INTRODUCTION OF A SOLID STATE, NON-INVASIVE HUMAN TOUCH BASED ALCOHOL SENSOR

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ABSTRACT

This paper presents an overview of the theory and implementation of a touch-based optical sensor (TruTouch sensor) for monitoring the alcohol concentration in the driver of a vehicle. This novel sensor is intended to improve driver safety by providing a non-intrusive means of notifying a driver when their blood alcohol concentration may be too high to operate a vehicle safely. The optical alcohol detection system has successfully completed several stages of development and validation. A commercially available, industrial version of the system (TruTouch 2500, or Mark 1) has undergone extensive clinical testing and field validation. Under the DADSS (Driver Alcohol Detection System for Safety) Program, a compact semiconductor version (Mark 2) of the optical system has been developed targeting use in consumer vehicles. Based on proven semiconductor laser technologies, the Mark 2 sensor system has demonstrated excellent spectral accuracy and precision and is currently undergoing laboratory validation testing. A demonstration vehicle version of the system has been designed and will be implemented following completion of the laboratory validation testing.

INTRODUCTION

The negative societal impact of alcohol (ethanol) impaired vehicle driving has been established through numerous clinical studies [1] and confirmed by accident statistics over many years [2]. Currently, the primary means of mitigating alcohol impaired driving is through education and legal enforcement. The percentage of alcohol in the blood circulatory system at any given time can be directly correlated with the neurological sensory, cognitive and reactive performance of the driver. Legal limits for alcohol concentration have been established for drivers of both private and commercial vehicles [3]. Today, the use of alcohol detection technology for driver safety is limited to law enforcement testing (post-accident, during traffic stops / checkpoints) or in the case of previously convicted DUI offenders through the installation of a breath based vehicle interlocks. These systems work well for the purpose of law enforcement but are unsuitable for routine use by consumers. The goal of the current sensor development is to produce a system that is seamlessly integrated into the vehicle's infrastructure, providing consumers with the knowledge of their alcohol concentration without imposing inconvenience to their daily driving experience. In order to accomplish this, a human machine interface (HMI) design has been proposed that incorporates the optical sensor into the vehicle start button. Advances in automotive buttons and touchscreens make it feasible to integrate skin based sensors and achieve appropriate visual, audio, and haptic feedback without compromising function [4]. During routine vehicle operation, the driver's alcohol concentration could be measured and communicated to the driver so that appropriate choices can be made (e.g. delay drive, alternate driver or alternate transportation method). The use of existing vehicle occupancy sensors combined with advanced signal processing supports a simple and practical anti-spoofing method, improving the safety and efficacy of the system.

SENSOR THEORY OF OPERATION

The TruTouch alcohol measurement technology has been validated using multiple approaches including *in vitro* (test tube) studies of multi-component samples, clinical studies involving alcohol dosing of humans, and real-world measurements by customers in a variety of challenging environments. The validation efforts are exemplified by multiple peer-reviewed journal articles and a strong intellectual property base.

Scientific Basis of the TruTouch Measurement

The TruTouch technology employs near-infrared (NIR) absorption spectroscopy to measure skin tissue. The NIR spectral region typically spans the portion of the electromagnetic spectrum between the visible, which is generally considered to end at 0.7 µm, and the infrared, which begins at 2.5 µm. However, for measuring alcohol *in vivo* (in human), some portions of the NIR are more advantageous than others. The features most commonly observed in the NIR are overtones and combinations of fundamental vibrations of hydrogen bonded to carbon, nitrogen, and oxygen [5,6,7,8,9].

The absorbance spectrum of alcohol shows features over the NIR region (see figure 1). The 1.25- µm 2.5 µm region contains the 1st overtone and combination bands of the carbon-hydrogen and oxygen-hydrogen bonds. The 0.7-1.25 µm region contains higher order overtones of these bonds. Examination of Figure 1 and its inset shows that the 0.7-1.25 µm region is 400 times weaker than the signal in the longer wavelength, 1.25- 2.5 µm region.

