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A MAGNETO-SENSITIVE SKIN FOR ROBOTS IN SPACE

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Abstract

This project has been concerned with the development of a robot arm proximity sensing skin that can sense intruding objects. The purpose of the sensor would be to prevent the robot from colliding with objects in space including human beings. Eventually a tri-mode system is envisioned including proximity, tactile and thermal. To date the primary emphasis has been on the proximity sensor which has evolved from one based on magneto-inductive principles to the current design which is based on a capacitive-reflector system. The capacitive sensing element, backed by a reflector driven at the same voltage and in phase with the sensor, is used to reflect field lines away from the grounded robot toward the intruding object. This results in an increased sensing range of up to twelve inches with the reflector on compared with only one inch with it off. It is believed that this design advances the state-of-the-art in capacitive sensor performance.

The original magneto-inductive sensor resulted in U.S. Patent #4,950,987 assigned to the University of North Carolina at Charlotte with John M. Vranish of NASA and Pradeep Yadav, formerly of UNC Charlotte as inventors. Details of the current design have been described in a paper accepted by the International Journal of Computers and Electrical Engineering, (Vranish et al., 1991)

1. INTRODUCTION

The objective of this project was to develop a robot arm proximity sensing skin that could sense intruding objects to prevent the robot from colliding with objects in space, particularly a human being. This sensing skin must be able to function reliably in the extreme environment of space and not disturb or to be disturbed by neighboring NASA instruments. It should be simple, compact and be incidental to the robot design. An approach proposed by Vranish and Chauhan (1990) based on an array of capacitors appears promising in solving both the proximity and tactile problems. However, the system must be able to detect objects (including humans) at ranges in excess of one foot so that the robot has time to react. To obtain ranges of this magnitude a capacitive sensor typically must be "stood off" from the grounded robot arm a considerable distance (approximately one inch). This would disfigure the robot arm, causing it to be bulkier than necessary. It would also make cross-talk between the sensor elements more pronounced and would likely impede the flow of heat from the robot arms to outer space (a serious problem for the Flight Telerobotic Service (FTS). The "capaciflector" (capacitive reflector) developed in this study solves these problems, and, in so doing, advances the state-of-the-art in capacitive sensor performance, (Vranish et al., 1991).

A single element proof-of-principle sensor has been demonstrated on a robot at the Goddard Space Flight Center. In this demonstration, the robot can routinely detect a human or an aluminum truss element at ranges of one foot. Even tiny objects, such as graphite lead in a pencil have been detected at ranges of five inches.

2. THE "CAPACIFLECTOR"

The "Capaciflector" is a capacitive sensing element backed by a reflector element which is driven by the same voltage as the sensor to reflect all field lines away from the grounded robot arm, thus extending the range of the sensor. This approach is an extension of the technique used in instrumentation systems where a shield or guard is used to eliminate stray capacitance (Webster, 1988).

The principle of operation of the "capaciflector" is shown in Figs. 1 and 2.

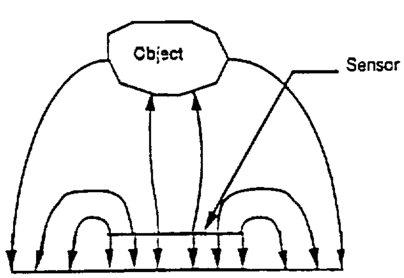

Fig. 1 Ground without reflector

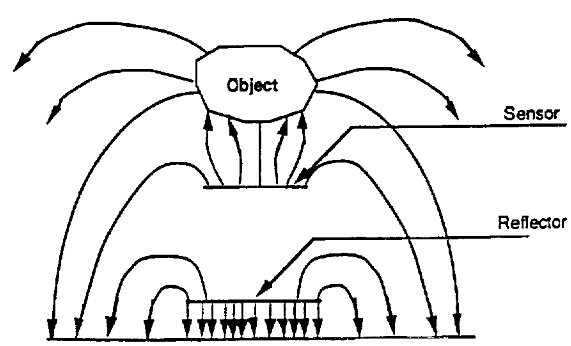

Fig. 2 Ground with reflector

Fig. 1 shows a capacitive sensor not using the "capaciflector" principle. Since we are using relatively low frequencies (approximately 20kHz) we have a quasi-static condition and static charges and electric fields can be used to determine the capacitance the sensor "sees". We can see that the smaller the stand-off from the grounded robot arm, the larger the capacitive coupling between the sensor and the ground. This, of course, has the effect of reducing the relative coupling between the sensor and the object being sensed, and hence reducing sensor range and sensitivity. On the other hand, increasing the stand-off increases the bulk of the robot arm and adds wires and wiring complications. And, when the insulation materials are added to support the stand-off, the ability of the robot arm to dissipate thermal energy into space is reduced. When the "capaciflector" principle is used as shown in Fig. 2, the field lines from the sensor are prevented from returning directly to ground. The effective stand-off is approximately the width of the active shield thickness (on the order of 0.060 inches) and a robot are can be built with very little bulk, and still have the performance of a large stand-off.

