data analysis and algorithm development. Each segment consists of 1600 frames of digital imagery. The resulting data was then divided into two independent sets. The first set, which consists of two drowsy segments and one alert segment, was used to develop a sufficient set of rules to discriminate between alert and drowsy states. The second set, consisting of the other three segments, was used to test the algorithms that were developed.

The recognition algorithms are robust enough to tolerate modest geometric distortion due to driver head movement. The algorithms track facial features, including the eyes and the eyelids, over time. The algorithms also use peculiar features that were identified as unique to the drowsy state, such as the partial closure of one eye, as additional "sufficient features" to enhance the confidence of a drowsy state declaration. Steering wheel motion was also used to further enhance the recognition performance.



A demonstration of the drowsiness recognition algorithms was developed on an Image Visualization and Analysis Station (IVAS) image processing workstation, using the digitized database described above. The images of Figures 2 through 5 represent snapshots of the demonstration. Figure 2 represents a snapshot within a sequence of alert images. The algorithms have determined that the imagery has the characteristics of an alert subject and that the steering wheel motion has the characteristics of alert driving. The steering wheel information is used by the algorithm only to confirm the decision arrived at by facial imagery analysis. Figure 3 represents a snapshot within a sequence of drowsy images. The algorithms have determined, for the first time, that the imagery has the characteristics of a drowsy subject, resulting in a "caution" state for the eye data. The algorithms are now "on the alert" for further signs of drowsiness. Figure 4 represents a later snapshot in the sequence of drowsy images. The algorithms have observed additional signs of drowsiness in the imagery, resulting in a "drowsy" state for the eye data. The algorithms have initially determined that the steering wheel motion also has the characteristics of drowsy driving, resulting in a "caution" state for the wheel data. A Level I Warning is initiated. Figure 5 represents confirmation of drowsiness based on both imagery analysis and steering wheel motion analysis; a Level II Warning is initiated.

The performance of the drowsiness recognition algorithms was further tested to determine their robustness, using an independent set of imagery obtained from a major domestic automobile manufacturer. The imagery was gathered in their driving simulator. The investigators digitized the imagery and tested the robustness of the image interpretation algorithms. Steering wheel motion analysis algorithms were not used in this test because steering wheel motion data was not provided. Figure 6 represents the first snapshot of the automobile manufacturer's imagery. The algorithms have not observed signs of drowsiness. Figure 7 represents a snapshot within a sequence of drowsy images. The algorithms have determined, for the first time, that the imagery has the characteristics of a drowsy subject, resulting in a "caution" state for the eye data. The algorithms are now "on the alert" for further signs of drowsiness. Figure 8 represents a later snapshot in the sequence of drowsy images. The algorithms have observed additional signs of drowsiness in the imagery, resulting in a "drowsy" state for the eye data. A Level I Warning is initiated.



**Alert Sequence**

**Eyes: AWAKE**

**Wheel: AWAKE**

**FIGURE 2 Alert Sequence**



**Drowsy Sequence**

**Eyes : CAUTION**

**Wheel : AWAKE**

**FIGURE 3 Initial Drowsy Sequence**



**Drowsy Sequence**

**Eyes: Drowsy**

**Wheel: CAUTION**

**Level I: Warning**

**FIGURE 4 Drowsy Sequence/Level I Warning**



**Drowsy Sequence**

**Eyes      Drowsy**  
**Wheel      Drowsy**

**Level II Warning**

**FIGURE 5 Drowsy Sequence/Level II Warning**



**Alert Sequence**

**Eyes:    AWAKE**

**FIGURE 6 Automaker's Alert Sequence**



**Drowsy Sequence**

**Eyes :   CAUTION**

**FIGURE 7 Automaker's Initial Drowsy Sequence**

The fact that the algorithms correctly identified signs of drowsiness in the automobile manufacturer's imagery

is especially significant because: (1) the drowsiness recognition algorithms were not altered before they were applied to the imagery, (2) the simulator that was used to gather the imagery had a different camera and lighting scheme, and (3) the subject in the video was wearing eyeglasses (with significant reflections).



