Non-Invasive Sensors for Commercial Applications

Frank Hartley
Jet Propulsion Laboratory, California Institute of Technology
Ph 818 354 3139;Fax 818 354 8153; fhartley@jpl.nasa.gov

Steve Walsh
University of New Mexico
Ph 505 277 8868; walsh@unm.edu

In metrology context the uncertainty principle states it is impossible to observe the exact state of a mattercule, as the actual energy of observation 'disturbs untouched nature'. A non-intrusive measurement is one where less of the observational energy input is transferred to a medium than that which would bias the measurand by the resolution of measurement. In physical context an intrusive transducer would specifically or collectively disturb its electrical, hydraulic, mechanical, chemical, thermal or gravitational environments. This paper presents differing types of non-invasive sensing technologies, differing market sectors that have requirements for these technologies and a manner to commercialize these technologies.

Introduction:
We have segmented our non-invasive technologies into six Product–Technology paradigms. They are: Dielectric, Temperature, Contact, Pressure, Flow and Level. We follow this with a commercialization paradigm and a commercialization imperative from JPL.

1. Dielectric

For mammalian in-vivo and explosive environments galvanic circuits are invasive from a safety perspective. Optically excited and encoded transducers are electrically (and magnetically) inert. In the early nineties the late Prof. Henry Guckel of the University of Wisconsin developed such a class of optically excited polysilicon microbeams that exhibited Fabry-Perot interferometer like properties. When the microbeam vibrates, incident and reflected light is modulated and the reflected light represents the frequency modulated resonance of the microbeam. It was also found that if the transducer is doped to have a high thermal coefficient of stiffness (different thermal expansion coefficient than silicon) the device acts as a temperature transducer. Honeywell and the University of Wisconsin jointly worked on developing these optically excited self resonant microbeams into highly sensitive strain transducers. They also teamed with Mobil Oil, and with ARPA support, developed a class of optically resonant microbeam thermometers[1].

Structure of Optomechanical Microbeam Resonator

Optically excited self-resonant microbeams uniquely combine silicon microfabrication technology with optoelectronic technology. The vibrating microbeam in its polysilicon vacuum enclosure is an effective optomechanical modulator driven by a built-in photodiode. When irradiated with unmodulated IR light the photo-generated charge attracts and bends the microbeam toward the diode, inducing resonance in beam that changes the 1/4 wave Fabry-Perot interferometric gaps above and below beam highly modulating reflected light. The microbeams are sensitive strain transducers (nanostrain) with high gage factors, low temperature sensitivity sensitive (-40 ppm/°C), and wide dynamic range (10^{-8}). Doped polysilicon cantilevered microbeams (different thermal expansion coefficient than silicon) acts as a sensitive temperature transducer with milidegree sensitivity and resonant frequencies in the Mhz.

Honeywell developed these milidegree thermometers with a range of resonant frequencies and coupled them into an optical fiber network. This frequency multiplexed multi-point thermometry network enabled the EMI immune and intrinsically safe monitoring of cracking tower temperatures.

JPL deployed tiny optically excited resonant cantilever transducers in the galvanically isolated measurement of the temperatures of various portions of an animal's muscle-tendon complex during locomotion. These thermally inert and low thermal capacity sensors were capable of providing the temperature profile of various muscle fibers and fiber bundles that are indicative of the work done by specific muscles.

Optical Micrograph Of Sealed Microbeam

The optically excited resonant microbeam is intimately coupled to stress member (housing), which alters the tension in the beam and thus its frequency of resonance. For thin stress members (thickness of silicon wafer) the nanostrain sensitivity resolves minute loads. To measure the localized strains and extensions among muscle facicles, JPL developed small load and extension measuring transducers. For muscular tension measurement, non-extensible fibers were glued to the ends of stress member attached to the two severed ends of a tendon. And for muscle extension measurement the stress member was be fitted with extensible fiber such that the tension measured, for the particular extensibility of fiber, represented a measure of the muscle extension.

Proposed in-vivo applications include the thermal monitoring of breast tissue as a cancer probe, pressure (strain) monitoring of stents and the monitoring of strains/loads across artificial limbs (knee).

