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CAPACITIVE TOOL STANDOFF SENSOR FOR DISMANTLEMENT TASKS

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Dan J. Schmitt
Sandia National Laboratories
P.O Box 5800, MS-1003
Albuquerque, NM 87185
(505)844-5542

Tom M. Weber
Sandia National Laboratories
P.O Box 5800, MS-1003
Albuquerque, NM 87185
(505)844-5476

Joanne C. Liu
University of Illinois - Urbana
Mechanical Engineering
Urbana, IL 61801
(217)359-7737

ABSTRACT

A capacitive sensing technology has been applied to develop a Standoff Sensor System for control of robotically deployed tools utilized in Decontamination and Dismantlement (D&D) activities. The system combines four individual sensor elements to provide non-contact, multiple degree-of-freedom control of tools at distances up to five inches from a surface. The Standoff Sensor has been successfully integrated to a metal cutting router and a pyrometer, and utilized for real-time control of each of these tools. Experiments demonstrate that the system can locate stationary surfaces with a repeatability of 0.034 millimeters.

I. INTRODUCTION

Decontamination and Dismantlement (D&D) tasks require a wide variety of tools for successful completion. These can include cutting tools such as plasma torches or metal cutting routers, or surface survey instruments such as a radiation or thermal monitor. For D&D processes where these tools are to be deployed robotically, a difficulty arises because the work environment can often be highly unstructured in that the relationship between the robot and the workpiece is not well known in advance. The difficulty is that most of these tools must be the proper distance and orientation with respect to a surface for proper operation. Therefore, a method must be provided to establish this relationship before the tools can be properly applied.

Sandia National Laboratories[a] has developed a capacitive Standoff Sensor System to provide such tool control. The development of this technology has been in collaboration with Oak Ridge National Laboratories for robotic systems which will be utilized for several Department of Energy (DOE) sponsored D&D tasks. The Standoff Sensor System consists of a 100 millimeter diameter capacitive sensor that is encapsulated inside a rugged plastic housing producing a light-weight assembly designed to be attached to a variety of robotically deployed tools. The sensor consists of four individual elements whose output can be combined in a variety of ways to control the critical degrees-of-freedom of the subject tool. Typically, the three degrees-of-freedom controlled are the distance of the tool from the surface, and the two orientations required to keep the tool normal to the surface.

This paper will describe the Standoff Sensor System and provide performance characteristics of the sensors and electronics. The Standoff Sensor System has been successfully integrated in a stand-alone mode to a Fanuc robot. The sensor data has been utilized in a real-time control system to dynamically track moving surfaces. The Standoff Sensor has also been integrated to a router for metal cutting and a pyrometer for non-contact thermal scanning of surfaces. The performance of these systems will be described.

II. SYSTEM COMPONENTS

A. Capacitive Standoff Sensor

Sandia National Laboratories has developed a unique, non-contact capacitive sensing technology (patent pending[1]) that can be applied to robotic systems for control of position and orientation during manufacturing processes.[2] This technology has previously been applied to robotic seam tracking for rocket thrust chamber manufacturing[3] and collision avoidance in unstructured environments.[4,5,6] Recently this sensing technology has been adapted, in a different geometry, to the problem of tool standoff and orientation control for the D&D program.

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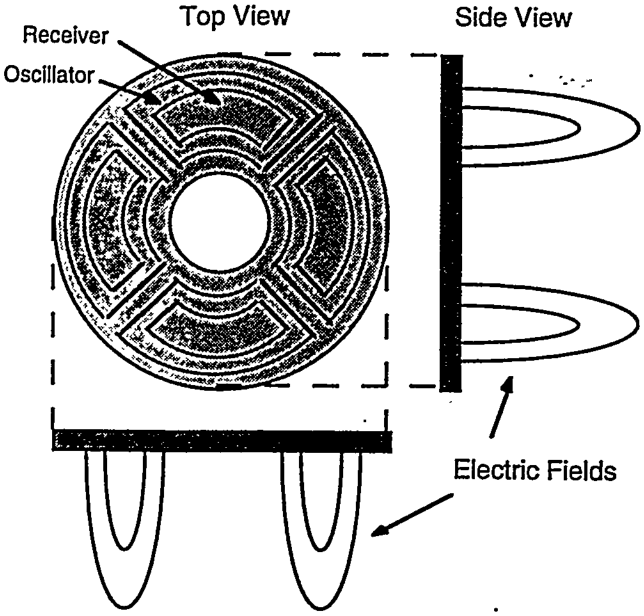