Furthermore, the utility of the visible region (0.3 to 0.7 µm) and the 0.7-1.25 µm part of the NIR are limited by the presence of skin pigmentation (melanin) that creates large differences between people, particularly of different ethnicities. In contrast, the longer wavelength region is virtually unaffected by pigmentation [10]. As a result of the larger signal and absence of pigmentation, the TruTouch technology is designed to measure the longer wavelength (1.25-2.5 µm) region.

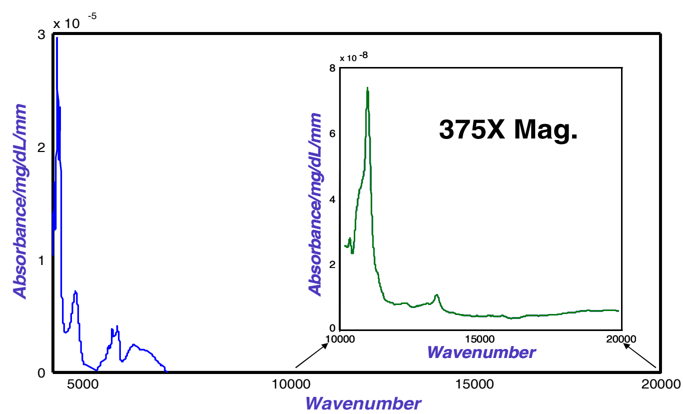
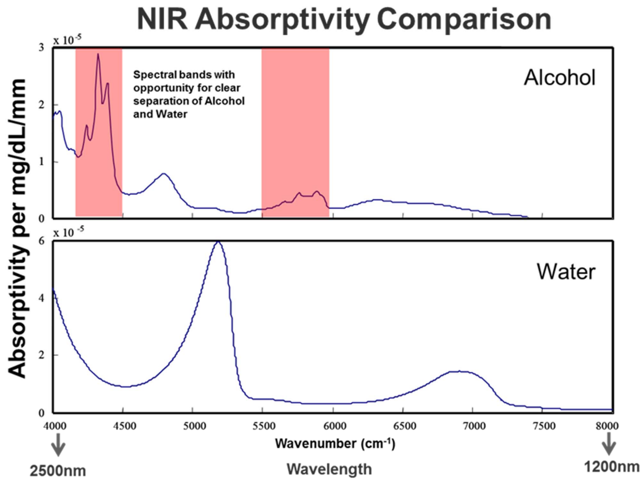
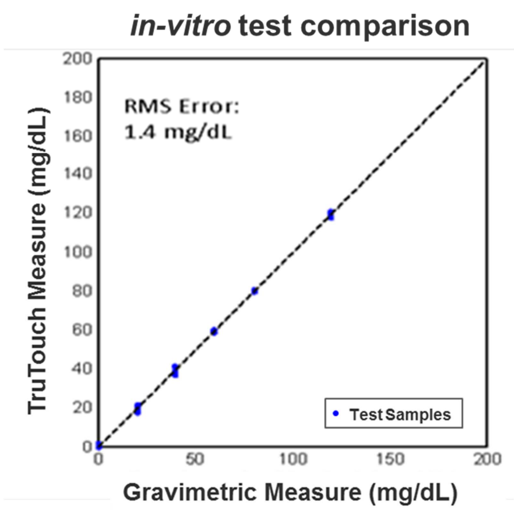


Figure 1. Absorptivity of alcohol in the NIR and visible.

In addition to the aforementioned advantages, the NIR spectral region (4000-8000 cm-1 or 1.25-2.5 µm) is of prime interest for non-invasive alcohol measurements because it offers specificity for a number of analytes, including alcohol and other organic molecules present in tissue, while supporting optical path lengths of several millimeters with acceptable absorbance characteristics [11,12,13,14,15]. Comparing NIR spectra (normalized to unit concentration) of alcohol and water collected using a TruTouch system, demonstrates the effect of molecular structure on NIR absorption spectra and indicates spectral regions of separation (see Figure 2a).



(a)



(b)

Figure 2. Comparison of Alcohol, Water in NIR (a);* Ethanol Test Results: 98 *in-vitro* samples *(b).

TruTouch systems (including Mark 1) are based on a Michelson interferometer Fourier Transform IR (FTIR) instrument that delivers NIR radiation to the skin and underlying tissue and collects the diffusely reflected signal using a fiber-based optical probe. The collected light contains spectral information which allows the determination of the subject's alcohol concentration directly from the measurement. Specific details of the industrial version of the optical alcohol detection system can be found in several issued United States Patents and applications [16,17,18,19,20].