**Drowsy Sequence**

**Eyes:    DROWSY**

**Level I Warning**

**FIGURE 8 Automaker's Drowsy Sequence/  
Level I Warning**

**ANTI-THEFT PROTECTION**

Northrop Grumman began work on iris verification for vehicle anti-theft protection before this ITS-IDEA project got underway. While working on the project, high resolution images of both eyes of six individuals were taken. These images were digitized and uploaded to a VAX mainframe computer for use in the definition of requirements. Evaluations of existing pattern matching algorithms were conducted to determine their suitability for iris verification. At that time the investigators became aware of an iris verification system that had been developed at Los Alamos National Laboratory.

Los Alamos National Laboratory developed the first system for automatically verifying the identity of people based on video images of the iris of the eye. After Northrop Grumman became aware of the work at Los Alamos, a demonstration of the system was arranged. Los Alamos National Laboratory personnel successfully demonstrated their current system during a visit to their facility. Northrop Grumman subsequently funded Los Alamos National Laboratory to examine issues specifically related to the performance of iris verification for anti-theft protection of vehicles. This report documents the results of that investigation.

## Background

Los Alamos National Laboratory's Bartas Iris Verification System, named after the French poet Seigneur du Bartas, received a 1994 R&D 100 award from *R&D Magazine*. Bartas verifies a person's identity by using an accelerated Quadra 650 computer to analyze a color video image of one of the person's irises. The color video image is then compared with a corresponding image in the enrollment database, using phenomenological and textural pattern analysis algorithms. Bartas' verification process currently takes 15-20 seconds, but should be reduced to 6 seconds after implementation of planned hardware and software improvements in 1996. Figure 9 depicts the Bartas Iris Verification System.

Unlike existing retinal scanning systems, Bartas is non-intrusive, user-friendly, and tolerant of variations in head and eye orientation. Bartas can perform its identity verification function when eyeglasses or contact lenses are worn, unless the contact lenses are strongly tinted. Bartas has demonstrated an equal error rate, where the false rejection rate equals the false acceptance rate, of 0.3 percent for light-eyed individuals and 6 percent for dark-eyed individuals. Thresholds can be adjusted to obtain lower false acceptance rates, with a commensurate increase in false rejections.

## Implementation of Iris Verification in a Vehicle

### *Color vs. Monochrome Video*

The Los Alamos National Laboratory (LANL) Bartas Iris Verification System currently acquires color (RGB) video images of each iris. Color information helps the reliability of both verification and identification, especially for individuals with green, hazel, or gray eyes. Irises of these colors tend to show the most interesting spatial color variations. Blue irises and dark irises typically show little variation in color across the iris. Color information is also useful when dealing with a database of thousands of people.

Color information is particularly useful for identification, in contrast to verification. For identification, knowing the color of the iris permits the computer to avoid wasting time searching a large database of brown irises to find a match with a person having blue eyes, for example.

The disadvantages of color video imaging compared to monochrome (black and white) video include larger sizes for the camera and lens, greater cost, larger data storage requirements, slower verification times, and illumination levels two to eight times greater.

