ROBOTIC ARM DESIGN FOR A REMOTELY-DEPLOYED, IN SITU WASTE CHARACTERIZATION PROBE*

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ABSTRACT

This paper describes some design considerations for a system which will combine robotics and laser spectroscopy to produce an in situ monitoring system for heterogeneous waste materials. The new system will provide faster, cheaper, safer, and more complete characterization of mixed solids and liquids stored in tanks and drums or buried in pits. A small, fiberoptic multiprobe that performs Raman and fluorescence measurements of wastes composed of a variety of organic and inorganic compounds will be described. Design considerations for a novel sensor platform that positions and stabilizes the multiprobe relative to the sampling point in order to make accurate spectroscopic measurements and deploys the sensor in hazardous environments with minimal risk to workers will be presented. The core of the platform will be a 3-Degrees-Of-Freedom (3-DOF), spherical coordinate end effector equipped with a proximity sensor that compensates for errors introduced by the flexible nature of the support arm. The platform can be adapted to operate with most robotic deployment systems used in hazardous environments. The multisensor probe will be coupled to remote, portable laser spectrometer systems by a fiber-optic bundle.

INTRODUCTION

Statement of the Problem

The U.S. Department of Energy (DOE) is faced with an enormous cleanup task at production facilities and national laboratories. For example, at the DOE site in Hanford, Washington, there are 149 single-shell waste storage tanks and 28 double-shelled tanks. Some of the tanks are 50 years old (they were first used as early as 1943 for the production of plutonium for the first nuclear bombs). The tanks contain approximately 60 million gallons of radioactive liquid, sludge, salt cake, and other assorted and unknown wastes. All of the single-shelled tanks have exceeded their design life, and 66 of the tanks have leaked or are suspected of having leaked liquid radioactive waste into the ground. None of the double-shelled tanks have leaked to date, but they are nearing the end of their design life. DOE estimates that it will take until the year 2000 to eliminate flammable gas danger from 23 of Hanford's 177 underground waste storage tanks and until the year 2004 to handle the problems of potential ferrocyanide explosions in 24 of the 177 tanks. Other sites have similar problems. DOE is already taking measures to alleviate the problem of underground storage tanks. Programs have been initiated to develop the technologies necessary for remediation of the underground storage tanks. One of the major difficulties with cleanup of the waste tanks is the unknown nature of the contents. Many times, inadequate records were kept or records were lost or destroyed. The problem is exacerbated by the fact that waste tank contents are not stable; therefore, adequate knowledge of the input does not ensure knowledge of the present contents.

To effectively plan and execute a tank cleanup, the contents of the tank will have to be assessed or characterized. Characterization of the waste contained in a tank or drum is problematic, however, because the contents are often a kaleidoscope of heterogeneous materials. For example, large storage tanks develop crusts composed of inorganic salt cakes over their liquid contents; the liquids, in turn, cover a layer of sludge or another immiscible liquid. In some cases, explosive hydrogen gas builds up beneath the crusts which contain potentially explosive materials.

Currently, there are two approaches to characterizing hazardous wastes. The first and safer approach is to collect and to analyze a few samples from a tank, drum, or burial pit; insufficient characterization is the result. The second approach, where many samples are collected, improves characterization but serves to compound the hazards when highly toxic or radioactive materials are present. Also, the second approach is very expensive in terms of time and dollars because of the special procedures that must be used and the large number of samples that must be analyzed.

The basis of this work is the design of a multisensor probe which can be deployed robotically in tanks, drums, or underground to rapidly and cost-effectively characterize heterogeneous wastes. The probe, arm, and end effector are shown schematically in a generic waste storage tank in Fig. 1 and a proposed probe end effector is shown in more detail in Fig. 2 (Next page). This design is patterned after the 3-DOF hopping machine of Raibert (1). The sensor probe will be a remotely operated fiber-optic device that is capable of making direct fluorescence and Raman measurements of solids and liquids in a few minutes or less and is shown schematically in Fig. 3.

