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OPTICAL MICROSYSTEM FOR ANALYZING ENGINE LUBRICANTS

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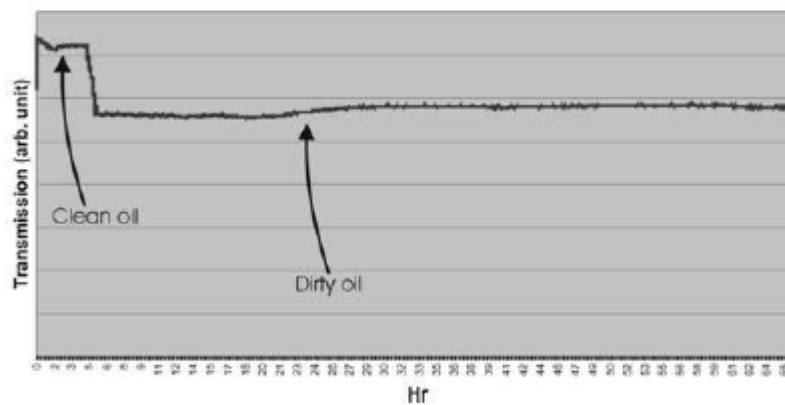
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Detection Soot



Optical microsystem for analyzing engine lubricants

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ABSTRACT

It is possible to dramatically improve the performance, reliability, and maintainability of vehicles and other similarly complex equipment if improved sensing and diagnostics systems are available. Each year military and commercial maintenance personnel unnecessarily replace, at scheduled intervals, significant amounts of lubricant fluids in vehicles, weapon systems, and supporting equipment. Personnel draw samples of fluids and send them to test labs for analysis to determine if replacement is necessary. Systematic use of either on-board (embedded) lubricant quality analysis capabilities will save millions of dollars each year in avoided fluid changes, saved labor, prevented damage to mechanical components while providing associated environmental benefits. This paper discusses the design, the manufacturing, and the evaluation of robust optical sensors designed to monitor the condition of industrial fluids. The sensors reported are manufactured from bulk fused silica substrates. They incorporate three-dimensional micro fluidic circuitry side-by-side with three-dimensional wave guided optical networks. The manufacturing of the optical waveguides are completed using a direct-write process based on the use of femtosecond laser pulses to locally alter the structure of the glass substrate at the nano-level. The microfluidic circuitry is produced using the same femtosecond laser based process, followed by an anisotropic wet chemical etching step. Data will be presented regarding the use of these sensors to monitor the quality of engine oil and possibly some other vehicle lubricants such as hydraulic oil.

Keywords: optical sensor, waveguide, microfluidic, glass, micro-machining, fused silica, femtosecond, oil, hydraulic

1. CONDITION BASED OIL MAINTENANCE

Proper lubrication of moving parts is a critical factor that affects internal combustion engine performance and reliability. Engine manufacturers recommend that the lubricants (engine oil for example) be changed on a time basis or mileage basis. When the lubricant change intervals are pushed too far, increased engine wear and even engine damage can result. On the other hand, premature oil changes are inconvenient, add to vehicle maintenance cost, and result in wasted natural resources. In order to determine the optimum oil change interval, it would be advantageous to move to a condition-based lubricant change.

The transportation industry and its suppliers have only recently started addressing the need to monitor the condition of the oil. Several automotive manufacturers are developing, and a few are deployed, software-based solutions.¹ A representative example is the General Motors Oil-Life System, first introduced commercially in the 1998 Oldsmobile, which determines when to change the oil and filter based on several operating parameters. This system does not actually measure directly the quality of the oil but rather monitors engine revolutions, operating temperature, and other factors that affect the oil change interval. DaimlerChrysler has a related oil monitoring system called ASSYST in Europe and Flexible Service System (FSS) in the USA. Daimler discovered that the breakdown in oil is determined by such factors as driving habits (frequent short trips vs. long trips), driving speed and failure to replenish low oil levels. Therefore, the FSS monitors time between oil changes, vehicle speed, coolant temperature, load signal, engine rpm, engine oil temperature and engine oil level. It uses this information to determine the remaining time and mileage before the next oil change and it displays the information in the vehicle's instrument cluster.