Laboratory and Clinical Validation

The objectives of any analytical measurement procedure are high sensitivity and high selectivity for the target analyte (e.g. alcohol concentration). Sensitivity refers to a method's ability to respond to quantity changes in the target analyte, while selectivity is the extent to which a method erroneously responds to changes in interfering analytes (e.g. water, collagen, proteins, and other chemicals present in the body). Ensuring the selectivity of an analyte measurement can be notoriously challenging in complex systems such as human tissue [21, 22]. Accordingly, careful design and controlled experiments are required to verify the validity of any measurement approach.

Historically, researchers have used *in-vitro* experiments to assess the sensitivity and selectivity of methods for quantifying analytes at physiological concentrations [23,24,25,26,27,28,29]. These experiments are useful diagnostics for the validity of a measurement approach because sample composition and the experimental conditions are controlled by the practitioner; allowing direct assessment of measurement sensitivity and selectivity. For laboratory validation of the alcohol sensor, an optically scattering tissue phantom was developed using 0.3 micron diameter polystyrene microspheres to mimic the optical properties of human skin.

To validate the Mark 1 sensor, a validation study comparing sensor measurements with tissue phantom samples containing gravimetric prepared ethanol, urea, creatinine, albumin, and saline was carried out. The study demonstrates the high degree of accuracy achievable with the touch based sensor (see figure 2b).

In Vivo Clinical Results

In order to demonstrate the accuracy of the sensor with human subjects, controlled clinical trials were conducted on the commercially available version of the system (TruTouch 2500, Mark 1). In these trials, venous blood samples were collected and sent to a certified forensic grade lab for gas chromatography analysis. Comparison data were collected on the TruTouch sensor, evidentiary grade breath sensor, and both compared against the venous blood samples. Alcohol excursions were induced in 108 subjects at Lovelace Scientific Resources (Albuquerque, NM) following overnight fasts. Written consent was obtained from each participant following explanation of the IRB-approved protocols (Quorum Review). Baseline blood and touch NIR alcohol measurements were taken upon arrival in order to verify zero initial alcohol concentration. The alcohol dose for all subjects was ingested orally with a target peak blood alcohol concentration of 120 mg/dL (0.12%). The mass of the alcohol dose was calculated for each subject using an estimate of total body water based upon gender and body mass [29]. The test results (see figure 3), indicate a strong correlation between the touch based sensor and venous blood measurements [30].

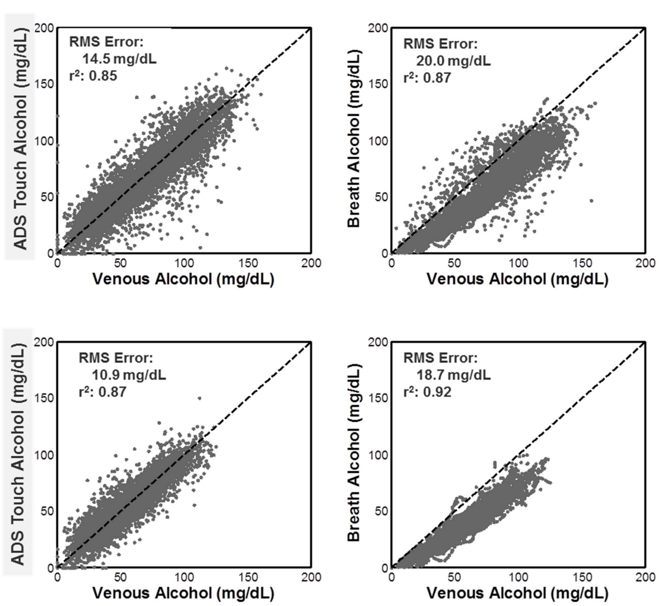


Figure 3. Human Subject (in-vivo) study results.

The top two plots compare the TruTouch sensor to venous blood measurements, and an evidential grade breath test to venous blood measurements, respectively. The bottom plots compare data, limited to the “elimination phase” of the alcohol excursion (e.g. after the initial rapid physiological alcohol uptake which is governed by gastric emptying and absorption of the alcohol in the small intestine during and after consumption).