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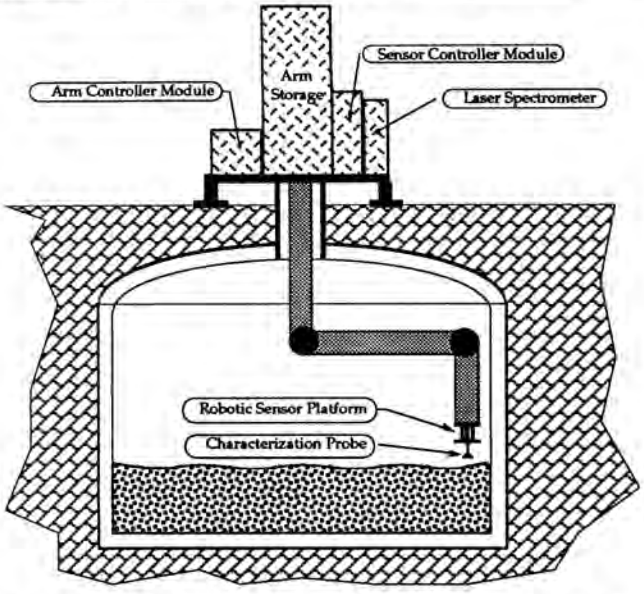

Fig. 1. Conceptual drawing of storage tank with long arm, platform, and sensor system.

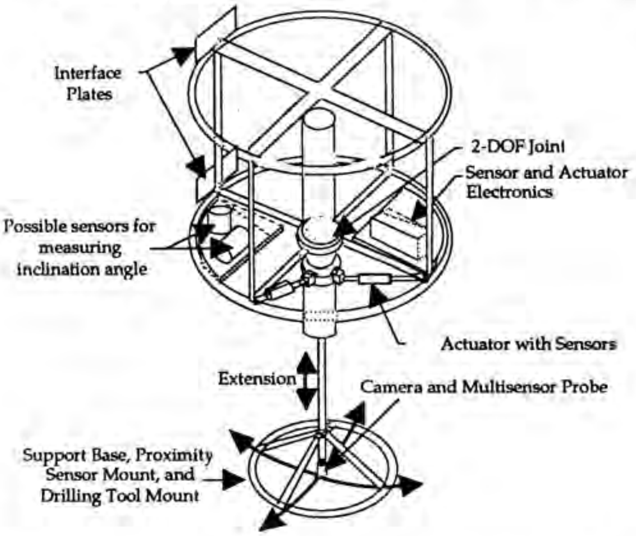

Fig. 2. Conceptual drawing of a robotic sensor platform.

The two sensor techniques proposed are complementary because fluorescence is applicable to low concentrations of select fluorophores whereas Raman spectroscopy is applicable to higher concentrations of a wide range of organic and inorganic materials. Robotic deployment of the sensor is critical to accurate characterization measurements, and it is the only safe way to use the sensor in hazardous environments.

Brief Description of Raman and Fluorescence Spectroscopy

Substances that emit radiant energy in the visible region when irradiated by short-wavelength energy (e.g., gamma rays, X rays, ultraviolet rays) or when receiving energy from fast-moving particles (e.g., alpha and beta) are said to fluoresce. When a molecule absorbs light, it moves to a higher energy state. Moving to a lower energy state by emission of radiation is fluorescence. Fluorescence is applicable to detecting low concentrations of select fluorophores (e.g., fuels, greases, oils, and aromatic solvents).