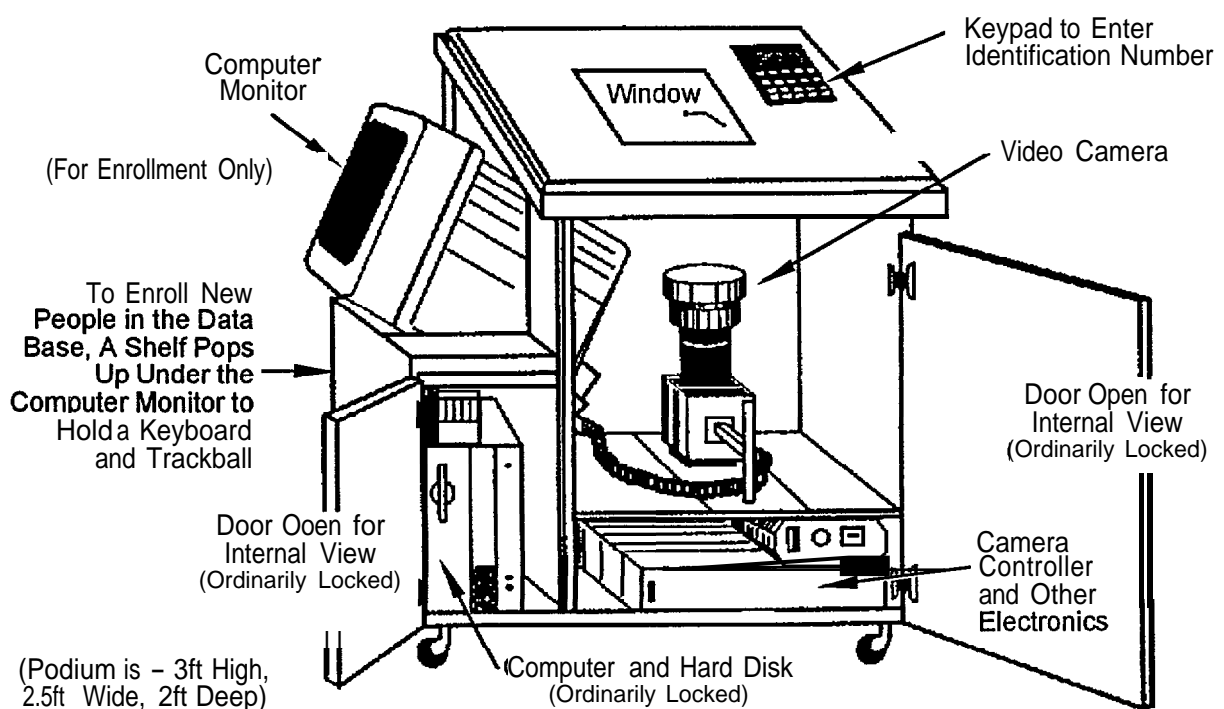


FIGURE 9 Bartas Iris Verification System

For access control in vehicles, preliminary work at LANL suggests that iris verification can probably be done quite satisfactorily using monochrome video. This is especially true if the number of individuals (authorized users) enrolled in the system is of the order of dozens, instead of thousands. Figure 10 depicts a typical monochrome image of a person's iris.

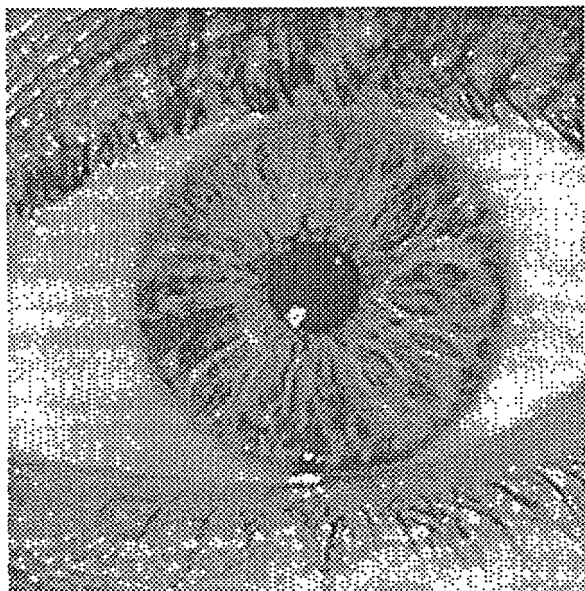


FIGURE 10 Monochrome Iris Image

#### *Resolution and Information Content*

The existing LANL Bartas Iris Verification System stores color iris images in the enrollment database with 196,600 total bytes: 256 X 256 pixels for each of the three rgb color planes. Non-iris portions of the image are discarded and are not counted in the 196,600 total bytes. LANL has demonstrated this to be overkill for both verification and identification.

Video images of 3 10 different irises from 184 different people were analyzed at LANL to determine the average auto-correlation length. The results of this study indicate that, on average, an image size of only 35 X 35 pixels is adequate to capture the essential details of the patterns on an iris. An image size of 35 X 35 pixels is thus 'optimal' for characterizing irises in the sense that adding a few more pixels to a well focused 35 X 35 image only very marginally increases the information content for an average iris.