Figure 1: Diagram of the Standoff Sensor

The Standoff Sensor is fabricated on a printed circuit board with four sets of electrodes on the sensor as shown in Figure 1. Each set of electrodes consists of an oscillator and a receiver. The oscillator electrode is driven by a low voltage sinusoidal signal in the 100 kHz range. This signal is coupled through the space in front of the sensor to the receiver electrode to produce an electric field which extends outward from the sensor face. The receiver electrode is connected to a charge amplifier stage for sensing capacitor charge. The output of the sensor is a signal of the same frequency as the oscillator, but reduced in magnitude according to the capacitance between the electrodes. Any objects or obstacles near the sensor will change the capacitance between the electrodes and result in a corresponding change in the amplitude of the sensor output signal. These amplitude changes are detected and converted by the signal conditioning electronics described in section II.B. Figure 2 shows the lines of equipotential for the electric field produced by one electrode pair. The electric field has a hemispherical shape which extends approximately five inches from the face of the sensor.

The sensor system has four channels of output, one for each electrode pair. Each channel is a signal proportional to the distance from one electrode pair to the surface of a workpiece. The four electrode pairs on the sensor face give it functionality for both standoff and orientation control.

Because the sensors are fabricated on ordinary printed circuit boards, they are economical to produce and can be made larger or smaller for different applications. This unique capacitive sensing technology is not affected by stray capacitances to ground (such as between the sensor and workpiece) and is insensitive to the electric potential of the workpiece. As a result, both conductive and nonconductive workpieces can be detected. Also, because the electric fields produced by the sensor can penetrate dielectric materials, the sensor can be protected from the environment by a plastic or epoxy covering. For the D&D applications, the Standoff Sensor is encapsulated inside a dense plastic (Delrin®) housing with a 6.4 millimeter (mm) wall thickness. Figure 3 shows the encapsulated Standoff Sensor (small disk) interfaced to a pyrometer for non-contact thermal scanning of surfaces.