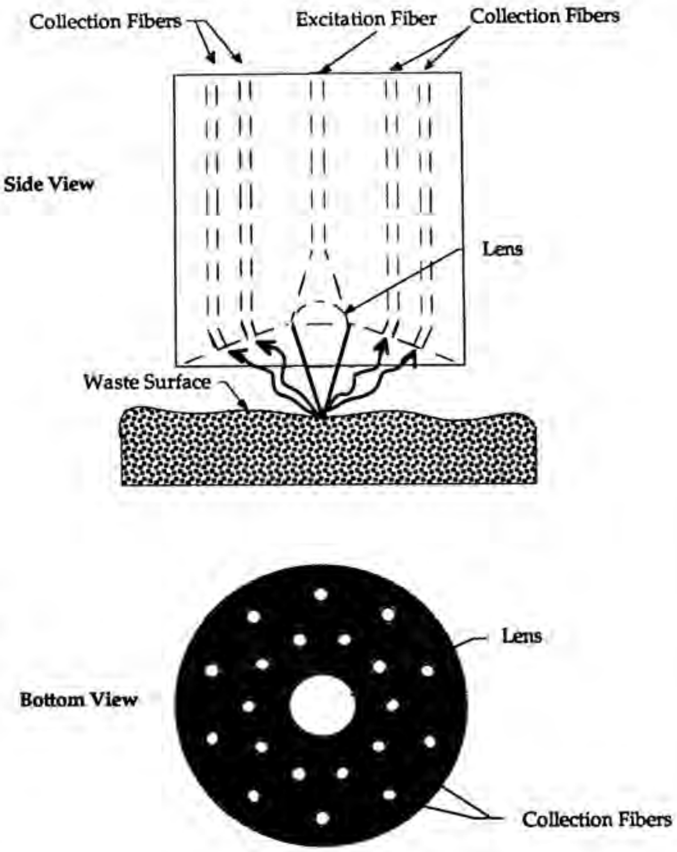

Fig. 3. Conceptual drawing of sensor probe.

Raman spectroscopy uses scattered laser light to produce a spectrum that can be related to the individual spectra of particular sample constituents. Raman spectra can be produced rapidly and from small (mg size) sample quantities. Basically, the Raman spectrum is produced when an incident photon from a monochromatic source loses or gains energy from an inelastic collision with a molecule. Energy can only be gained or lost in increments of the molecular vibrational energy ($h\nu_1$), thus the frequency of the laser light scattered from an inelastic molecular collision is displaced a fixed amount ($\pm h\nu_1$) from the frequency of the laser light scattered from elastic collisions in which no energy is exchanged, i.e., light scattered at the incident frequency. This record of the displacements of the scattered light from the incident frequency is the Raman spectrum. The Raman effect differs from fluorescence in that the incident radiation is not absorbed by the molecule. In addition, samples for Raman spectroscopy can be viewed through glass or dissolved in water, and solids can be measured directly without requiring formation into disks or wafers; definite advantages for in-situ characterization. Raman spectroscopy is applicable to a wide range of organic and inorganic materials including chelating agents, nitrate and cyanide salts, etc. Figure 4 shows Raman spectra of typical inorganic salts found in storage tank crusts. For greater detail refer to Refs. (2) and (3).

MECHANICAL DESIGN ISSUES

Any spectroscopic measurement requires accurate and stable positioning. Positioning must be held to within 1 to 2 mm and angles to within 0.5° during a sampling process in

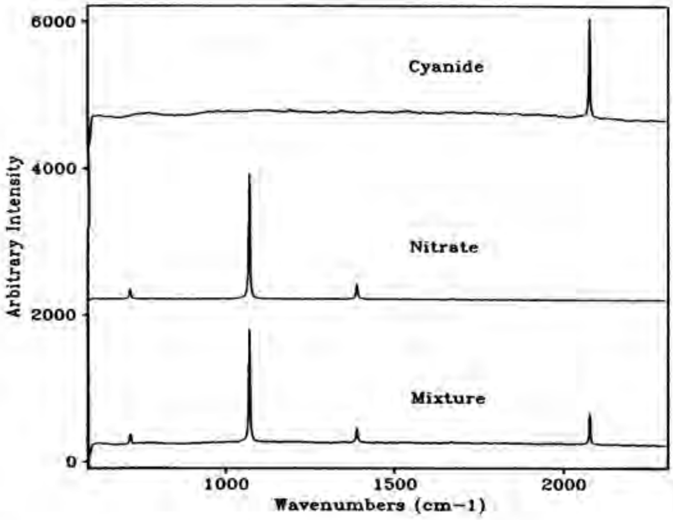

Fig. 4. Raman spectra of typical inorganic salts found in tank crusts.

order to have an accurate measurement. The long length of the support arm and the small sizes required to operate in and around tanks and drums presents many serious design problems.

