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A Collision Avoidance System for Workpiece Protection

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Abstract

This paper describes an application of Sandia's non-contact capacitive sensing technology for collision avoidance during the manufacturing of rocket engine thrust chambers. The collision avoidance system consists of an octagon shaped collar with a capacitive proximity sensor mounted on each face. The sensors produce electric fields which extend several inches from the face of the collar and detect potential collisions between the robot and the workpiece. A signal conditioning system processes the sensor output and provides varying voltage signals to the robot controller for stopping the robot.

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1 Introduction

The avoidance of accidental contact between a robot and its workpiece is of significant importance in flexible automation systems because such collisions can result in damage to both the robot and workpiece. While devices currently exist to minimize such damage, many rely on initial contact triggering mechanisms. A more desirable approach utilizes non-contacting methods to detect potential collisions. Sandia National Laboratories[1] and the Rocketdyne Division of Rockwell International have entered into a cooperative research and development agreement (CRADA) to address these issues for the manufacturing of rocket engine components.

Rocketdyne is a world leader in the manufacturing of rocket engines. They currently manufacture engines for Delta and Atlas main rocket boosters and for the Space Shuttle Main Engine (SSME). Rocketdyne is continually improving the efficiency of its manufacturing operations using robotic equipment to contribute to these efforts. This paper focuses on the development of a non-contact collision avoidance system for use during robotic manufacturing of rocket engine thrust chambers. This system utilizes a unique, non-contact capacitive sensor to detect potential collisions between the robot and thrust chamber surface. Output from the sensor system is used within the robot motion control program to stop robot motion when such potential collisions are detected. This paper will review the automated manufacturing process, describe the components of the sensor-based collision avoidance system, and review the performance of the implemented system.

2 Thrust Chamber Manufacturing

The thrust chamber portion of the rocket engine consists of hundreds of individual tubes which are brazed together to form a solid heat exchanger assembly. Figure 1 shows a photograph of a typical thrust chamber during manufacturing. During engine operation, fuel is circulated through the tubes for the dual purpose of cooling the thrust chamber jacket and pre-heating the fuel before combustion. The individual tubes have a continuously varying cross-section to form the bell-like structure and to provide optimal fluid dynamics for the circulating fuel.

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Rocketdyne fabricates thrust chamber assemblies by initially fixturing the individual tubes into the final bell-like shape. Nickel powder followed by a palladium-silver braze paste is then dispensed into the seams between the fixtured tubes. After all seams on the thrust chamber have been filled, the entire assembly is placed in a gas fired furnace where the braze paste melts to produce the final solid structure.