The correct way to think of the 35 X 35 pixel image size is to assume that this is the minimum image size that can be used for verification, but that images of this size have a good probability of providing reliable verification.

#### *Daytime Illumination Issues*

The existing LANL Bartas Iris Verification System uses fairly high intensity, point-source illumination, typically 880 lux of visible light. This is needed because of the use of a high resolution 3 CCD co-site sampling rgb video camera. This type of artificial illuminance at visible wavelengths, however, is not desirable inside a vehicle during the daytime.

An experimental study undertaken at LANL for Northrop Grumman indicates that the average daytime illuminance inside 13 untinted truck cabs during daytime is quite high. The illuminance at the driver's eye while looking horizontally out the windshield averaged (25±9) percent of the horizontal illuminance outside the truck. The illuminance at the driver's eye while looking at the steering wheel was (14±3) percent of the external horizontal illuminance. Based on typical daytime illuminance values, this means the illuminance reaching the driver's eye while he looks horizontally out the windshield is typically of the order of 4000 lux, with 2500 lux illuminance when he looks at the steering wheel.

This high ambient illuminance reaching the driver's eye means that the pupil will be quite small--typically 2 to 3 mm in diameter. This affords a maximal view of the iris tissue, but poses a serious problem. Because the 2500-4000 lux illuminance coming through the windshield is not coming from a point source, the reflection off the driver's eyeball seriously obscures the iris patterns. This can be easily seen just by looking into the eyes of a car or truck driver during the daytime. Because the eyeball is roughly spherical, the reflection cannot be eliminated simply by having the driver look down.

The most practical solution to the illumination problem during daytime is to use infrared (IR) imaging of the iris, instead of visible color imaging. A standard black and white video camera images very well in the 0.8-1.2  $\mu\text{m}$  wavelength range. An IR filter will be needed to block most of the visible light in the eyeball reflection. An IR illuminator, ideally a point source, will then be used to provide most of the eye illumination. This IR light should be located near the video camera, presumably on the steering column. Arrays of light emitting diodes (LEDs) work very well as inexpensive IR illuminators. Light from an IR illuminator will not bother the driver because it is invisible. There are no safety issues, as long as the IR illumination is kept to reasonable levels.

As an alternative to IR illumination and imaging during daytime, it may be possible to use visible illumination and video imaging at a fixed visible wavelength using an optical filter. It is advantageous to record iris patterns in visible light, for all except the most

dark-eyed individuals. This is because more structural details are present at visible wavelengths than at IR wavelengths. To perform non-IR monochrome video imaging of irises during daytime conditions, it would be necessary to provide a bright illumination source of perhaps 25-300 lux at a very narrow wavelength. The video camera would record the iris image through a narrow interference filter. This filter would remove most of the ambient light not produced by the single wavelength source and would remove most of the reflection of the windshield seen in the iris.

#### *Nighttime Illumination Issues*

The illuminance inside a truck cab at night, even with the instrument panels lit, is usually under 1 lux. Exceptions occur when the driver is looking into oncoming headlights, or for extremely well-lit parking lots. Most of the time, therefore, the pupil diameter will be quite large, typically 7-8 mm out of an average iris diameter of about 12 mm. This means that relatively little of the iris will be visible.

Work at LANL suggests this isn't necessarily a problem, particularly for verification (as opposed to identification). Experiments were previously done with human subjects using drugs to artificially dilate the pupil. Except for the most extreme pupil dilation (9-11 mm), enough of the iris can be seen to do reliable verification. The pattern-matching algorithms can automatically correct for variable pupil size.

Monochrome imaging of the iris in visible light at nighttime is possible, but would require visible illumination at the driver's eye in the range of 3 to 15 lux. Although this is less illumination than a driver typically receives from oncoming or trailing headlights, it could be annoying. However, if iris verification is only performed when the vehicle is started, this would not be a major problem.

The most practical illumination scheme to use for nighttime driving is probably the same as for daytime driving: IR illumination. To improve reliability, it might be desirable to enroll drivers separately for daytime and nighttime conditions, although this may not be necessary.