SOLID STATE TOUCH SENSOR (MARK 2)

The Mark 2 sensor under development for potential application to vehicle operation uses standard automotive electronic design (see figure 4a) and discrete semiconductor lasers to encode the specific spectral information necessary for alcohol measurements.

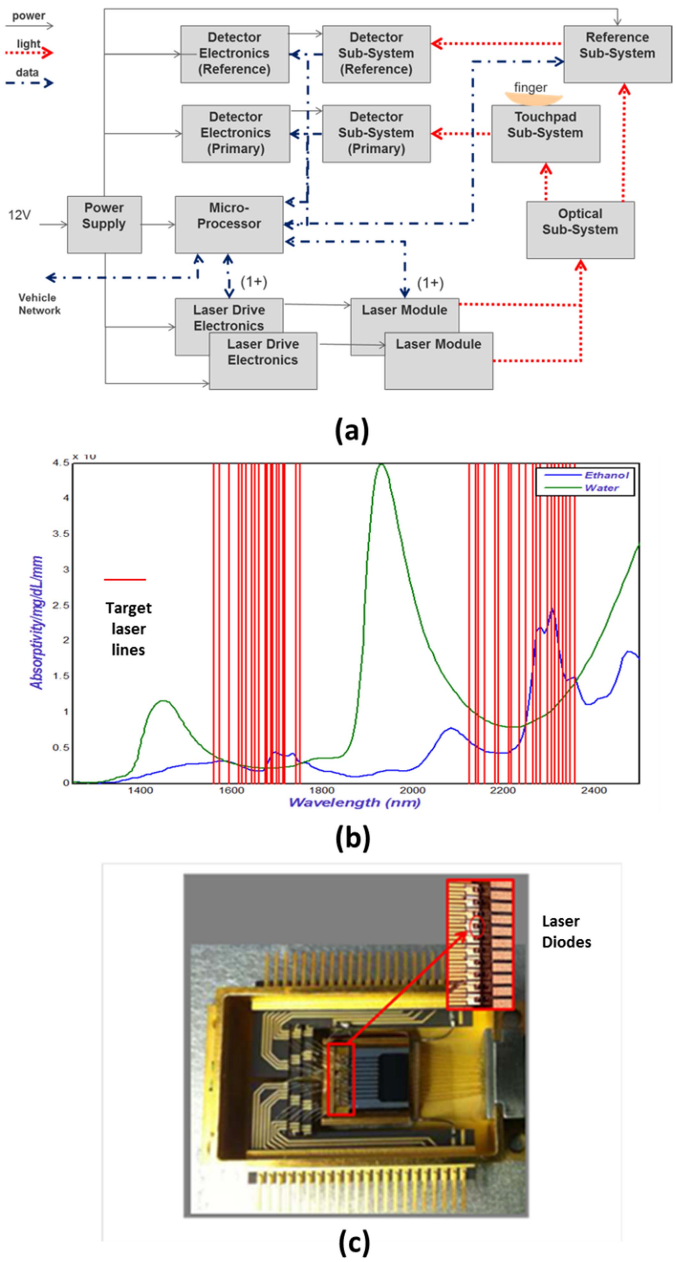


Figure 4. Solid State Design (a), Laser line targets (b), Prototype Multi laser Module (c).

In contrast to the Mark 1 sensor, which measures a semi-continuous spectrum, the new design uses discrete, narrow-band spectral lines specifically chosen through analysis of several hundred thousand *in-vivo* alcohol tests. The laser wavelengths are targeted to spectral regions where ethanol and water absorbance levels are separable (see figure 4b), optimizing ethanol detection while avoiding the strong water absorbance features.

The use of multiple discrete lasers to interrogate spectral information allows for a highly integrated, compact optical module. For the Mark 2 design, a custom 12 laser prototype module was developed with individual controllable laser die mounted on ceramic substrates (see figure 4c). The inset detailed view shows the individual laser die mounted on the ceramic substrate. The design is compact, even at the prototype phase, and can be further integrated using packaging techniques developed for laser applications in other industries.