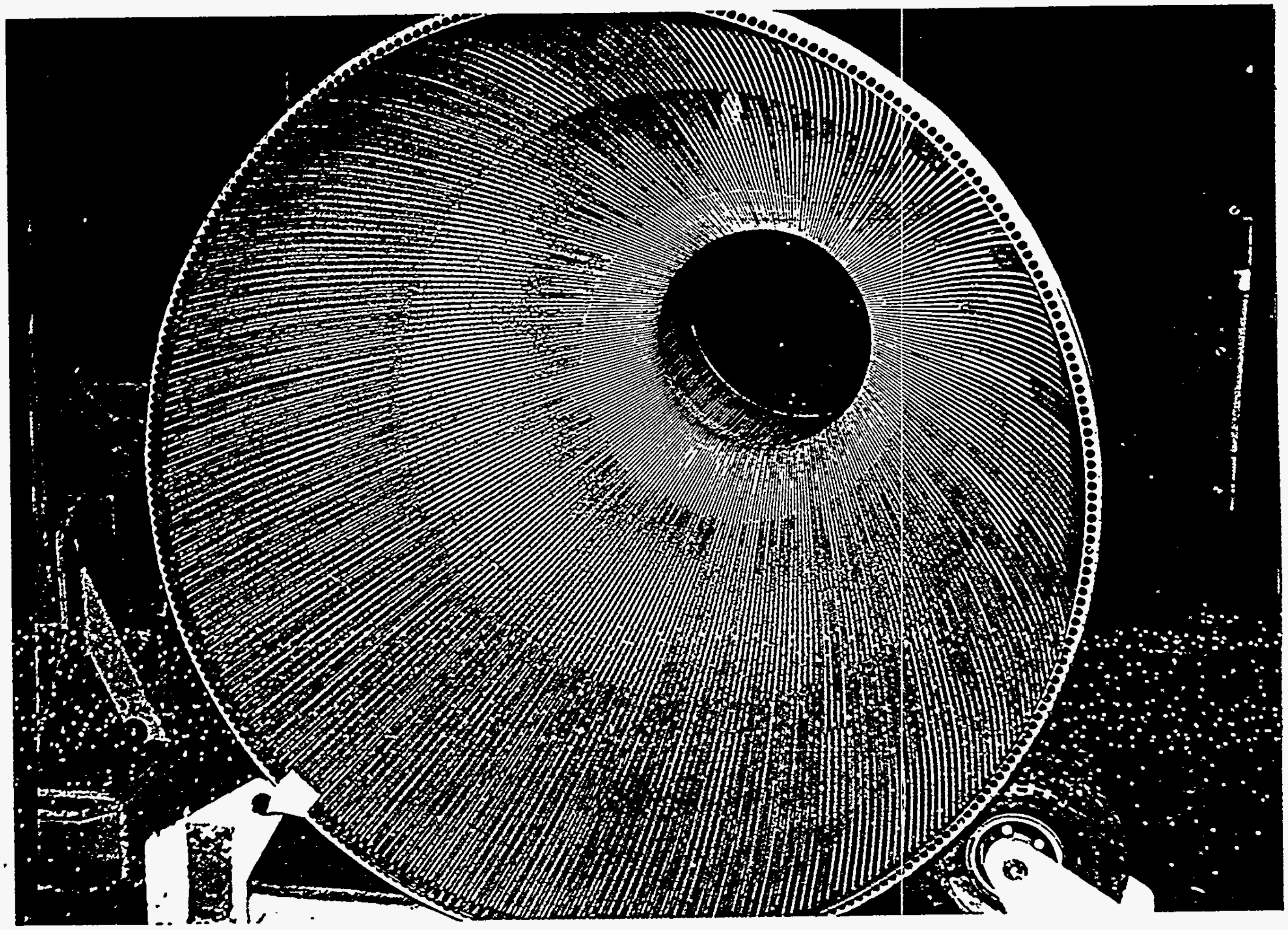

Figure 1: Thrust chamber component of a rocket engine during manufacturing

Rocketdyne and Sandia have collaborated to produce an automated system for dispensing the nickel powder and braze paste into the seams. The goal in automating this system was to reduce the amount of labor hours and excess precious materials required. The automated system consists of a robot on a linear track, precision dispensing equipment for the nickel powder and braze paste, and a non-contact capacitive seam locating system [1].

A major concern in automating this manufacturing process was protecting the thrust chamber from potential damage caused by accidental contact between the robot and the chamber surface. While the capacitive seam tracking system will guide the robot along the surface without contact, it was desired to have an independent safety system to prevent collisions in case of unforeseen problems. It was also desirable that this safety system should prevent collisions without any initial contact as the triggering mechanism. Any contact with a tube surface could cause surface imperfections that would require disassembly of the fixtured structure for replacement of individual tubes.

3 System Components

3.1 Capacitive Sensor

Sandia National Laboratories has previously developed a unique, non-contact capacitive sensing technology for proximity sensing and collision avoidance on robotic systems [2-6]. A collision avoidance system based on this sensor technology has been constructed to prevent contact between the robot and thrust chamber surface in the automated braze paste dispensing system. Sensor signals indicate the proximity of the end effector to the workpiece and are used by the robot motion control program to stop motion in case of a near contact. Figure 2 shows a diagram of the individual sensor elements in this system.

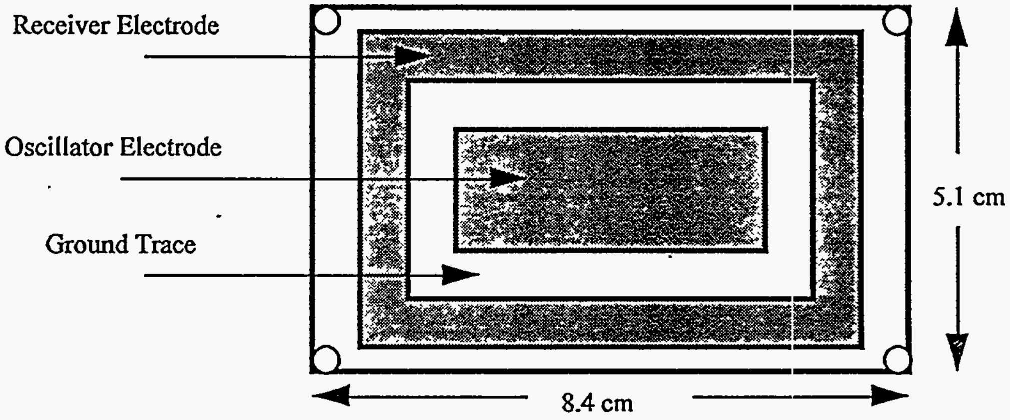

Figure 2: Collision avoidance sensor element

The collision avoidance sensor is fabricated from an inexpensive, multi-layer printed circuit board and measures 8.4 cm (3.3 in) by 5.1 cm (2.0 in). While this size was specifically chosen for this application to fit around the dispensing equipment, the sensors can be fabricated in many different shapes and sizes to fit a particular application. The sensor face consists of an oscillator electrode and a receiver electrode separated by a grounded trace. The arrangement of these electrodes creates an electric field that extends from the sensor surface in an approximately hemispherical shape. The equipotential lines of the electric field in air are shown in Figure 3.

The electric field generated by the sensor is perturbed by changes in sensor position relative to the thrust chamber surface. These perturbations in the electric field are detected as capacitance variations between the oscillator and receiver electrodes, and are converted to voltage changes by the signal conditioning system. Because the configuration measures displacement currents between the oscillator and receiver electrodes, stray capacitances to ground (such as between the sensor and workpiece) do not affect the measurement. No active shielding is required, and this type of capacitive sensor is insensitive to the electrical potential of the workpiece.

As shown in the functional schematic of the sensor in Figure 4, the oscillator electrode is driven with a signal in the 100 kHz range. The receiver electrode is connected to a charge amplifier stage for sensing capacitor charge. All further signal processing is accomplished in a remotely located electronics enclosure. The output of the charge amplifier stage, V_S, has the same frequency as the oscillator signal, with its amplitude proportional to the capacitance between the oscillator and receiver electrodes. As the sensor moves closer to the workpiece surface, this capacitance decreases due to a shielding effect. The output of the charge amplifier stage is connected to the signal processing electronics to convert the sensor signal into useful position information. When using multiple sensors in close proximity, the associated electric fields will overlap. By using a unique driving frequency for each sensor, crosstalk can be eliminated.