#### *Positioning/Focusing*

One of the early issues that had to be addressed for the Bartas system was the issue of camera focusing. The high-resolution color imaging sensor used in the Bartas system has a very narrow depth of field of approximately 5 mm. Autofocusing methods (e.g., ultrasonic, IR, or frequency content of the image) did not prove practical. Leaving the focusing up to the user, based on having him/her look at his/her iris image in the TV monitor,

proved to be the most reliable and cheapest solution for the Bartas system.

However, a much lower image resolution will be adequate for vehicle applications. This is encouraging because lower resolution means smaller lenses can be used, and also that greater depth of field is possible. The question of how best to deal with focusing issues in a vehicle, however, remains an open question.

#### *System Size*

The investigators determined that iris verification can be performed using many of the same optical and processing components used for drowsy driver recognition. Many of the bulky components that comprise the current Bartas system can be replaced with much smaller components. Hence, the system can be sized and packaged for installation in vehicles.

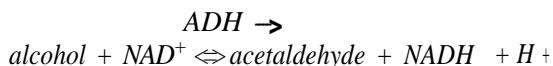
### ALCOHOL IMPAIRED DRIVER RECOGNITION

The investigators successfully demonstrated the feasibility of detecting signs of consumption of alcohol. Specifically, by-products of the breakdown of alcohol found in the tear film of the eye alter consumption were analyzed in vitro. Spectroscopic analysis showed minute but observable absorption differences induced by the presence of these by-products. In vivo detection was not attempted.

#### Nicotinamide Adenine Dinucleotide (NAD) and Alcohol Dehydrogenase (ADH) for Alcohol Detection

Direct detection of the level of blood alcohol in a driver by applying spectroscopic techniques to optical observations of the driver's tear film and other structures of the eye was initially proposed. Since then, it has become clear that direct detection of alcohol can only be adequately performed in the near-infrared and medium-wavelength infrared spectral regions. Although this method is viable, it requires a completely separate optical train and detector, resulting in a severe compromise in the affordability of the system.

In the meantime, ongoing literature search revealed a more elegant, albeit more challenging avenue of investigation. The human body and most living things contain several chemicals that are apparently intimately involved in the assimilation of alcohol. Specifically, nicotinamide adenine dinucleotide (NAD), NAD<sup>+</sup>'s reduced form- nicotinamide adenine dinucleotide hydride (NADH), alcohol dehydrogenase (ADH) and alcohol are involved in the following reaction:



>> where ADH is the primary enzyme that promotes the reaction to the right and  $NAD^+$  and NADH are essentially co-enzymes, since they are not really consumed in the reaction and the reaction is readily reversed. Alcohol is therefore technically the substrate.

Much of the research related to ADH involves the role that it,  $NAD^+$  and NADH play in protecting the eye from ultraviolet light damage from sunlight. This is the impetus for investigating  $NAD^+$  and ADH as agents for measuring blood alcohol level. There is a basic absorption peak in NADH that is not present in  $NAD^+$ . It is this difference that could be exploited to assess blood alcohol levels in a driver.

### Chemical Pedigree

The chemicals used in the investigation were purchased from a commercial biochemical supply company. While the NAD and NADH are fairly simple compounds, the ADH is not. In fact, there are literally hundreds of varieties of ADH, with humans having at least seven alone. The ADH used in this investigation is derived from Brewer's yeast. The only issue of any significance is the degree of enzyme activity, but as results will show, the reaction of  $NAD^+$  with ethyl alcohol (EtOH) will proceed even without ADH. ADH is merely the enzyme that promotes the reaction of alcohol to acetaldehyde to complete consumption of the reactants.

Note that NADH is not actually needed for the direct purposes of the investigation, since the ADH and  $NAD^+$ /EtOH reaction produces NADH naturally. The purchased NADH simply provides a direct baseline of the expected spectral characteristics.

The reactants are dissolved in a buffer solution of 100 millimolar (mM) glycine with Sodium Hydroxide (NaOH) added to adjust the pH to -10.5, as this is the generally accepted solvent for ADH and  $NAD^+$  in research.

### Investigation Results

The basic feasibility of in-vitro alcohol detection using the  $NAD^+$ /ADH enzymatic reaction was demonstrated. As  $NAD^+$  reacts with EtOH to form NADH and acetaldehyde, the absorption peak of NADH dominates the spectral transmission of the solution.