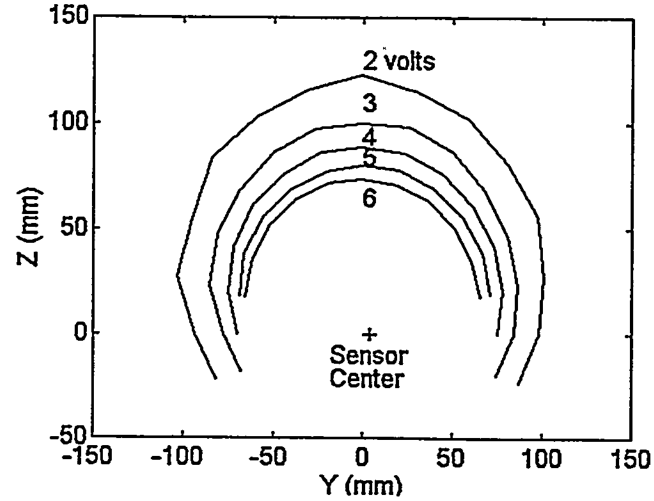

Figure 2: Equipotential lines of the sensor electric field

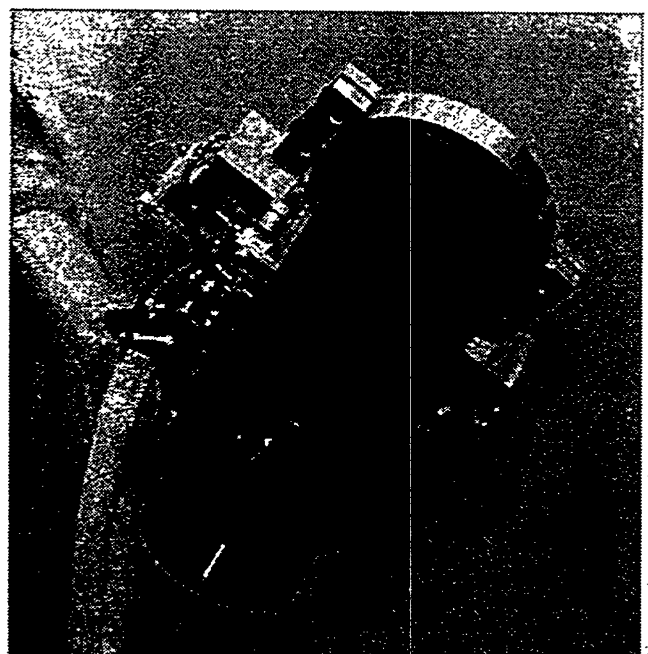

Figure 3: Standoff Sensor interfaced to a pyrometer for non-contact surface scanning

B. Signal Conditioning Electronics

Signal conditioning electronics convert the sensor signals into analog voltages to provide useful information about workpiece proximity. The analog signal processing consists of a mixer stage, a synchronous demodulator stage, and an output gain/filter stage. These electronics measure the small amplitude changes in the 100 kHz sensor signal caused by changes in capacitance between the sensor electrodes. The synchronous demodulator stage rejects noise and signals of other frequencies.

Sensor signals can be processed at different gain settings to produce various distance detection ranges. These detection ranges are made accessible through discrete gain jumper settings within the signal conditioning electronics. In addition, the output of an individual sensor element can be simultaneously processed through multiple signal processing channels at different gain settings to produce multiple detection ranges at the same time. For this D&D application, each sensor signal is simultaneously processed through two signal processing channels. Thus, the four sensor elements on the Standoff Sensor result in eight channels of output from the signal conditioning electronics. The output range of all signals is ±10 volts.

The signal conditioning electronics as described can be located up to 15 meters from the sensor. For remote sensing applications such as the D&D application discussed here, cable runs longer than 15 meters are required. To solve this problem, an embedded computer was integrated with the signal conditioning electronics to convert the sensor signals into a serial data stream. The output voltage signals from the analog electronics board are digitized by the computer and converted into a serial data stream suitable for transmission via an RS-485 or other network. The electronics package is compact enough that it can be placed at the end effector of the robot as shown in Figure 3 (long cylinder), or in an enclosure at the base of the robot. The serial data stream can then be interpreted by the robot controller and used to control the position and orientation of the robot arm.

C. Robotic Equipment

The experiments described in this paper were performed using a Fanuc S-700 robot with an RJ controller. The application software was written in Karel, the Pascal-like proprietary language for the Fanuc product. The Delta-Tool feature of the language was used for the real-time control experiments discussed in Section IV.B. Delta-Tool allows real-time updates based on sensor data to be applied to an executing path. Delta-Tool was used at an update rate of 56 milliseconds (ms). Sensor data was accessed as analog input through the controller's analog-to-digital (A/D) converter modules. The system uses a 12 bit A/D converter to map the ± 10 volt output of the sensor over 4096 counts. Fanuc's OLPC off-line programming software was used for application development.

III. SENSOR CALIBRATION

The analog output of the Standoff Sensor must be calibrated with respect to the work surface. Calibration is required so that the sensor output can be converted to absolute distances and orientations with respect to the surface. Calibration parameters are required for each degree-of-freedom to be controlled.