To show the spectral measurement accuracy of the Mark 2 system, several standard benchmark measurements have been performed and compared to both the Mark 1 system and to laboratory grade FTIR spectrometers (see figure 5). Measurements to date indicate good agreement with laboratory grade and Mark 1 system measurements. Additional testing is ongoing and planned including *in-vitro* and *in-vivo* studies similar to those previously described to verify performance that exceeds all previous FTIR systems and approaches performance targets for a vehicle based system.

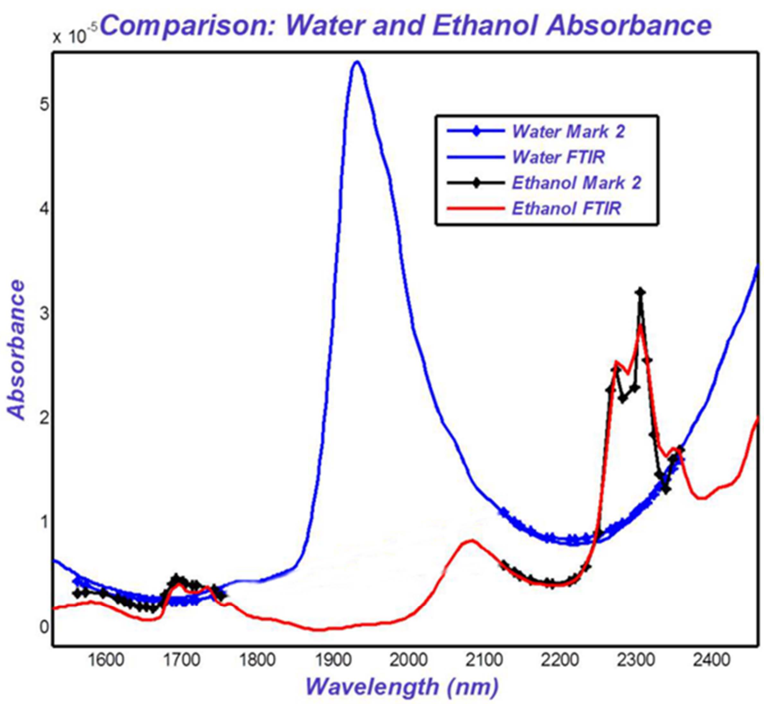


Figure 5. Mark 2 Measurement performance comparison compared to FTIR.

AUTOMOTIVE ADS SYSTEM CONSIDERATIONS

Although significant progress has been made towards establishing the feasibility of a non-invasive touch based alcohol measurement system, continued research and development is necessary to achieve a production automotive system that can meet aggressive targets for performance, measurement time, reliability and robustness. Several key considerations in the touch based design are explored further below.

Human Machine Interface A touch based sensor provides a natural opportunity to integrate the sensor touchpad into a standard starter ignition switch. Inclusion of proximity and/or touch sensors in the design supports the ability to enable alcohol measurements only when appropriate. Inclusion of a haptic actuator(s) and/or light(s) provides for natural HMI feedback (see figure 6). For example, light and haptic actuators can be used to provide driver feedback on proper finger placement, measurement initiation, measurement result and other desired HMI feedback.