### UV/Visible Spectroscopy

The basic tool for this investigation is the ultraviolet (UV)/visible spectrophotometer. The samples are placed in various analysis cells and the spectral transmission is measured.

There are two basic types of analysis cell used in this investigation, a 10 mm cell and a 25 um cell. The 10 mm cell is a standard cuvette used in spectroscopy that is shaped as a rectangular box with 10 mm internal lateral dimensions and roughly 50 mm tall with the exception that these cells are constructed of quartz to assure adequate transmission in the ultraviolet regime. The 25 um cell is constructed from two slabs of  $BaF_2$  that have a thin cavity that is 25 um thick. The slabs are held together with metal plates and screws. The analyte is injected through standard Luer fittings.

The 10 mm cuvette analysis cell provides clear indication of the bulk transmission spectra of the analytes. The 25 um cell provides an indication of the spectral transmission of the analytes as might be experienced in the reflection spectrum of the human eye tear film. While the exact thickness of the tear film varies, 25 um is a reasonable approximation.

### Experimental Conditions

The  $NAD^+$  is dissolved in the 100 mM glycine buffer at a concentration of 0.5 mM in the solution. Given the small amounts of buffer solution, this concentration represents -1 mg of material dissolved in 3 ml of solution. The EtOH is added as a percentage by volume of the  $NAD^+$  solution and the ADH is added in trace amounts, as there is no consumption of the ADH in the reaction itself. It is estimated that less than 0.1 mg of ADH is added to the solutions in the tests. All tests were performed at room temperature.

### Laboratory Results

NAD by itself shows little absorption while NAD with only the EtOH shows some absorption. ADH significantly promotes the conversion of EtOH and NAD to acetaldehyde and NADH.

The reacted NAD solution containing NADH still has a detectable absorption at the wavelength of interest compared to the unreacted NAD solution. While the differential transmission is only about 1 percent, this may be sufficient to produce quantitative results given additional development of algorithms specifically designed for this type of detection.

## Potential Sensor Configuration

The initial proposal for the three in one sensor assumed use of a diffractive grating to spectrally separate the light reflected from the operator's eye; there was somewhat increased complexity from the diffraction grating due to the necessity of removing the higher order diffracted light. This situation could be simplified by the use of a wedged interference filter that has a continuously variable transmission wavelength as a function of position across the filter. Such an approach would be simpler and potentially less expensive.

## Safety

Since the detection of the NADH absorption peak requires illumination in the range of 300 to 400 nm, this raises some question as to potential ultraviolet light safety and damage to the eye and associated tissues. Using the ANSI standard 2136.1-1986, American National Standard for the Safe Use of Lasers as a guide, the minimum maximum permissible exposure (MPE) limit in the ultraviolet range of 300 to 400 nm is on the order of  $3 \times 10^{-3} \text{ J/cm}^2$ , which should be significantly higher than any level that an in-vehicle sensor might contemplate.

Tissue damage from most ultraviolet exposures are cumulative. Since the actual required illumination levels have not yet been established for this particular application, there may be some potential issues with regard to cumulative exposure limits. These limits will be explored at a later date.

## Interference Issues from Physiological Factors

Since the human body is host to literally millions of chemical reactions, there are numerous reactions that could potentially impact the sensitivity of the detection and the false alarm rate. In particular, the  $\text{NAD}^+$  and NADH related reactions in the body are naturally occurring, even in the absence of alcohol, thus, there is some possibility of false indications of alcohol if the absolute presence of NADH is used. This will require additional baselining of the natural concentration of NADH and its impact on the absorption spectrum.

Additionally, physiological problems such as certain diseases may cause an abundance of acetaldehydes or ketones, which can potentially reverse the reaction, thus lowering the amount of NADH that can be detected. Furthermore, there is ample evidence from other investigations that show that ADH may be inactivated from strong *W* exposure, thus allowing the reaction to reverse and thus lessening the ability to detect the NADH product.