Calibration first involves understanding the performance of the sensor. Figure 4 shows data obtained by positioning the sensor parallel to a flat metal surface and collecting sensor output as it is scanned away from the surface. This figure shows the output of one sensor element at four different gain settings. The output plotted is the relative change from a baseline reading established when the sensor is undisturbed by any objects. Sensor output at gains A1 and A2 are produced simultaneously from the output of this one sensor element. Similarly, sensor output at gains B1 and B2 are produced simultaneously by using separate gain jumper settings within the electronics. The sensor output is saturated near the surface and then decays as the sensor moves away from the surface. The point at which saturation occurs is established by the gain setting. This provides the sensor's capability to provide different distance sensitivity ranges. Normally, a change in sensor reading of greater than 400 counts is required to reliably detect a surface. Using this criteria, Figure 4 shows a detection range of 200 mm for the Standoff Sensor when using the higher gain setting B2.

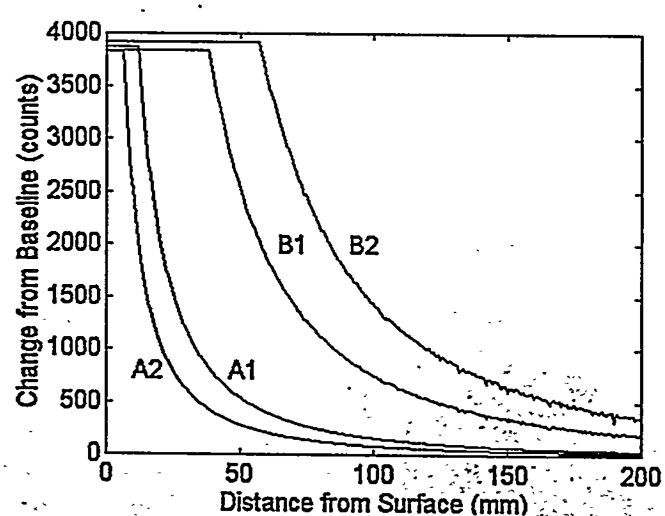

Figure 4: Standoff Sensor output at four gain settings

For controlling the critical degrees-of-freedom of a dismantlement tool, the individual sensor elements can be combined in a variety of ways. To control the distance from a surface, the four individual channels can be summed. The robot control system can use this combined signal to establish a distance from a surface by moving the robot to a point where this summed value equals that established during calibration. For orientation control, the sensor elements 180 degrees apart can be differenced. The tool can be established as normal to a surface when the output from these sensor elements is balanced. In practice, however, this difference is not exactly zero due to slight manufacturing differences in each sensor element and its associated electronics, so an offset is applied. An angle with respect to the surface can also be established by moving to a non-zero difference as established during calibration. The sensor elements which are 180 degrees apart can also be used to center a tool over appropriately sized projections. In this case, these sensor elements are differenced and used to control translational moves to produce this centering.

Calibration involves establishing the appropriately combined sensor reading corresponding to the desired distance or orientation with respect to the surface. Two values are normally required for control purposes. These are the combined output value at the calibration point and the rate of change (slope) of this value about the calibration point. The slope is required to convert sensor signals which indicate an error from the goal position into absolute robot movements to achieve the goal. A linearized slope value is usually sufficient since the sensor will normally operate near this goal point.

Calibration parameters can be extracted from a continuous output scan as shown in Figure 4. However, calibration can more easily be performed by having the robot move the sensor directly to a reference goal point to establish the combined sensor output. Slight perturbations to either side of the goal point will produce the data required to calculate the slope.

IV. STANDOFF SENSOR TESTS

The Standoff Sensor System interfaced to a robot has been tested to determine both the system's static repeatability and its dynamic tracking accuracy.

A. Static Repeatability

Static repeatability tests indicate the Standoff Sensor System's ability to repeatably locate a stationary surface. Tests were conducted to evaluate distance repeatability using the sum of all four sensor elements. Tests were conducted by initially calibrating the sensors at the desired distance with respect to a flat metal plate. The robot then repeatedly located the surface based on this calibration value and the actual distance from the surface was compared with the calibration distance to determine the repeatability.