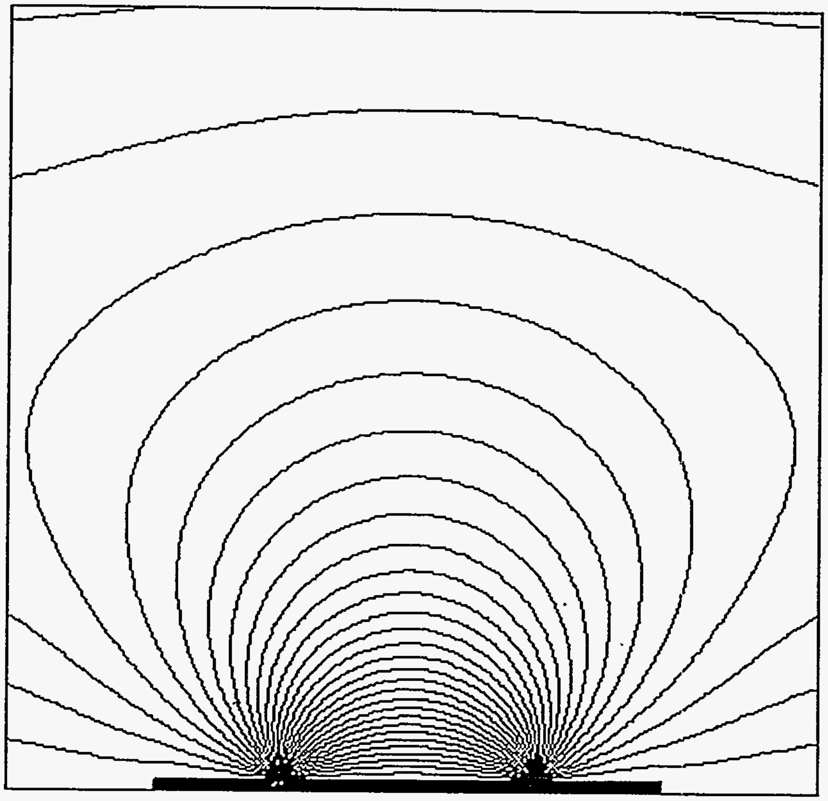

Figure 3: Equipotential lines of the sensor electric field in air

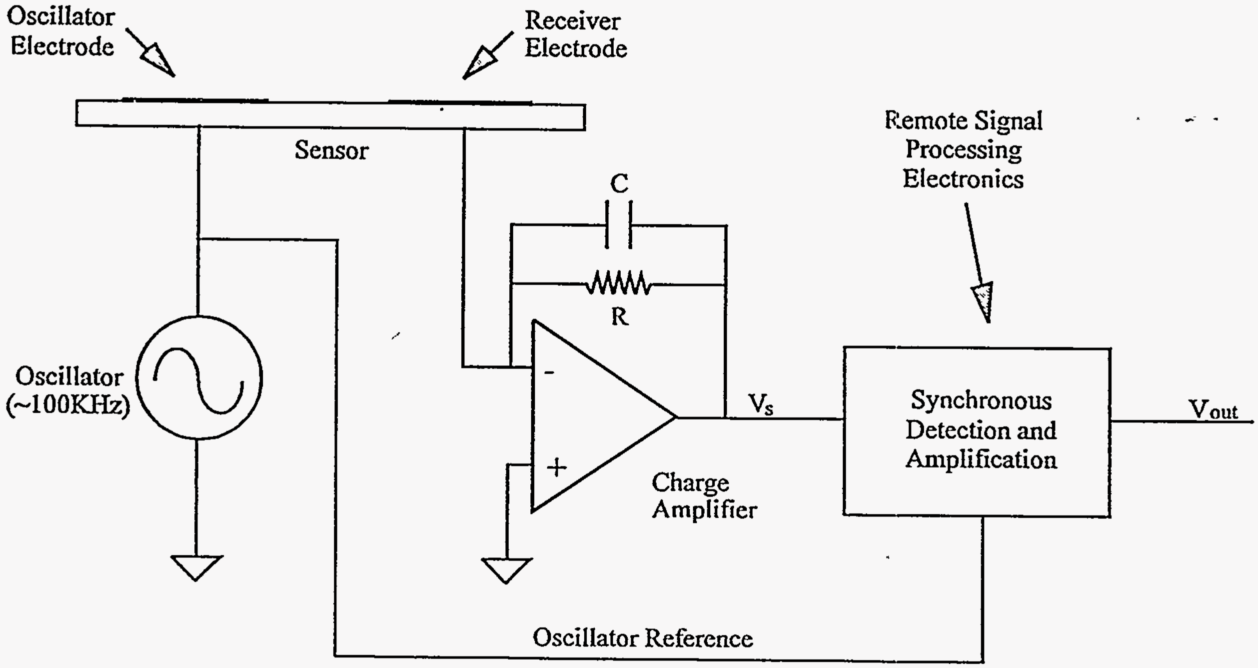

Figure 4: Collision avoidance sensor functional schematic

3.2 Collision Avoidance Collar

An octagon shaped collar (Figure 5) has been designed to provide 360 degree detection of approaching objects. The assembly is approximately 23 cm (9 in) wide with one collision avoidance sensor attached to each of the eight faces. This arrangement surrounds the dispensing equipment and provides sufficient overlap of the individual electric fields to provide 360 degree coverage of the robot's end effector. A cable which wraps around the inside of the collar attaches the sensors to the signal conditioning system located remotely from the robot arm. The collar assembly is designed to attach between the end effector tooling and the face plate of the robot. The back plate is removable to provide easy conversion to a variety of face plate bolt patterns.