Software-based solutions may be acceptable in instances when the vehicle usage falls within a well-documented operational pattern for which a large database is available. Its applicability to cases where the vehicle usage is

unpredictable or unusual is much more questionable. For these cases, direct measurements of the relevant engine oil physical parameters are required. Note that, even when the vehicle usage pattern is predictable, software-based approaches may need to be supplemented with some direct measurements. For example, Daimler has fitted V-6 and V-8 engines with a digital oil quality dielectric sensor, which is mounted above the oil pan. This sensor measures changes in capacitance, which are somewhat related to the amount and type of contaminants and oil degradation products present in the oil. An increase in dielectric constant indicates oil contamination and degradation. Delphi is developing a related electrical sensor (INTELLEK Oil Condition Sensor).²

2. SUPPLEMENTING THE ARMY OIL ANALYSIS PROGRAM

The usage pattern associated with most US Army vehicles is unusual and unpredictable. Consequently, software-based monitoring systems are unlikely to provide the information necessary to evaluate the condition of the lubricant. In order to determine impending lubricant failure the Army has developed the Army Oil Analysis Program (AOAP), which is part of a DOD-wide effort to determine impending component failures and to determine lubricant condition through periodic laboratory evaluation of used oil samples. The effectiveness of the AOAP as a predictive maintenance diagnostic tool has been instrumental in improving operational readiness by assisting Commanders in keeping their combat assets in the fight. 92% of these tests show that the fluid is still acceptable, 2% lead to on-condition oil change recommendations, and 0.2% indicates potential costly impending failures. Finally, in extreme cases, the vehicle or equipment may be operating with an unsuitable lubricant whose poor quality may be the result of a serious component failure or may itself cause a system failure. Furthermore, reduced equipment down time and reduced in-field failure rates will save the lives of soldiers and workers who depend on this equipment in hazardous duties. The AOAP approach does however suffer from some shortcomings: (I) a significant effort is dedicated to analyze samples that are in excellent condition, (II) there is a delay associated with the sample collection and its transportation to the closest AOAP laboratory, and (III) the sample must be representative of the fluid condition (Proper sample collection is not necessarily a trivial task.)

Our program addresses these shortcomings. We are developing fluid condition monitoring sensors that are sufficiently robust to be installed onboard military vehicles. These devices continually monitor the fluid of interest, measuring various physical parameters that are representative of the condition of the fluid. The data is analyzed in real-time and the results provided immediately to the end users. Unlike most commercial condition-monitoring systems demonstrated to date, our devices rely mainly on optical techniques to assess the quality of the fluid.

3. OPTICAL CONDITION-MONITORING SENSORS

3.1 Concept

We are developing oil-condition monitoring sensors that measure the optical characteristics of engine oil, and correlate these optical properties to the physical and chemical properties of oil. These optical measurements may be complemented with other physical measurements (temperature, pressure, etc.). The sensors are designed to constantly monitor the oil while the engine is operating. Oil is continuously diverted from the main oil system, routed to the sensor, before being brought back to the engine. Our sensors are sufficiently robust to be mounted within the engine compartment. However they must be kept away from the hottest spots, such as the exhaust system. The firewall, which is relatively cool, is a preferred location. The data is collected and (partially) processed at the level of the sensor before being forwarded via wireless means to the end users.

3.2 Sensor Design

Our sensors measure a variety of optical parameters to assess the quality of the oil. An exemplary device is shown in Figure 1. This device measures an array of optical parameters in order to quantitatively assess the quality of engine oil. We measure absorption in the visible to assess the amount of soot present in the fluid. In parallel, we measure absorption in the near-UV to assess the chemical degradation of the oil. Scattering (forward, backward, or side) is measured in order to determine the presence of solid particulates. Finally, the index of refraction of the fluid is measured through phase interferometry. This last measurement provides information related to water contamination. Additional optical parameters such as fluorescence may be monitored to determine the presence of specific contaminants such as coolant.