2. Temperature

One of the toughest technology challenges in thermal engineering for the Space Interferometry Mission and other future ORIGINS programs is the maintenance of milikelvin temperature stability in the critical components in space. Conventional thermal design methods and temperature-sensing devices used in the past three decades are inadequate to meet this requirement. Ultimately, thermal control precision cannot exceed the accuracy of temperature measurement, which mandates accurate and reliable temperature sensors that can resolve sub-milikelvin temperatures. Conventional temperature sensors (thermocouples, PRTs, and thermistors) are affected by the resistive heating of sensors, the distributed heating of conductors, and/or the interaction between the sensors and their immediate thermal environment, and cannot attain the level of sensitivity/accuracy required.

Optically excited resonant cantilevered microbeams are thermally inert, with their high Q (100,000) requiring only femto-watts of optical excitation energy, precision temperature sensors that suffer none of these problems. These optical resonant beam thermometers have demonstrated sensitivities of 265 Hertz/^{o}K and temperature resolutions of 0.0001 K ^{o}.

The goal of a Comet regolith thermal properties penetrator is to measure heat flow from the direct measurement of thermal gradient and from the indirect temporal analytic determination of thermal conductivity. Thermal gradient determinations are made by the multi-depth discrete measurements of penetrator wall temperatures. At each of these measurement depths, determinations of thermal conductivity can be made as the temperature rise (dissipation of kinetic energy of penetration) in the soil nearest the penetration cavity equilibrates. To obtain precise heat flow estimations it is essential that the thermal sensors along the probe tether accurately measure the temperatures of the adjacent regolith. The low thermal capacity of the regolith mandates that the measurement system itself does not influence the thermal environment by thermal conduction of the instrumentation material, the resistive heating of instrumentation sensors, or the distributed heating of instrumentation conductors.

Again the optically excited resonant cantilevered microbeams are thermally inert precision temperature sensors with demonstrated temperature resolution of 0.0001^{o}K. By utilizing sensors with different resonant frequencies many thermometers can have their respective reflected resonance (modulated light) frequency multiplexed over a single fiber frequency multiplexing their respective resonances. This furthers reducing the propensity for contamination by thermal conduction along a single fiber rather than conduction along many fibers.

3. Contact

Biological quarantine requirements for the terrestrial import of Martian materials mandates that the samples are contained in hermetically sealed canisters. Establishing that a canister is in fact sealed translates into a requirement for the accurate monitor the gas pressure (7 Torr) within canister over long periods, over large temperature excursions and over ambient pressure excursion from vacuum to 780 Torr (return to Earth). Conventional pressure transducers do not have the required accuracy or dynamic range, require penetration of the hermetic seal, and necessitate joints and couplings: the latter having the propensity for slow leaks.

Further requirements are that the canister is transferred from a Martian rover to a mechanically sealable container on the sample return vehicle and that the canister's pressure sensor instrumentation is coupled to the sample return vehicle's avionics. A feat that essentially eliminates direct electrical connection.

The strain generated in the walls of tubes, cylinders or canisters measures hoop stain that is directly proportional to the pressure differential between inside and outside of vessel (gauge). Measurement of the circumferential strain in the outer surface of hermetic sealed canister is thus a non-invasive measurement of the gas pressure within canister. The double-pinned optically excited resonant microbeams are highly sensitive to axial strain and when microbeam housing is intimately coupled to the surface of canister the surface stress changes the tension in the beam altering its frequency of resonance. The gage factors for these optically excited resonant beam sensors are in the nano-strain arena (several orders of magnitude greater than the most sensitive conventional gages) which, when fixed to the thin canister wall, will resolve differential pressures to the sub-ppm.

A non-contact measurement of canister pressure is achieved by projecting the optical excitation and collecting frequency encoded reflections from these beams over a millimeter gap. The avionics interface in sealable container (launch vehicle) is an optical fiber ferrule in container wall and the mechanical alignment a simple tapered floor. The canister hoop-strain measurement provides a measure of the differential pressure between gas inside canister and gas in sealed container. Similarly, the container hoop-strain measurement provides a measure of the differential pressure between the gas inside container and the environment 'outside'. Finally, the absolute ambient pressure need be measured, be it Martian atmosphere (7 Torr), vacuum of space or Terrestrial atmosphere (780 Torr).

This non-contact strain measurement technology has been proposed for the measurement of torque on rotating structures.