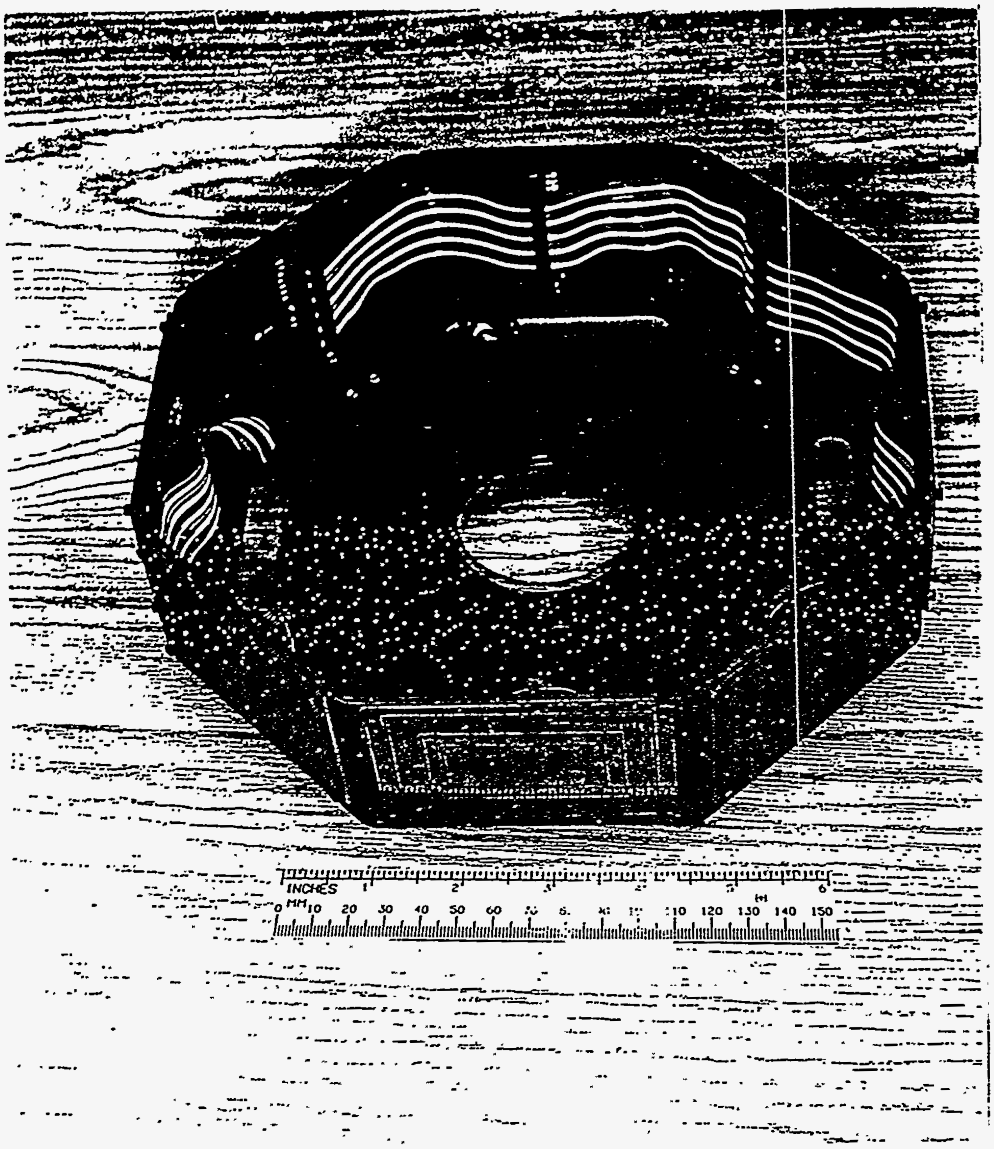

Figure 5: Collision avoidance collar assembly

3.3 Signal Conditioning System

The signal conditioning system is located remotely from the robot arm. This circuitry provides the driving signals for the collision avoidance sensors and processes the return signals to provide eight analog outputs to the robot controller. Figure 6 shows a photograph of the signal conditioning electronics which consists of two boards mounted in a chassis. The oscillator board generates the driving frequencies and reference signals for each of the individual sensors. To avoid coupling between sensors, eight distinct frequencies in the 100 kHz range are used to drive the eight sensors.