Kinematics

A long flexible arm will be needed to position the sensor platform in the waste storage tank. Typical kinematic designs are considered in Jansen (4). These designs provide 3 DOFs; a base rotation, a pitch, and either an extension or another pitch. Six DOFs are required to position and to orient a manipulator end effector in space (three are needed for x,y,z positioning and three for orientation). The remaining DOFs must come from the sensor platform. It is possible to make the arm with redundant DOFs. A redundant arm is an arm having more than six DOFs. The addition of one or more additional DOFs allows one to optimize arm configuration to avoid obstacles, maximize capacity, avoid singularities, or improve some other performance criteria; however, the control of redundant arms is far more complicated than nonredundant arms. With the floor-to-ceiling obstacles present in typical tanks (e.g., instrument risers and supports), the extra DOF has limited utility.

Frequency and Deflection

The deflection and natural frequency for long reach arms typical of designs proposed for waste tank application can be a significant problem to an in situ characterization system. Values for typical designs were presented by Jansen (4). For a 9.14-m (30-foot) steel arm with a 0.508-m (20-inch) diameter circular cross section, end deflection without considering joint deflection is 0.010 m (0.4 inches), and natural frequency is limited to 6 Hz.

Consider a cantilevered beam with concentrated end mass as shown in Fig. 5.

The fundamental natural frequency of the beam/concentrated mass system shown in Fig. 5 assuming a circular cross section is governed by Eq. (1) (5).

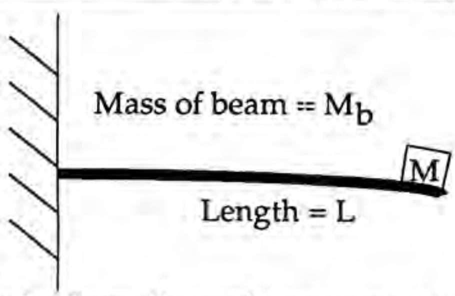

Fig. 5. Cantilevered beam with concentrated end mass.

$$f_1 < \frac{D_o}{4\pi L^2}\left[\frac{3\left(\frac{E}{\rho}\right)}{2\left(\frac{M}{M_b} + 0.24\right)}\right]^{1/2} , \qquad \text{(Eq. 1)}$$

where

f_1 = natural frequency,
E = modulus of elasticity,
I = moment of inertia,
L = beam length,
M = concentrated end mass,
M_b = beam mass ($M_b = \rho A$),
ρ = beam material density,
A = cross sectional area.

This is derived from an approximate relationship (presented in Blevins (5) having an error of about 1% from the exact solution. The best case having the highest natural frequency is when the end mass, M, is zero. The first natural frequency is governed by Eq. (2) from Jansen (4):

$$f_{1_{M/M_b=0}} < \frac{\lambda_1^2 D_o}{4\pi L^2}\left[\left(\frac{1}{2}\right)\left(\frac{E}{\rho}\right)\right]^{1/2} . \qquad \text{(Eq. 2)}$$

where λ_1 is the eigenvalue corresponding to the primary mode shape and has a value of 1.85 for a cantilevered beam with no end weight. This is an exact equation. The approximate factor for reducing the natural frequency of a beam without a mass to include the effects of an end mass is given by:

$$K_1 = \frac{1}{\lambda_1^2}\left[\frac{3}{(M/M_b + 0.24)}\right]^{1/2} . \qquad \text{Eq. 3)}$$

Table I shows the maximum values of the fundamental natural frequencies for 9.14-m (30-foot) circular cross section beams from Eq. (2).