## Sensitivity Issues

As the laboratory results show, the differential transmission of the unreacted and reacted NAD solutions is barely 1 percent. Since the EtOH concentration was 0.5 percent, this means that the sensor must be able to resolve better than 0.2 percent in the reflection coefficient. This would require at least 10 bit analog/digital (A/D) conversion resolution and the use of higher order processing, such as extraction of the slope of the reflection coefficient to augment the A/D resolution.

Additionally, as mentioned above, there may be interference from physiological and *W* exposure factors that could impact the ultimate sensitivity of this method.

## Conclusions

The feasibility of detecting alcohol in vitro with an essentially non-invasive technique has been demonstrated. Given additional investigation and development, it may be possible to advance this technology into a viable commercial product. There is some potential difficulty in detecting the minute absorption difference induced by the increased NADH concentration. Additionally, the investigators note that there are physiological and environmental factors that can also lessen the sensitivity of this method.

## BREADBOARD/PROTOTYPE HARDWARE CONSIDERATIONS

The Three-In-One Vehicle Operator Sensor requires certain levels of performance in three areas: optical imaging, spectral processing, and computer algorithms/software producing timely results. However, the investigators will focus future product development on the drowsy driver recognition and the anti-theft protection functions.

## Configuration

The primary optical path will support both drowsy driver recognition and driver identity verification. For the breadboard configuration, a commercially available CCD camera will be interfaced to a IBM-PC compatible based frame grabber board that will then transfer the collected image data to a TMS320C80 (CSO) processor board that will actually implement the algorithms developed for these applications. The CSO processor also contains video timing controllers that can significantly simplify the ultimate product development by already incorporating the camera control interface on-chip.

Direct connection between the frame grabber board and the C80 processor board can result in data transfer bandwidths in excess of 10 Mbytes/sec, which is more than adequate for anticipated video data rates.

#### Processor Candidate

The ability to detect the drowsiness of the vehicle operator is critically dependent on the ability to process the image data in real time. Since the images could be 512x512 at RS-170 standard rates, nearly 8,000,000 pixels per second must be processed to maintain real time operation. The total processor throughput should be less than several hundred million operations per second, which makes the C80 multiple digital signal processor an ideal candidate for this application. A commercially available co-processor board for the IBM-PC compatible with a PCI interface bus could be ideal for this application. This board contains a single C80 processor. The C80 itself contains five processors, a single general purpose processor with floating point performance of 100 million floating point operations per second (MFLOPS) and four digital signal processors (DSPs) that are interconnected with a multi-way crossbar switch that allows any of the DSPs to communicate to a variety of system resources and memory. Moreover, the C80 contains two video interface controllers, which will greatly simplify the video interface to the frame capture and display in the breadboard system.

The C80 has a basic clock rate of 50 MHz and, given the single instruction per cycle format, is capable of executing 200 million instructions per second (MIPS) in the DSP section alone. The DSP instruction word is 64 bits long and is highly reminiscent of microcode in that the instruction format contains various fields that specify the many parallel operations that can occur. Additionally, each DSP contains internal address units that can access memory simultaneously in a single cycle and three zero-overhead loop/branch controllers. Thus, the DSPs are capable of very efficient and tight execution loops as well as several internal operations in a single instruction cycle. This results in an effective throughput rate of several times higher than the basic 200 MIPS.

The C80 contains 50 Kbytes of on-chip static random access memory that can be accessed from any processor through the crossbar switch. This large on-chip memory will result in highly efficient instruction execution by allowing large amounts of data to be stored on-chip in a very high speed access memory. Additionally, the segmented memory coupled with the crossbar switch should result in extremely rapid context-switching, resulting in high performance real-time operation.

#### Data Storage

This is the actually the most complicated aspect of the breadboard system. Based on experience from previous programs, the necessity of collecting and storing as much data as possible cannot be over stressed. Thus, the data recording for a breadboard system must include video camera recordings for basic ground truthing as well as digital data recording of the collected camera images during drowsy driver monitoring. Given a 512 X 512 or 640 X 480 pixel camera format and a 30 Hz camera frame rate, the recorder must have a bandwidth of 10 Mbytes/sec while recording. A multitrack streaming tape system must be considered for this aspect of the data collection.