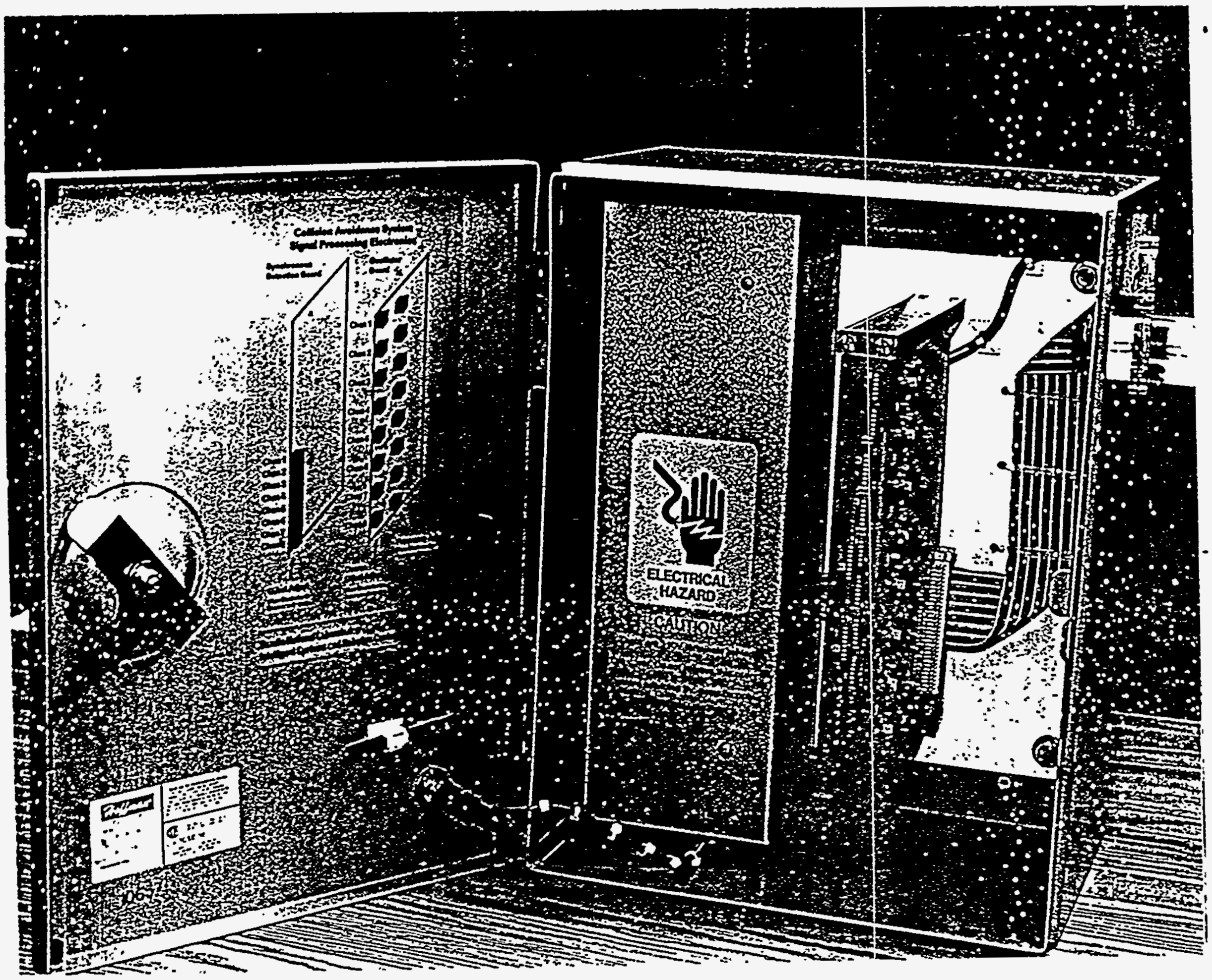

Figure 6: Signal conditioning system

The other circuit board incorporates eight channels of synchronous detection circuitry to measure the amplitude of the return signal from each sensor. Because each sensor is driven with a unique frequency, each channel of this circuitry detects the signal of only one sensor, thereby rejecting any noise or signals from other sensors. The detection circuitry generates an extremely low noise signal output, which is amplified to provide a high-level (±10V) signal to the robot controller. The output signal level corresponds to the relative distance from the sensor to the workpiece or other obstacles. The eight output channels are read directly into the robot controller through analog to digital (A/D) converters.

3.4 Sensor Calibration

The incoming collision avoidance sensor signals are calibrated with respect to the workpiece surface. Calibration is required so that the sensor signals, in A/D counts, can be converted to absolute distances with respect to the workpiece. A flat bundle of 9.5 mm (.375 in) outer diameter tubes, shown in Figure 7, simulates the rocket nozzle assembly and was used as the calibration fixture. Calibration data was obtained by positioning an individual sensor parallel to the bundle surface and recording the output as it was moved away from the bundle. The relative changes in sensor readings from a baseline value established when the sensor fields are undisturbed by objects are plotted in Figure 8. Sensors typically saturate near the tube bundle surface, and then their output decays asymptotically as the distance increases. While each of the sensors has similar performance characteristics, individual variations in the sensor fabrication and electronics design produce slightly different responses.

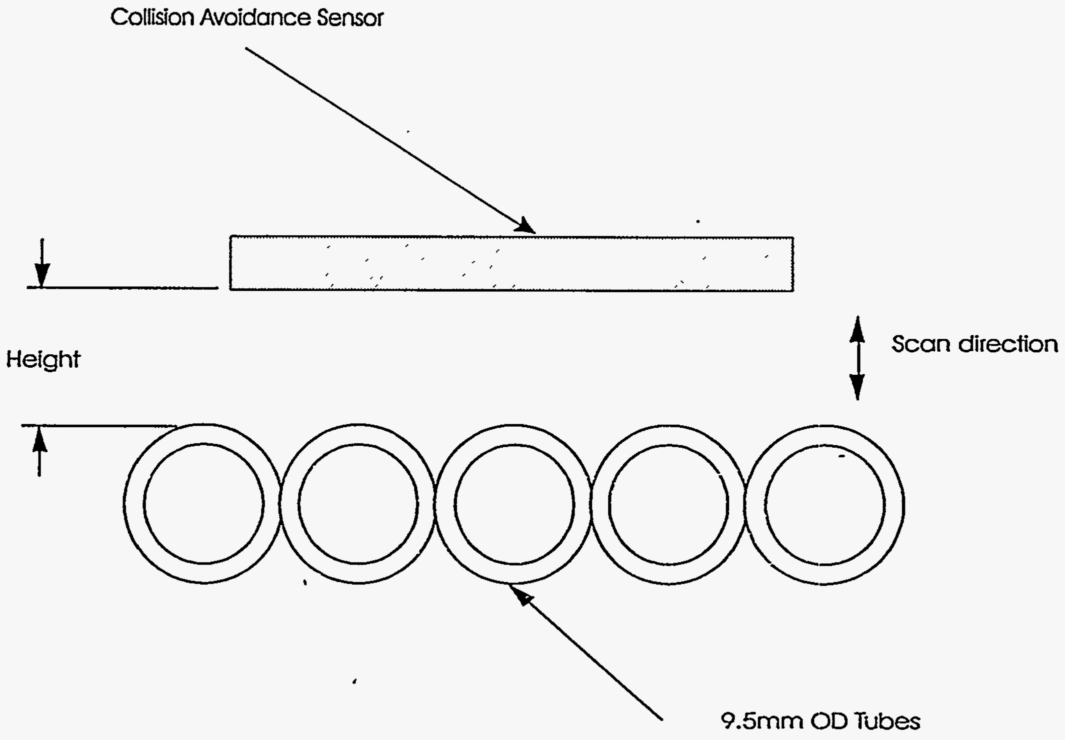

Figure 7: Scan direction for calibration

Rather than calibrate the sensors over their entire range, a simple thresholding technique was adopted. Condition handlers on the robot controller test for sensor values above the predetermined threshold (i.e. when the sensor moves too close to the thrust chamber surface.) For the automated braze paste dispensing application, the desired stopping threshold was 25 mm. The sensor calibration process was automated by having the robot move each sensor face of the collar assembly 25 mm above the calibration fixture surface and recording these threshold values. These values are stored in a file and loaded at the beginning of the automated braze paste dispensing process.