Typical values for the reduction factor K_1 in Eq. (3) are 1, 0.87, and 0.59 for the ratio M/M_b of 0, 0.1, and 0.5 respectively. Keeping the ratio of the concentrated mass to the beam mass low is desirable. A typical mass for a circular cross section beam having a 0.127-m (5-inch) outside diameter and a 0.102-m (4-inch) inside diameter is 115.2 kg (254 lb_m) for aluminum and 323.4 kg (713 lb_m) for steel. Neither of these allow for massive end effectors if it is desired to keep the ratio of M/M_b at or below 0.1.

Consider now the case where the arm is braced or the end effector is resting on the waste surface. The fundamental natural frequency of the beam/concentrated mass system with bracing shown in Fig. 6 is given by Eq. (4) from Blevins (5).

TABLE I

Maximum Fundamental Natural Frequency for 9.14-m (30-foot) Circular Cross Section Beams

D_o		Aluminum	Steel
(m)	(in)	f_1 Max (Hz)	f_1 Max (Hz)
0.127	5	1.46	1.51
0.254	10	2.92	3.02
0.381	5	4.38	4.54
0.508	20	5.84	6.05

$$f_1 = \frac{4}{\pi}\left\{\frac{3EI}{L^3\left[M + (\alpha + \beta)M_b\right]}\right\}^{1/2} , \qquad \text{(Eq. 4)}$$

where the constants α and β are given by:

$$\alpha = \frac{a}{a+b}\left[\frac{(3a+b)^2}{28b^2} + \frac{9(a+b)^2}{20b^2} - \frac{(a+b)(3a+b)}{4b^2}\right] , \qquad \text{(Eq. 5a)}$$

and

$$\beta = \frac{b}{a+b}\left[\frac{(3b+a)^2}{28a^2} + \frac{9(a+b)^2}{20a^2} - \frac{(a+b)(3b+a)}{4a^2}\right] , \qquad \text{(Eq. 5b)}$$

respectively. Taking the limit of Eqs. (5a) and (5b) as "a" approaches 0 places the concentrated mass at the very end of the braced beam. That is, the sensor end effector is resting on the waste surface. The frequency with the end resting on the surface is 8 times greater than the cantilevered frequency. Clearly, bracing the beam or resting the end effector on the waste surface is an advantage.

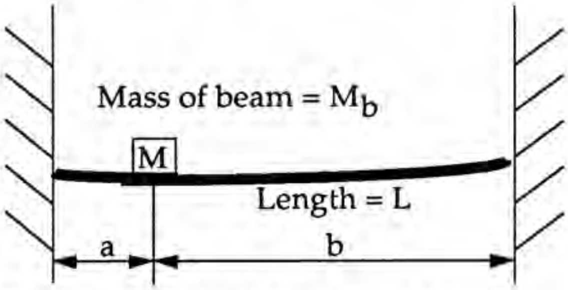

Fig. 6. Braced beam with concentrated mass.

Input from Tools -- Reciprocating or Rotating Masses

Figure 7 shows a simple model of an end effector/arm equivalent mass connected to ground through a spring and a damper. The tool input is represented as a harmonic disturbance force.

The equation describing the motion of this system is

$$M\ddot{x} + c\dot{x} + kx = F_o\sin(\omega t) \ . \qquad \text{(Eq. 6)}$$

The solution of this equation for x is given in any standard vibrations textbook. For input frequencies, ω, at or near the natural frequency, ω_n, the amplitude of the response is dependant upon the magnitude of the system damping because the only force opposing the impressed force is the damping force ($c\omega x$). No real systems have zero damping; however, for systems with very little damping, operation at or near the fundamental frequency will be a problem. Amplitude of vibration can be very large. A harmonic force can be generated by a reciprocating tool or a rotating tool as shown in Figs. 8a and 8b.