The distance repeatability experiments were conducted at a distance of 25 mm. All four sensor elements were set on gain A1. The calibration factors for these tests were 4015 counts (the sum of the four sensor readings) and 186 counts/mm (the linear slope of the sum at ±5 mm about the goal). Twenty tests showed an average distance repeatability of 0.00427 mm with a standard deviation (σ) of 0.00992 mm. This results in a $+3\sigma$ repeatability of .0340 mm. The robot test program used the sensor output to attempt to servo to within ±1 A/D count of the goal. The slope of 186 counts/mm indicates a resolution of 0.0054 mm /count. When taking into account that some noise will exist in the sensor system, these test results are in agreement with the resolution value. The orientation slopes at this calibration distance were 81 counts/degree (tool yaw) and 87 counts/degree (tool pitch). These value indicate an angular resolution of 0.0123 degrees/count and 0.0115 degrees/count respectively.

Figure 4 shows that the calibration distance of 25 mm on gain curve A1 chosen for these repeatability tests is on the steeper slope of the curve to the left of the knee. The distance repeatability is dependent on the portion of the curve at which calibration is performed as the slope changes significantly to the right of the knee. Therefore, maximum sensitivity is achieved by operating to the left of this knee.

B. Dynamic Tracking Accuracy

Experiments were conducted to determine how accurately the Standoff Sensor System could track the surface of a flat metal plate. Such tracking would be required for a radiation survey or thermal survey of a surface. This type of surface tracking requires real-time control in three degrees-of-freedom. These degrees-of-freedom are the distance (tool z) from the surface, and the two orientations (tool yaw and pitch) required to keep the tool normal to the surface.

Before the tracking experiments could be performed, a real-time control system had to be developed. The development of such a system for a Fanuc S-700 robot is described in reference 7. The control system uses the Delta-Tool function of the Karel language. A PID filter at the application program level is used to provide real time updates based on sensor data to provide a fast, stable tracking response.[8] Figure 5 shows the system block diagram.

The experiments involved using the Standoff Sensor to initially locate a position normal to the plate surface at a standoff distance of 25 mm. Once this initial position was located, a nominal path was defined for the robot to follow. This nominal path was intentionally defined with errors in order to demonstrate the capabilities of the sensor system. For these tests, a nominal path was defined consisting of two points: the initial sensor located surface point described above, and a calculated point 600 mm away in tool x, with a tool z error of 25 mm and a tool yaw error of 10 degrees. This nominal path produces a disturbance in tool z which linearly ramps from 0 to 25 mm, and a disturbance in tool yaw which linearly ramps from 0 to 10 degrees. The slope of this ramp is proportional to the tracking velocity. The robot was commanded to follow this nominal path and sensor updates were applied every 56 ms to keep the tool normal to the surface at the required standoff distance of 25 mm. Figure 6 shows the resulting tracking error in tool z at tracking velocities of 25 mm/sec and 50 mm/sec. Figure 7 shows the orientation tracking error in tool yaw for the same velocities.