To avoid system failure due to noise or drift in the baseline sensor adjustment, the system used deadbands of ±300 A/D counts (1.5 volts) to define the useful range of the sensors. System sensitivity is low at large distances from the object and this deadband provides sufficient margin to avoid premature triggering. At distances close to the object the sensor signals reach saturation and the deadband provides a margin to avoid a failure to trigger. Varied gain settings of 1, 10 and 100 provide for different sensitive ranges of the sensors. Figure 9 compares the response of one sensor at these three gain settings. Applying the ±300 A/D count deadband, this sensor provides ranges of 7 mm to 22 mm at a gain of 1, 18 mm to 60 mm at a gain of 10, and 53 mm to 100 mm at a gain of 100.

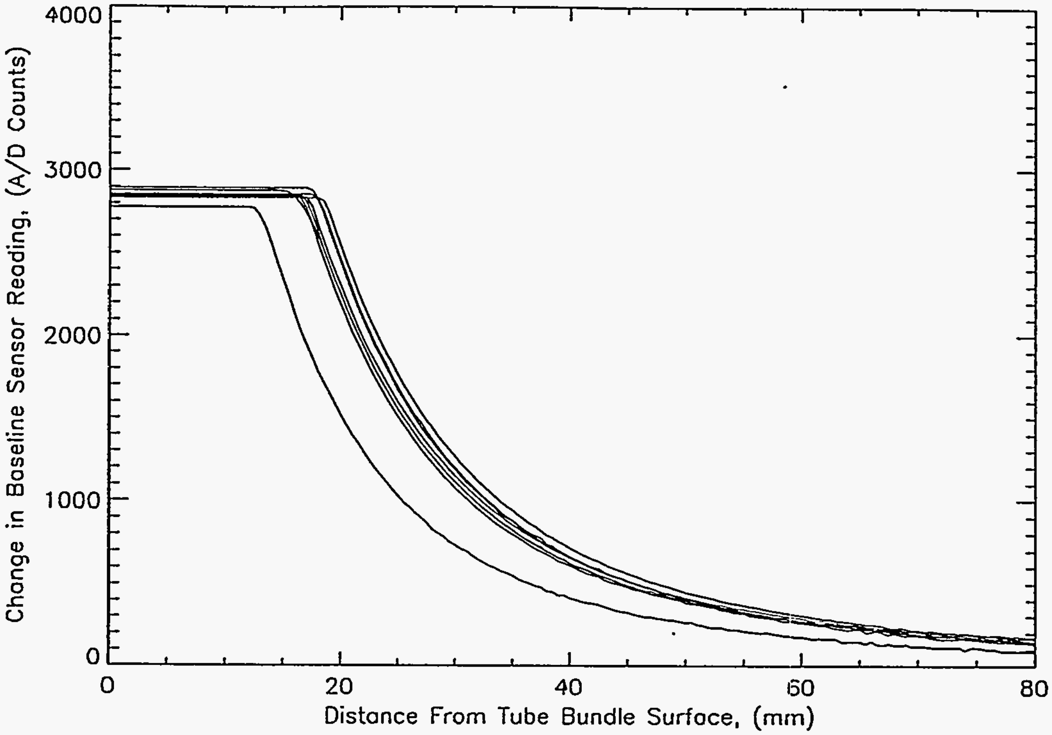

Figure 8: Calibration data for all eight sensors on one collision collar assembly