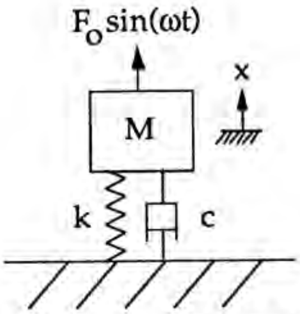

Fig. 7. Tool interaction model.

The resulting motion of these two models is governed by Eq. (6). The impressed force, F_0, is now an inertia force and has a magnitude of $me\omega^2$. The resulting amplitude of vibration is modified by the factor M/M + m.

Response Speed of Sensor Platform

The required response speed of the end effector is important to the design. Consider a model where the characterization probe must remain perpendicular to a rough surface. The surface can be approximately described by

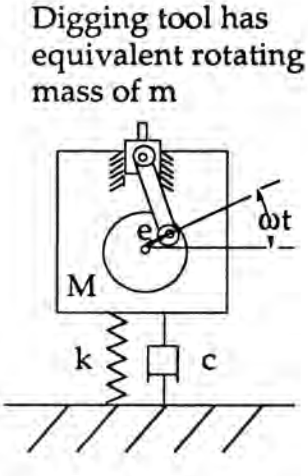

Fig. 8a. Reciprocating tool.

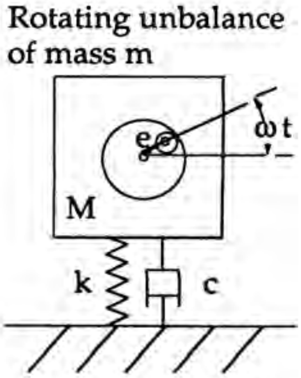

Fig. 8b. Rotating tool.

$$s = A \sin\left(\frac{2\pi x}{L}\right) , \qquad \text{(Eq. 7)}$$

where L represents the characteristic length of the surface roughness and A the characteristic amplitude. To maintain perpendicularity, the end effector is required to maintain an angle, ϕ, with respect to the vertical given by

$$\tan \phi = \frac{2\pi A}{L} \cos\left(\frac{2\pi x}{L}\right) . \qquad \text{(Eq. 8)}$$

If the scan is required to cover a complete feature (i.e., one-half period of the sine wave of Eq. (7)), and if the arm is moving in an oscillating pattern with period T given by

$$y = \frac{L}{4} \sin\left(\frac{2\pi t}{T}\right) , \qquad \text{(Eq. 9)}$$

then the required angular velocity of the end effector is

$$\dot{\phi} = \frac{4}{T} \tan^{-1}\left(\frac{2\pi A}{L}\right) . \qquad \text{(Eq. 10)}$$

For example, to scan one feature of a surface with roughness amplitude of $L/2\pi$ with scan periods of 1 second and 0.1 second, the end effector would be required to rotate at approximately π and 10π rad/s (30 and 300 RPM), respectively. A more general case has been derived but lack of space precludes its inclusion here.

Additional, Limited-Range-of-Motion DOF

It is possible to add an additional, limited-range-of-motion DOF between the end effector and the arm to provide some extra flexibility. This DOF would not be a fully active DOF but instead would rotate in finite increments and would generally remain locked for extended periods of operation. A typical limited-range-of-motion DOF would move in 0.262-radian (15°) increments and would allow the end effector to be aimed at surfaces which are horizontal, vertical, or above the end effector without having to significantly reposition the arm.

CONCLUSIONS

This paper presented some simple models that provide insight into the design of a deployment system for an in situ waste characterization probe. Deflection and low natural frequency are problems for the long flexible arms required for deploying sensors in and around waste tanks and drums. Potential solutions include careful design of the end effector and tools to reduce the end effector mass and to reduce the amount of force input to the end effector/arm through the tool. The required response speed of the end effector was quantized by a simple analysis that can be extended to more general cases. Finally, the combination of robotics and laser spectroscopy provides a unique in situ characterization capability for faster, safer, and more complete characterization of heterogeneous waste.

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