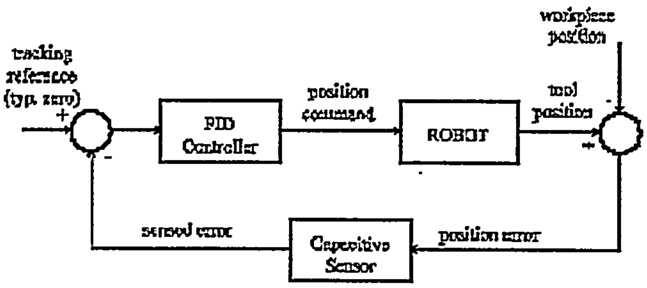

Figure 5: System block diagram

These experiments were repeated ten times at each of the tracking velocities. At a velocity of 25 mm/sec, the average maximum tool z error was 0.446 mm with a standard deviation (σ) of 0.0241 mm. This yields a $+3\sigma$ tool z error of 0.518 mm. The average maximum tool yaw error was 0.169 degrees with a standard deviation of 0.0055 degrees. This yields a $+3\sigma$ tool yaw error of 0.185 degrees. At a tracking velocity of 50 mm/sec, the average maximum tool z error was 0.723 mm with a standard deviation of 0.0188 mm. This yields a $+3\sigma$ tool z error of 0.779 mm. The average maximum tool yaw error at this velocity was 0.314 degrees with a standard deviation of 0.0076 degrees. This yields a $+3\sigma$ tool yaw error of 0.337 degrees.

V. INSTRUMENTED TOOLS

The Standoff Sensor System has been successfully interfaced to a metal cutting router and a pyrometer, two tools which are typical for D&D tasks. For the metal cutting router, the sensor system is used to keep the tool normal and the proper distance from the work surface. This interface takes advantage of the system's ability to simultaneously provide sensing at two ranges. The longer sensing range is used to position the router with respect to the surface before tool contact is made. The closer sensing range is then used to control the tool as it engages and plunges into the surface to the proper depth of cut. During cutting, all three degrees of freedom (tool z, yaw and pitch) are controlled. Figure 8 shows a photograph of the integrated tool.

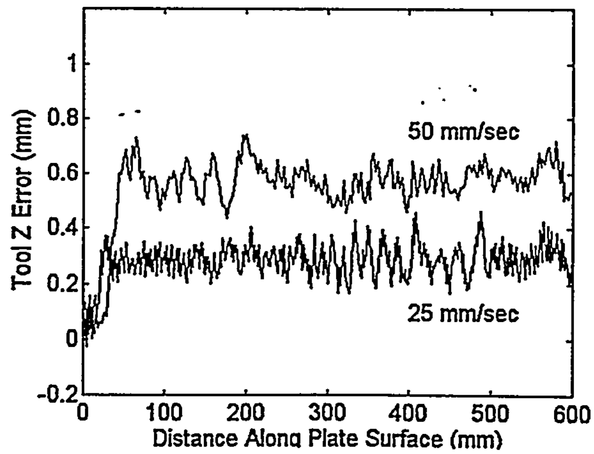

Figure 6: Tool Z tracking error at two velocities

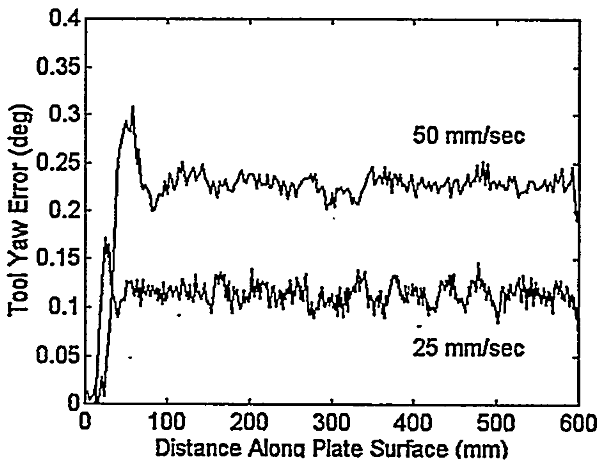

Figure 7: Tool yaw tracking error at two velocities

This interface to the router provides several challenges for the functionality of the Standoff Sensor. First, the sensor must not be effected by the electromagnetic field produced by the router's electric motor. Second, the system must not be effected by the router's bit rotating in the field. And third, the system must not be effected by the metal chips produced during cutting. We have performed tests doing plunge cuts into 3.2 mm thick aluminum plates and cutting 25 mm square cut-outs to demonstrate the system's functionality. The Standoff Sensor System was able to reject any noise produced by the routing environment to provide stable control of the process.