4. Pressure

A non-invasive transducer, from a chemical context, must be inert to erosion from highly reactive materials and its installation must not introduce quiescent voids, cavities or protrusion sites for stagnative corrosion. Microstrain gages applied to the exterior tubing wall provide a non-invasive solution where the transducer is the feed tube (no additional mass, no protrusions or welded tee-offs) and there is no diaphragm (aside from tube wall itself)[2].

Flat Surface Laser Cut Gages

From a mechanical prospective the non-invasive transducer has virtually no mass (thin film gage mass virtually zero or negative if tube polished off material excluded) and no protrubences, which ensure extreme resilience to shock and vibrational loads – a major driver for spacecraft. The figure illustrates a flat surface arrangement where gage grids have been laser cut in Nickel-Chromium piezo resistive film providing neutral strains (outer gages) on the surface of the tube as well as pressure induced tensile strains (central gages). The response to mechanically induced bending or torsional strains are minimize by orienting two strain gages at approximately 61.3 degrees to the tube axis (optimum angle of orientation is solely a function of Poisson's ratio for material) and wiring them into opposite arms of the Wheatstone Bridge (hoop strain reduced by ~83%). To increase accuracy, temperature measurements are taken to compensate for thermal disparities, and individual calibrations of each assembly accommodate discontinuities in wall thickness, gage resistances and material properties. An encapsulating insulator sputtered over gages and wiring provides the ultimate in 'packaging' simplicity. The co-location of RTD with active gages results in residual errors of around 0.025% f.s. and the strains produced by mechanical loading are not pressure dependent and, at worst, fifteen (typically much greater) times less sensitive to strains produced by mechanical loading.

Sputtered thin film gages and dielectric coatings are in intimate contact with tube surface at the molecular level. From a transduction perspective this intimate coupling increases 'gage factor', increases response rate (MHertz), simplifies thermal coefficients, reduces thermal time constant and diminishes long-term drift and zero shift. From a thermal perspective the high dissociation temperatures of dielectrics and piezoresistive films enables operation at high temperatures and the thin intimate structure extends operation down to cryogenic temperatures.

5. Flow

From a metrology context a flow transducer should have no physically intrusive regimes, no restrictions, no diversions and no cavities that might influence flow resistance or regime. In the transfer of propellants and other highly reactive or corrosive fluids (liquids/vapors) non-invasive sensing is desirable to avert material compatibility problems with transducers and with plumbing journals and fittings. For spacecraft applications it is also mandatory that flow measurements be done under both large accelerations and zeroG.

Non-invasive (gravity invariant) flow measurement is best achieved by measuring the thermal mass flow rate of the fluid in the tube. The placement of a circumferential electrical heating element around a tube and a circumferential thermometer down stream (and optionally up steam) facilitates the direct measurement of thermal conductance – which is related to the heater power, convective transfer (between tube-fluid-tube), to the thermal capacity of fluid and to its flow rate through tube.

The lowest mass and most robust (reliable) implementation involves the placement of a thin dielectric around the outer circumference of a (metal) tube, sputtering a thin platinum coating over dielectric and patterning two narrow annular ring (platinum strip) around the circumference of tube at two positions down the tube. The up-stream platinum ring is then deployed as a resistance thermometer the central platinum band is deployed as a heater/resistance thermometer and the down-stream platinum ring is deployed as a resistance thermometer. Once the flow transducer has been characterized and calibrated it will provide a gravity (acceleration) invariant measurement of fluid flow rate. Integrating fluid flow rate over time provides a measure of fluid (tank) volume or fluid consumed, transferred, etc.

The thermal conductance of flowing fluid is directly proportional to flow rate and independent of flow regime (turbulent or laminar flow). The first graph presents the flow characteristic for liquid hydrazine in 3-mm diameter titanium tube for a range of flow rates for different spacecraft thrusters. The second graph presents the flow characteristics for a variety of gasses in 1-mm diameter titanium tube.

6. Level

In the containment of propellants and other highly reactive or corrosive fluids (liquids/vapors) non-invasive sensing is desirable to avert material compatibility problems with transducers and with plumbing journals and fittings. For spacecraft applications it is also mandatory that fuel volume measurements be done under large accelerations, various acceleration vectors, at zeroG and with high impedance flow. Non-invasive (gravity invariant) 'level' or liquid volume measurement is best achieved by measuring the vapor volume and deducting it from the volume of the vessel.