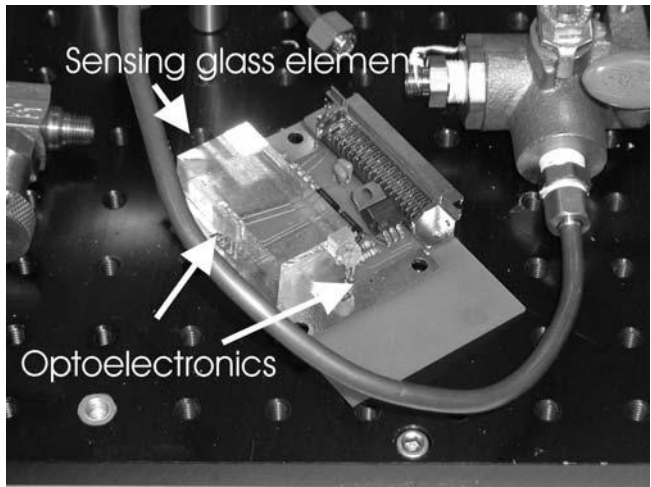
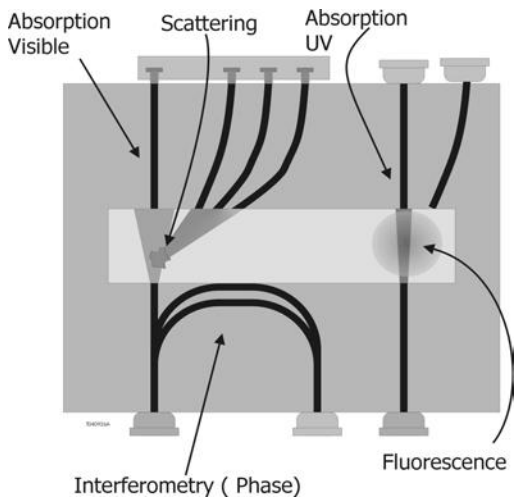


Figure 1: Multifunction optical sensor concept (left) and early implementation (right).

3.3 Manufacturing

These sensors are based on Translume's proprietary processes to micromachine glass. The base material is fused silica – a glass that is highly compatible with our applications. Fused silica is transparent deep in the UV and does not autofluoresce. Fused silica is also transparent in the visible and the mid-infrared (up to 4- μm). Furthermore, fused silica does not react to any of the fluids commonly found in vehicular applications. Fused silica is stable too extremely high temperature (melting point close to 2000 °C).

We use a first laser-based process (*femtoWrite*) to manufacture optical waveguides. A second laser-based process (*femtoEtch*) combined with a wet etch process is used to manufacture the fluid circuitry, to create various optical elements such as collimating lenses, and to delineate the outside edge of the glass sensing element. These two processes are illustrated in Figure 2.

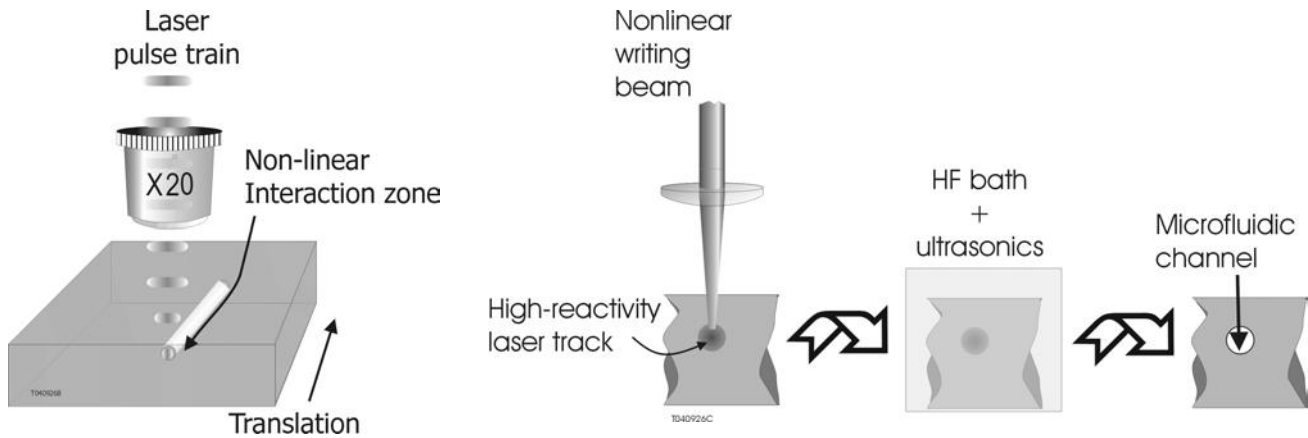


Figure 2: *femtoWrite* (left) and *femtoEtch* (right).