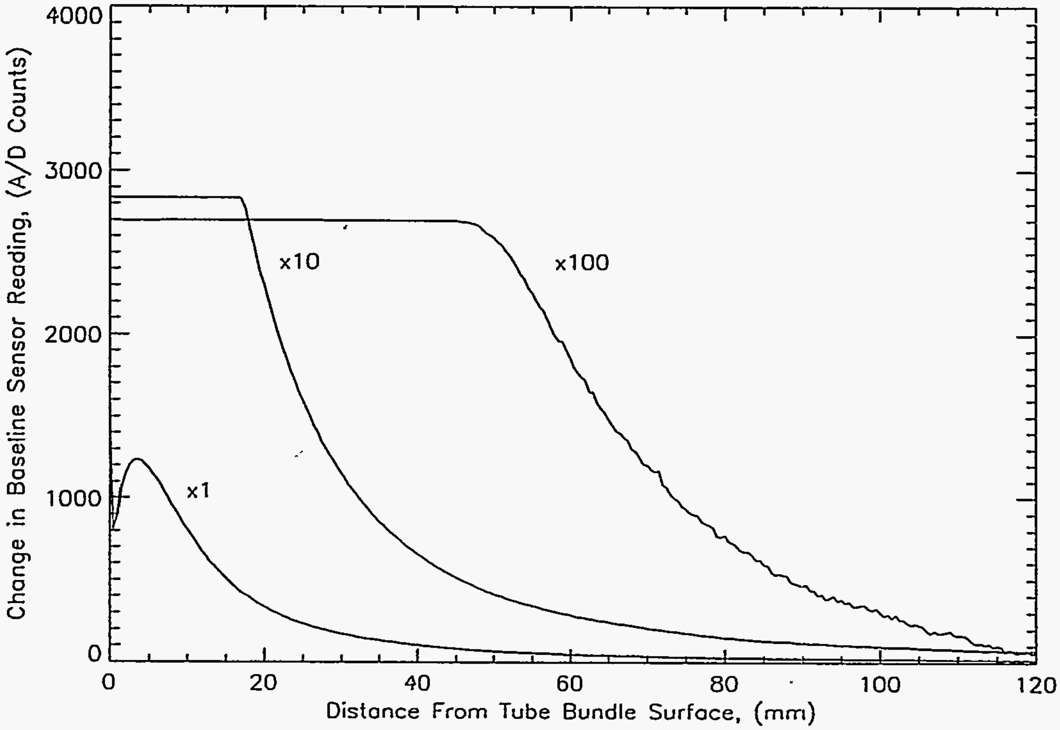

Figure 9: Collision avoidance sensor output at three gain settings

4 Robotic Equipment

The collision avoidance experiments conducted at Sandia and described in this paper were performed using a Fanuc S-700 robot with an RJ controller. Figure 10 shows a photograph of the collision avoidance collar attached to the end of the robot arm along with a capacitive seam tracking sensor [1]. The RJ controller contains a 16 MHz CPU with a 68881 floating-point coprocessor. The application software was written in Karel, a Pascal-like proprietary language for the Fanuc controller. The Karel feature of condition handlers was utilized to continuously monitor the collision avoidance system output and to stop motion when the user selected thresholds were exceeded. Fanuc's Off-Line Programming Software (OLPC) provided the link between a workstation and the robot controller.

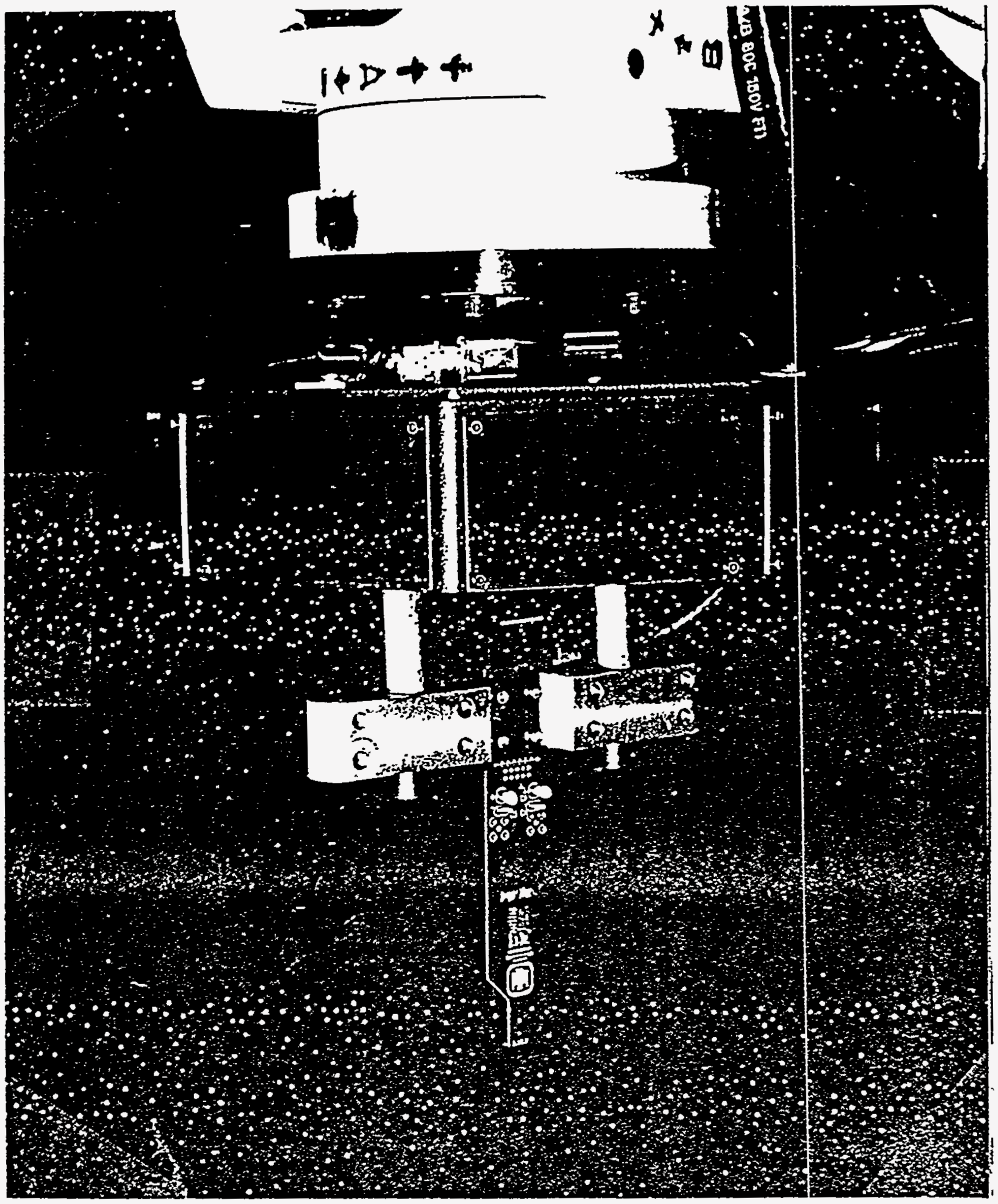

Figure 10: Collision avoidance collar attached to the Fanuc S-700 robot

The production robotic equipment at Rocketdyne consists of a Fanuc S-500 robot mounted on a linear track and controlled by the RJ controller. This system will provide complete access to all sections of the thrust chamber assembly. Rocketdyne has specified and procured special end effectors for dispensing the nickel powder and palladium silver braze paste. The collision avoidance system has been successfully integrated with this production equipment.

5 Collision Avoidance Tests

Experiments were conducted to evaluate the collision avoidance system's ability to stop robot motion using two different implementations. First, the condition handlers within the Karel application program which monitor sensor output were used to trigger a robot emergency stop upon detecting a potential collision. Implementation on the Fanuc R-J controller requires the condition handler to trigger a digital output. This digital output closes a relay which is connected to the controller's emergency stop circuitry. The advantage of this approach is the most rapid stopping of robot motion. Unfortunately program execution is halted and there is no opportunity for the application program to provide diagnostic information to the operator.