In a reversible adiabatic compression/expansion process there is no heat transfer (short measurement interval) and fluid temperature is constant i.e. $\left(\frac{\partial P}{\partial V}\right)_s = \frac{C_P}{C_v}\left(\frac{\partial P}{\partial V}\right)_T$
For an ideal gas $\left(\frac{\partial P}{\partial V}\right)_T = -\frac{P}{V}$, for a particular gas $\gamma = \frac{C_P}{C_v}$ is a constant and $\left(\frac{\partial P}{\partial V}\right)_s = \left(\frac{\Delta P}{\Delta V}\right)$.

Thus $V = -\gamma P \frac{\Delta V}{\Delta P}$ where P and ΔP are measured and ΔV is known or measured.

Vapor volume sensor

In zero gravity there is no 'down' and essentially nothing to keep liquid in one body. Where the liquid resides, or in how many liquid globules (or even mist) it might be, is immaterial to measuring the volume of vapor in a vessel. The mean pressure in vessel must be measured, ΔV is known and produces a change in pressure (ΔP) that is measured. Substituting these variables in the adiabatic compression relationship provides an estimate (measurement) of the volume of vapor in vessel. The adiabatic relationship is established where the compression-expansion cycles are short compared with thermal equilibration times so that no heat is transferred. To function while a vessel is being filled or emptied (equivalent to a high impedance leak) the volumetric perturbations must be fast enough to be significantly greater than the volume (over cycle period) of injected or expelled fluid. Subtracting the 'measured' vapor volume from the 'known' vessel volume provides an estimate of liquid volume.

A 94-liter tank was coupled with a small solenoid actuated 0.02-liter bellows (1/4700 tank capacity) and filled with water/air at atmospheric pressure. The graph presents the performance of 'level' gauge. The measurement was independent of temperature and the worst resolution (empty tank) was better than 1% of volume. Trials with liquid nitrogen and liquid helium provide comparable performance.

Commercialization

NASA's charter, in addition to aerospace developments, emphasizes the transfer of its technology to American industry. Publishing of 'Tech Briefs' and the establishment and funding of Centers for Technology Commercialization around the country are part of this endeavor. JPL's role involves the direct licensing of technology (Patented) and, through the Technology Affiliates Program, the adaptation of Patented technology or the development of new technology for exclusive license. Caltech has an Industrial Relations Center, a Technology Transfer Office and a Center for Neuromorphic System Engineering that are responsible for technology transfer, patent licensing and enterprise establishment. Here we present work that has met the challenges of critical components that had to work in extreme environments. These can meet commercial solution challenges facing today's business environment.

Devices that non-invasively measure critical, hostile environments are necessary in today's industry. A shortfall in the Microsystems applications has been the inability to accomplish this. Our sets of sensors accomplish this in the most arduous of "space" applications and have compelling value propositions in many industrial arenas. Our problem is not, "Can we prototype these devices" nor, "Can we manufacture them" but rather which of the numerous compelling application areas is the "Low-hanging fruit". Your problem is identifying which of NASA, JPL or Caltech is best to team with to "Ripen" or "Pick" what you identify as the "Low-hanging fruit".

Value position

We present product technology paradigms that can sense think and act in hostile environments. We provide a product platform that can start by solving a critical business need and provide a product platform that transcends industrial limits. We provide this value platform on a "Noah's Arch" system of six differing sensing technologies. Here we provide brief application areas in all of those sensing domains.

Dielectric

For example, Safety is the over-arching requirement for galvanic isolation in in-vivo and explosive environment transducers. The 'value position' for optically excited and encoded transducers is their electrical and magnetic inert (galvanically non-invasive circuits) attributes. Market sectors that have these would benefit from these features are listed below by benefit typology.

Value Proposition Sectors

Explosive Chemicals

- Petro-chemical processing
- Gaseous fuels
- Propellant handling

Medical

- Dialysis networks
- In-vivo measurements
- EMI immune
- NMR immune

Electrical

- RF immune

Temperature

Thermal isolation of transducer is crucial for both precision temperature measurement and the temperature measurement of low thermal capacity bodies. The 'value position' for optical thermometry is the thermal inert (non-invasive) attributes of femto-watt observational energy in high resolution temperature measurement (0.0001 ^{o}K) and low thermal capacity measurement.