Combining these two processes, we are able to manufacture unique glass-based sensors, which incorporate three-dimensional microfluidic circuitry side-by-side with three-dimensional waveguided optical networks.³

3.4 Packaging

Our sensing systems include several subsystems as illustrated in Figure 3. At the heart of the system is the laser-machined glass-sensing element. It is surrounded by various opto-electronics components such as photodetectors and light sources. These are directly bounded to the glass element. It has been suggested that these components could be located remotely and connected via optical fibers. However, our admittedly limited experience has been that direct coupling result in designs that are more robust.

In order to improve signal to noise ratio and increase the sensitivity of our devices we are developing laser-based manufacturing procedures to machine coupling lenses (either cylindrical or spherical), as well as light traps, directly into the glass sensing substrate.

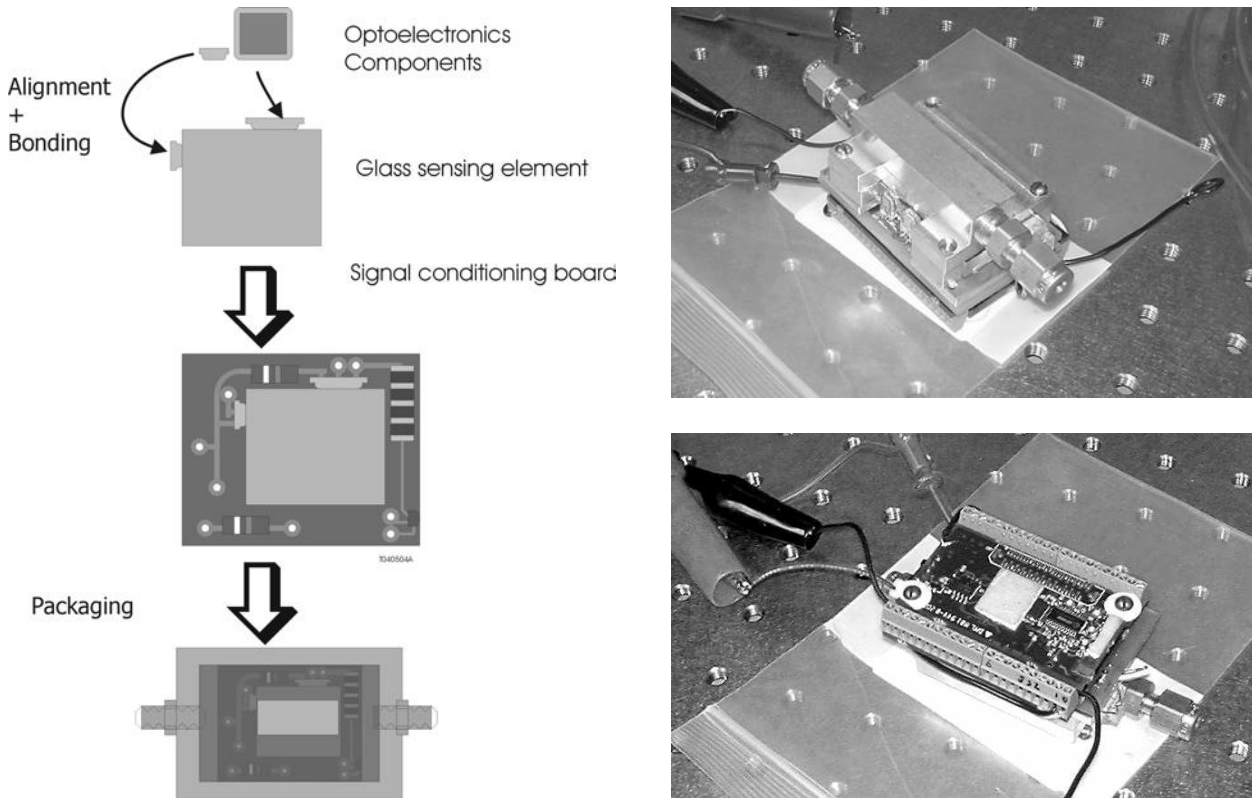


Figure 3: Packaging concept (left) and Prototype (right).

3.5 Interface

The data collected by the sensor is transmitted by wireless means from the engine compartment to the user, where it is displayed to show relevant information. We have developed a first generation user interface (as shown in Figure 4).