While the video recordings can be used to digitize images for later analysis, there is some risk of losing vital information since the analog video recordings have slightly degraded performance compared to the live video. Additionally, recorded video cannot sustain the high quality horizontal sync performance of live video, which will result in image data with noticeable line jitter that might low the performance of the algorithms.

#### Conclusions

The basic hardware configuration for a breadboard system will be predicated on the ability to acquire commercially available hardware subassemblies. This is quite reasonable given the high performance that can be currently acquired and will allow us to devote resources to refining the basic electro-optical and image processing techniques and algorithms. Total hardware investment in the breadboard system will be quite inexpensive, while being capable of real-time operation.

## DEPLOYMENT

Northrop Grumman perceives great market interest in the drowsy driver recognition function of the sensor. Significant interest has also been expressed in anti-theft protection, but little market interest has been noted concerning the alcohol impaired driver recognition aspect of the sensor.

The investigators initially intend to develop and deploy a drowsy driver recognition sensor, for application to commercial trucks. Wider application to passenger automobiles will follow closely. A sensor that performs both drowsy driver recognition and anti-theft protection is envisioned next. If market interest in alcohol impaired driver recognition becomes evident, development of this function will follow. This staged approach to development will facilitate earlier introduction of a sensor performing the functions that the marketplace desires



most. Table 1 depicts the anticipated schedule for deployment of the sensor.

TABLE 1 Sensor Deployment Schedule

<u>Sensor Function</u>	<u>Deployment Date</u>	
	<u>Heavy Trucks</u>	<u>Autos/Light Trucks</u>
Drowsy Driver Recognition	Late 1997	1999-2000
Anti-Theft/Iris Verification	1998	2001
Alcohol Identification	2005	2008

The ATA Foundation has provided significant input regarding the desired functionality of the sensor as well as its potential marketability. Several automobile manufacturers have expressed interest in the sensor, particularly the drowsy driver recognition function. Northrop Grumman intends to work with the ATA Foundation and major domestic automobile manufacturers and their suppliers in the development and deployment of the sensor.

## CONCLUSIONS

The Three-in-One Vehicle Operator Sensor envisioned by Northrop Grumman uses non-intrusive eye tracking and image analysis to perform drowsy driver recognition, anti-theft protection, and alcohol impaired driver recognition. The investigators successfully demonstrated drowsy driver recognition algorithms during the execution of this ITS-IDEA contract. The feasibility of alcohol impaired driver recognition was also demonstrated, in vitro.

While independently working on anti-theft protection, Northrop Grumman became aware of an iris verification system that had been developed at Los Alamos National Laboratory. The investigators visited Los Alamos and witnessed successful demonstrations of their system, which was developed under the sponsorship of an agency of the U.S. government. Discussions indicated that their approach could facilitate vehicle anti-theft protection. The investigators subsequently funded Los Alamos National Laboratory, using Independent Research and Development funds, to examine issues specifically related to the performance of iris verification for anti-theft protection of vehicles.

The sensor could have a significant impact on safety by decreasing the number of accidents caused by either drowsy drivers or intoxicated drivers. Additionally, the sensor will help prevent vehicle theft by verifying the identity of authorized vehicle operators based on physical characteristics of their eyes (iris verification). This feature could reduce asset losses of individual owners and, collectively, the insurance industry. Various schemes for application of the identity verification feature may even prove to be a deterrent to vehicle hijacking. Based on the results of this research, the investigators will concentrate future development on drowsy driver recognition and anti-theft protection.

The investigators intend to further test the robustness of the sensor system by using imagery data from planned sleep studies at the Walter Reed Army Institute of Research. The studies are scheduled to begin in the fall of 1995 and will employ a large number of truck drivers as subjects. This data will be used to further validate and, if necessary, refine the drowsiness recognition algorithms.

A prototype sensor will be constructed, based on the results of this ITS-IDEA project, for testing in both simulation facilities and in vehicles. The investigators will work with representatives of the user community, such as the ATA Foundation, as well as domestic automobile manufacturers and their suppliers in the ongoing development and deployment of the Three-In-One Vehicle Operator Sensor.