An alternate approach uses the condition handlers to stop robot motion using the Karel STOP command. This approach stops the robot by decelerating the executing motion. This allows the application program to continue execution and provide the operator with information about the potential collision (e.g. sensor which triggered). However, since it takes time to decelerate robot motion to zero velocity, the final position of the robot may be closer to the thrust chamber than the desired threshold. Experiments were conducted to fully understand the impact of this deceleration time.

In these experiments, the collision avoidance system was initially calibrated for a specific collision threshold distance. The robot then moved toward the calibration fixture at a fixed speed until the collision avoidance sensors indicate that the threshold distance has been exceeded. The condition handler then stops the robot by decelerating the motion. Figure 11 shows test data from one collision avoidance collar. Plotted is the average final distance from the fixture for tests using each of the eight sensors on the collision collar assembly. Tests were conducted at collision threshold distances of 25 mm and 50 mm and speeds ranging from 10 mm/sec to 150 mm/sec. The figure shows that as the speed is increased, the final distance from the fixture decreases. For collision threshold distances of 25 mm and 50 mm, speeds of 75 mm/sec and 150 mm/sec respectively would result in collision with the object before motion could be stopped. For the Rocketdyne braze paste dispensing application, the requirements call for a robot speed of 25 mm/sec and a collision threshold distance of 25 mm. Testing indicates an actual stopping distance of 14.8 mm which is an acceptable distance for this application. It should be noted that these experiments were conducted using the standard settings for the Fanuc system variables. Improvement in stopping distances may be obtained by optimizing system variables associated with motion deceleration and condition handler priority.

6 Summary

This paper presents a capacitive collision avoidance system used for workpiece protection during the robotic manufacturing of a rocket thrust chamber assembly. The non-contact collision avoidance sensors produce electric fields which are used to detect potential collisions between the robot and the chamber assembly. An octagon shaped collar assembly with one sensor on each face attaches to the robot tool plate to provide 360 degree collision avoidance protection. Experiments have shown that the system can successfully stop robot motion without collisions when a safe threshold distance of 25 mm is exceeded.

7 Acknowledgment

We would like to thank Sandia's Jon Bryan and Robert Waldschmidt for their efforts in fabricating the collision avoidance sensors and the signal conditioning system and Jim Akins for setting up the robot workcell and computer hardware.

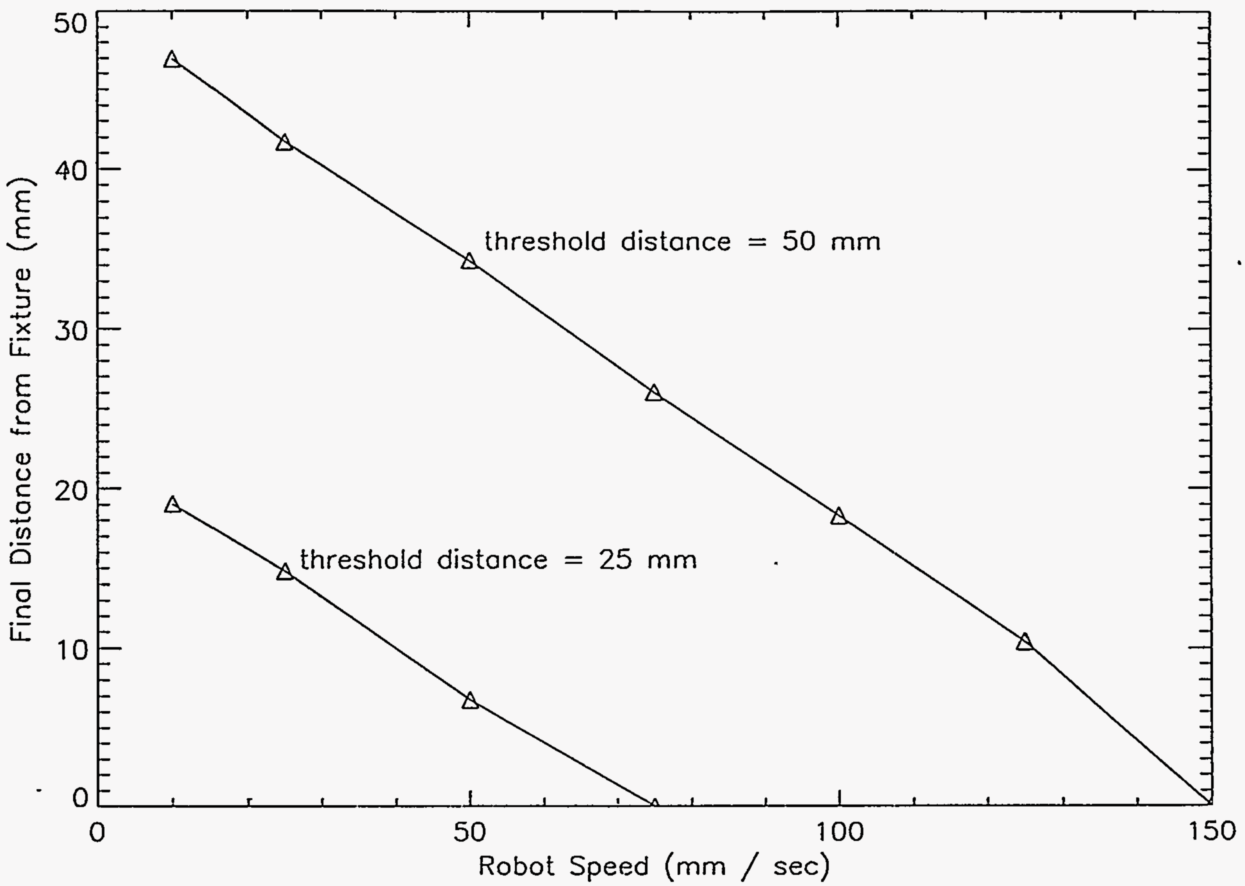

Figure 11: Final stopping distances at various speeds for collision threshold distances of 25 mm and 50 mm

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