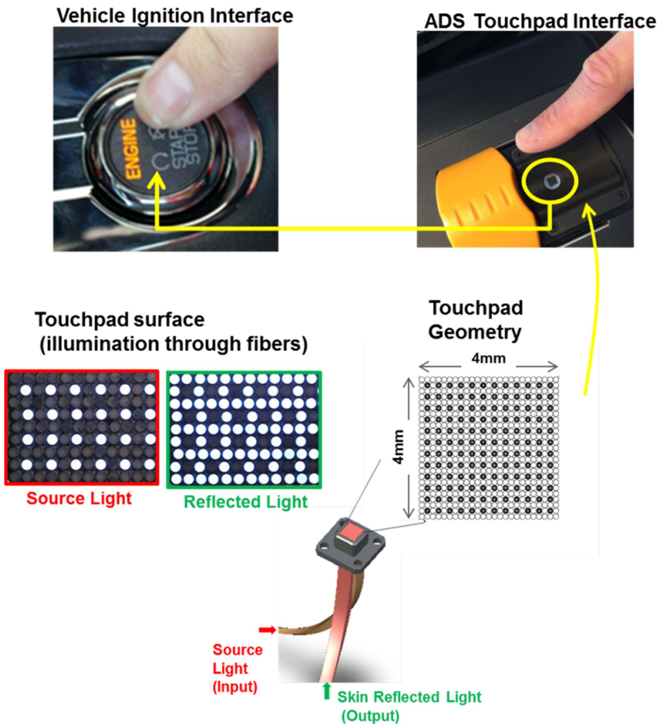


Figure 6. Prototype alcohol measurement ignition switch integration concept.

A vehicle ignition system provides one natural touch based measurement location; other viable locations throughout a vehicle exist where a driver/operator skin touch interface might be used for initial or periodic alcohol measurements.

Anti-Spoofing Concept

Based on the proposed ignition switch HMI integration, there is the potential for non-impaired occupants to try and test (start the vehicle) on behalf of another person, who intends to drive, but is impaired. To mitigate this situation, a simple anti-spoofing method can be achieved through the integration of an electric field Occupant Classification System (OCS) within the driver seat. Such systems are often used in production vehicles for the front passenger seat to satisfy a regulatory requirement to distinguish child seats from empty or full size human occupants. The information is often used to suppress airbag deployment in the case of child seats or empty seats. Electric field based OCS systems emit a controlled signal in proximity to the seat occupant. This harmless signal is influenced by the seated occupant and is transmitted through anything that the occupant touches. Because the ignition switch is touched by the driver, detection of this OCS signal can be used to distinguish the seated driver from others touching the ignition switch. The alcohol measurement control logic can be configured to require a new ignition touch (measurement) for all driver seat occupancy state changes (e.g. ingress/egress). This anti-spoofing concept could be further enhanced through signal integrity methods currently used in secure, safety automotive systems.

Environmental, Life and Ruggedness

The Mark 2 design is based on electro-optical components widely used in aerospace, defense, communications and commercial industries requiring high accuracy and precision in a rugged environment and over long operational life. Lasers and detectors of the type utilized have been verified for long term operation through military specification environmental and ruggedness testing [31, 32]. However, the Mark 2 application, introduces new technical and commercial challenges. For example, the measurement touch probe surface must be designed to operate with a wide range of finger surface chemicals and mechanical abuse such as scratching or impact. In addition, the system must be capable of reliable and accurate operation over full vehicle life, despite natural sub-system aging and drift. To mitigate these effects, the Mark 2 design incorporates an absolute chemical reference to allow for variance, bias and drift removal from measurements, over the course of the system life, in addition to providing a method to verify measurement quality and viability. Such techniques are widely used in other safety critical automotive sensors.

Commercial Challenges

The primary technical limiting factor in the development of the Mark 2 system is the fabrication and manufacturing base immaturity of the laser module and supporting optical interfaces. While advancements in the field of lasers is widespread [33,34], particularly due to new applications and markets evolving quickly, there are currently limited fully developed applications for semi-conductor lasers with the target wavelengths and optical powers targeted for the Mark 2 system.

To date, many of the target high laser wavelengths are only required in small volume specialized applications or in clinical research. On the contrary, many of the lower wavelength lasers required for the Mark 2 design are used in high volume, high reliability, and moderate to low cost packages for high bandwidth telecommunications. Lessons learned in the evolutionary technology and manufacturing growth of laser diodes can help accelerate the maturity and availability of higher wavelength diodes for use in this application. Research and development in non-invasive medical sensing is accelerating, driving new applications and markets; organically increasing manufacturing base and test investment necessary to lead to competition for low cost, high reliability automotive quality laser modules for non-invasive alcohol sensing.

CONCLUSIONS

Establishing the technical feasibility for a touch based sensor that could be used to accurately and precisely measure blood alcohol concentrations is a key initial step towards providing technical solutions to reduce alcohol impaired driving. The solid state Mark 2 system prototype provides a technically feasible architecture based on initial testing, with concepts to achieve naturalistic HMI and an anti-spoofing method. However, additional testing and design iteration are required towards a system that is capable of meeting automotive requirements.

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