Value Proposition Sectors

Thermal control

- Cryo temperatures
- MiliKelvin

Thermal capacity

- Micro reactors
- Protenase
- Micro channel control

Contact

Physical isolation of transducers may be required for thermal, galvanic, economic or mechanical reasons. The 'value position' for the optically excited resonant cantilevered microbeams is their non-contact attributes.

Value Proposition Sectors

Mechanical

- Confined tolerances
- Awkward shapes
- Moving surfaces

Medical

- Proximity micro-channel temperature
- Proximity micro-channel pressure
- Through skin in-vivo measurements

Machines

- Temperature
- Load
- Torque

'Hoop strain' pressure transducer

From a chemical perspective this 'non-invasive' attribute eliminates reactive chemical corrosion of materials, such as fittings, seals and diaphragm, and in quiescent voids in diaphragm cavity and around seals and internal journal threads. From hygienic and toxicity perspectives this 'non-invasive' attribute eliminates sites for materials to stagnate and ferment and enhances thorough 'cleaning' of network. From a rheological perspective this 'non-invasive' attribute eliminates erratic dynamics; reduces propensities for cavitation and 'frothing';

and enables the unimpeded transport of pulps, slurries, viscous fluids and biological materials. From a mechanical prospective the transducer is essentially part of the tube (virtually no mass) with no protrubences, which enables the sustenance of extreme shock and vibrational loads.

Value Proposition Sectors

Reactive Chemicals

- Processing fluids and vapors for electronics and MEMS foundries
- Fuel cell agents
- Propellant handling
- Chemical reactors

Medical and Food processing

- Dialysis networks
- Heart-lung oxygenator systems
- Pathology instruments
- Pulps and slurries
- Essence concentrates and beverages

Aviation, Agricultural, Automotive, Construction

- Hydraulic brake, suspension, actuation and transmission networks
- Fuel flow and aspiration regulation
- HVAC and refrigeration networks
- Slurry transport

Flow transducer

From a chemical perspective this 'non-invasive' attribute eliminates reactive chemical corrosion of materials, such as fittings, seals and turbines, and in quiescent voids around orifice plates, seals and internal journal threads. From hygienic and toxicity perspectives this 'non-invasive' attribute eliminates sites for materials to stagnate and ferment and enhances thorough 'cleaning' of network. From a rheological perspective this 'non-invasive' attribute eliminates erratic dynamics; reduces propensities for cavitation and 'frothing'; and enables the unimpeded transport of pulps, slurries, viscous fluids and biological materials. From a mechanical prospective the transducer is essentially part of the tube (virtually no mass) with no protrubences, which enables the sustenance of extreme shock and vibrational loads.

Value Proposition Sectors

Reactive Chemicals

- Processing fluids and vapors for electronics and MEMS foundries
- Fuel cell agents
- Propellant handling
- Chemical reactors

Medical and Food processing

- Dialysis networks
- Heart-lung oxygenator systems
- Pathology instruments

- Pulps and slurries
- Essence concentrates and beverages

Industrial, Commercial, Aviation, Agricultural and Automotive

- Fuel flow and aspiration regulation
- HVAC and refrigeration networks

Level
In the containment of propellants and other highly reactive or corrosive fluids (liquids/vapors) non-invasive sensing is desirable to avert material compatibility problems with transducers and with plumbing journals and fittings.

Adiabatic compression/expansion measurement of vapor volume facilitates liquid volume measurements that are unaffected by acceleration vectors, shapes of tank or high impedance flow.

Value Proposition Sectors

Stationary structures

- Shape invariant
- Orientation immune
- Compartment versatile (baffles)
- Boundary versatile (foam matrix)

Portable – mobile structures

- Shape invariant
- Orientation immune
- Compartment versatile (baffles)
- Boundary versatile (foam matrix)
- Acceleration immune

ACKNOWLEDGMENTS

The work described was made possible under funding for California Institute of Technology from NASA general contract (NAS7-1407). The authors would like to thank Tim O'Donnell and Charles Yarbrough for their support and encouragement of the Mars Chemical Propulsion and Mars Mechanical Integration programs.

---

[1] M. L. Wilson, D.W. Burns and J.D. Zook, "An optical network of silicon micromachined sensors",

[2] Frank Hartley, "Microtechnology Alternatives to Conventional Pressure Transducers", JPL Publication D00-16, December 2000.