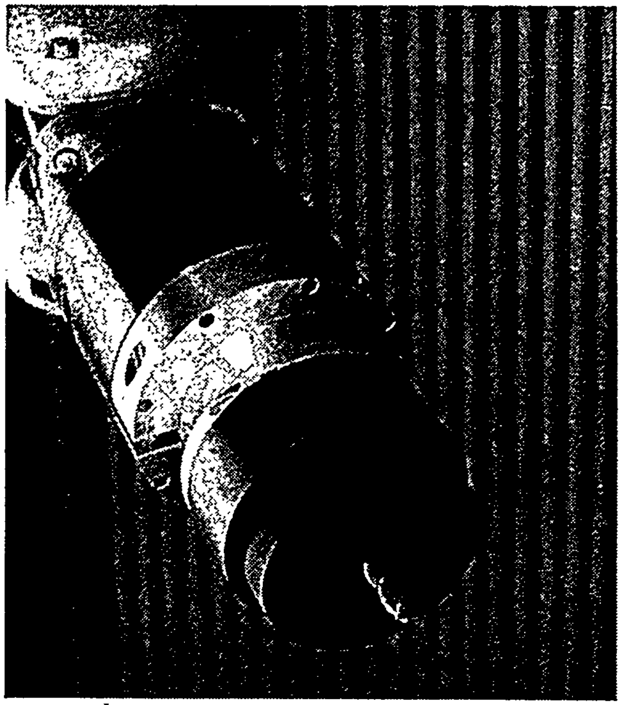

Figure 8: Standoff Sensor integrated to a metal cutting router

The interface to the pyrometer successfully demonstrated the sensor's ability to perform non-contact surface scanning. This process could also be used for a radiation monitor. The Standoff Sensor's function is to control the pyrometer's standoff distance and normality to the surface. Figure 3 shows the entire end effector tool. The pyrometer can be seen protruding through the center of the Standoff Sensor housing. The long cylinder behind the Standoff Sensor contains both the signal conditioning electronics and the electronics for the pyrometer. This tool can be used for real-time thermal scanning of a surface. Performance results discussed in Section IV.B would be typical of this type of tool.

VI. SUMMARY AND CONCLUSIONS

A Standoff Sensor System for control of tools used during D&D processes has been developed. The system consists of a 100 mm diameter sensor which is encapsulated inside a dense plastic housing. The system produces four individual electric fields which can be combined in a variety of ways to control the critical degrees-of-freedom of a tool. Tests have shown that the system can repeatably locate a stationary surface to within 0.034 mm. Dynamic testing indicates that a surface can be tracked at 25 mm/sec within a distance accuracy of 0.518 mm and an orientation accuracy of 0.185 degrees.

The dynamic tracking accuracy results discussed in Section IV.B. are indicative of the performance of the control system as a whole. The results are influenced by the initial accuracy of the nominal path, the update rate of the robot controller and the bandwidth of the sensor system. For the dynamic tests discussed in this paper, the nominal path was intentionally chosen to contain inaccuracies in order to demonstrate the error correcting capabilities of the sensor system. A more accurate nominal path could easily be generated from the initial surface point located by the sensor and would result in improved tracking accuracy. An update rate of 56 ms was chosen as this was the fastest possible rate which allowed sufficient user computation time to access sensor data and compute the Delta Tool updates. Faster update rates would result in improved tracking accuracy. As for the Standoff Sensor System itself, it is capable of providing updates to a robot controller at rates of 1.0 ms or faster and is therefore not the limiting factor in the performance of the control system.

VII. ACKNOWLEDGMENT

We would like to thank Sandia's Robert Waldschmidt and Jon Bryan for their efforts in fabricating the Standoff Sensors and the signal conditioning electronics, as well as for robotic workcell setup. We would also like to thank Dennis Haley and Mark Noakes of Oak Ridge National Laboratories for their D&D needs assessment which revealed the need for this tool control sensor technology.

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