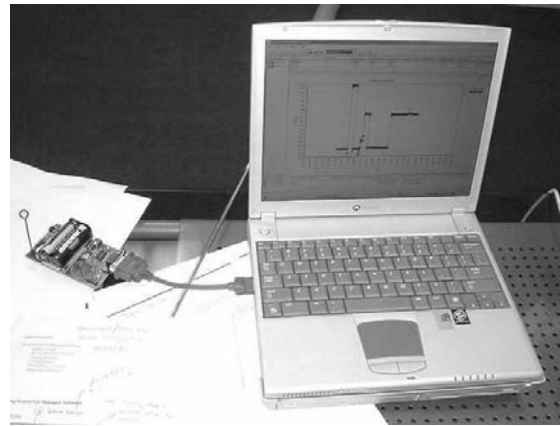
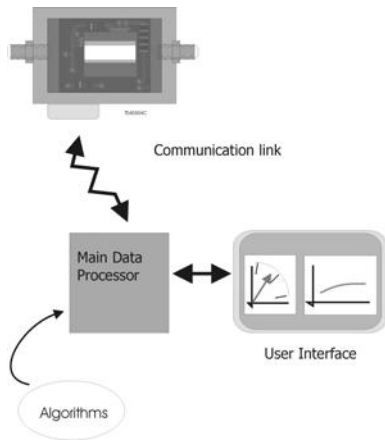


Figure 4: Wireless transmission concept (left) and Prototype user interface (right).

3.6 Experimental Data

We have developed and tested several generations of fluid condition-monitoring sensors, with progressively higher performances. Initially we concentrated on soot measurements. The amount of soot present in the fluid is determined through absorption in the visible or the near infrared. We showed experimentally that our sensors are stable. Baseline fluctuation of the order of plus or minus 1 % was measured over weeks as shown in Figure 5. Furthermore, we showed that we could easily differentiate between clean and dirty oil. Some typical data is shown in Figure 5.

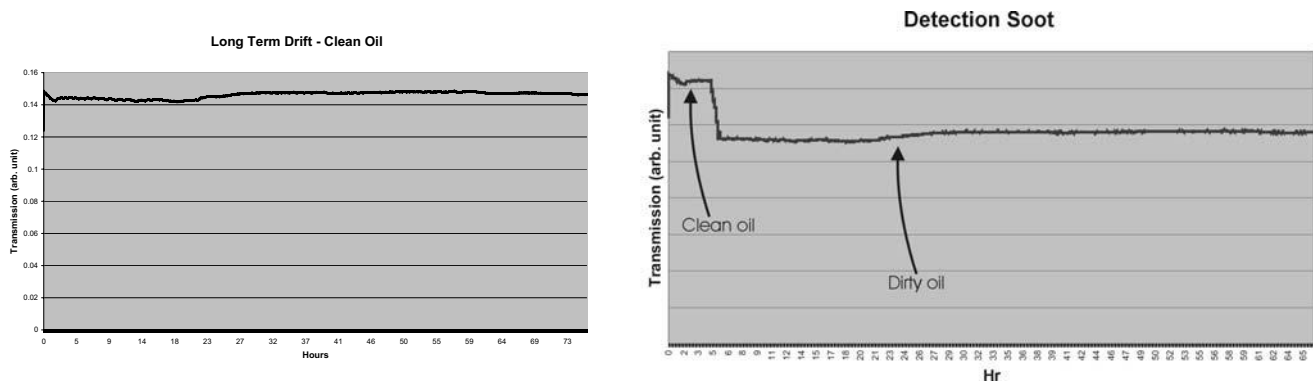


Figure 5: Experimental data – sensor drift (left) and differential signal clean oil –dirty oil (right).

3.7 Future work

We are adding to our sensor a capability to detect solid particulates and to trace chemical degradation.

4. CONCLUSION

Condition-based maintenance is an emerging concept, which is expected to play a key role in the military. Vehicle lubricant condition monitoring is far from a mature technology. As this technology develops, as sensors become more powerful, condition base maintenance will complement and progressively replace today's standard maintenance practices and reduce equipment down time and reduce in-field failure rates which will save the lives of soldiers and workers who depend on this equipment in hazardous duties as well as saving millions of dollars and environmental waste.

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