The electronic circuitry for the "capaciflector" is illustrated in Fig. 3.

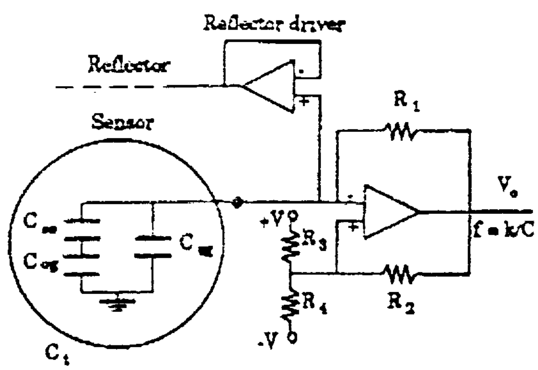

Fig. 3. "Capaciflector" Circuitry

The capacitive coupling between the sensor and the object being sensed is used as the input capacitance tuning the oscillator frequency. As an object comes closer, the capacitance increases and the oscillator frequency decreases. On the other hand, the reflector is attached to the output of the voltage follower so it is electrically isolated and prevented from affecting the tuning of the oscillator frequency. At the same time, the voltage of the reflector follows that of the oscillator. Thus, the reflector is in phase with (and reflects) the electric field of the sensor without being affected by the coupling between the sensor and an approaching object.

3. DETECTION

The means by which the sensor detects an object is examined. The discussion is limited to conductors for simplicity although dielectrics can also be detected. Both the grounded and ungrounded cases are examined.

For low frequency, (approximately 20 kHz), quasi-static conditions can be assumed. Assuming a momentary positive potential V in Fig. 2, we can see that the electric field lines emanating from the sensor towards the object induce negative charges on the object surface nearest the sensor. Thus that surface can be considered one plate of a capacitor and the sensor the other. But, an ungrounded conductive object is charge neutral so an equal amount of positive charge will form on the surface away from the sensor to ensure that there is no net electric field in the conductor. These charges couple back to ground which creates a second capacitor in series with the one mentioned above. These are labeled in Fig. 3, as C_{so} and C_{og}, respectively. There also is a path where the electric fields from the sensor can go around the active shield and couple to ground directly. This is labeled as C_{sg}. Thus the tuning capacitance, C_t, is given by the relation

$$C_t = \frac{C_{so}C_{og}}{C_{so}+C_{og}} + C_{sg}$$

In the case where the object is grounded, equation 1 reduces to

$$C_t = C_{sg} + C_{so}$$

Examining equations 1 and 2 above, since we are looking for small changes in C_t, it is clear we want C_{sg} to be small. Therefore, we want the shield or reflector to force the field lines from the sensor towards the object as much as possible.

We now turn to the case where the object is not grounded, (Fischer, 1989, Hayt, 1989, Lorrain et al., 1988). We know that

$$C = \frac{Q}{V}$$

We also know that a good conductor must have the same potential everywhere on its surface. Therefore the potential on the object will be that of its furthest point from the sensor. We will call the potential on the sensor V and the object potential V_o. Thus we have

$$C_{so}=\frac{Q_i}{V-V_o};\ and$$

$$C_{og}=\frac{Q_i}{V_o}$$

where Q_i is the charge induced in the object.

It is apparent that an object with any dimension more than a few inches in any direction (for example length) forces the potential on the entire surface of the object to be very low. And, as the experimental evidence shows, all objects are approximately grounded.

4. MODELING

The frequency of oscillation of the circuit in Fig. 3 can be shown to be

$$f=\frac{ln(0.5)}{2R_1C}$$

where $R_3 = R_4 = 2R_2$. This implies

$$\frac{\Delta f}{f_o}=\frac{\Delta C_t}{C_{to}+\Delta C_t}$$

where f_o and C_{to} represent the frequency and the capacitance of the sensor in the absence of an object, and Δf and ΔC_t represent the change in frequency and capacitance respectively because of the introduction of an object. Therefore the relationship between change in capacitance and sensor configurations is key to improving the sensor's sensitivity. A computer model was developed to track the change in capacitance as the object moves towards the sensor for various configurations of the sensor.

A two dimensional model was assumed for the simulations. The boundary integral method (McAllister, 1985) was used to determine the charge distribution leading to the determination of the capacitance. The modeling approach is similar to that used by Volakis et al., (1987).

The system considered in the model consists of three linear entities (representing the grounded robot arm, the shield, and the sensor), and one circular entity (representing the object). For a given configuration of the ground, shield and sensor, the program tracks the sensor capacitance as the object moves towards the sensor along the vertical and the horizontal directions. This is done by first defining a planar grid above the sensor, positioning the object center at a grid point, and computing the sensor capacitance for each such object position. The program automatically generates new configurations (over which the user has control), and performs the above operations for each configuration.

5. RESULTS

5.1 Modeling Results

The computer model was used to determine frequency change as a function of distance of the object from the sensor. Simulations were performed for four configurations as indicated in Fig. 4.

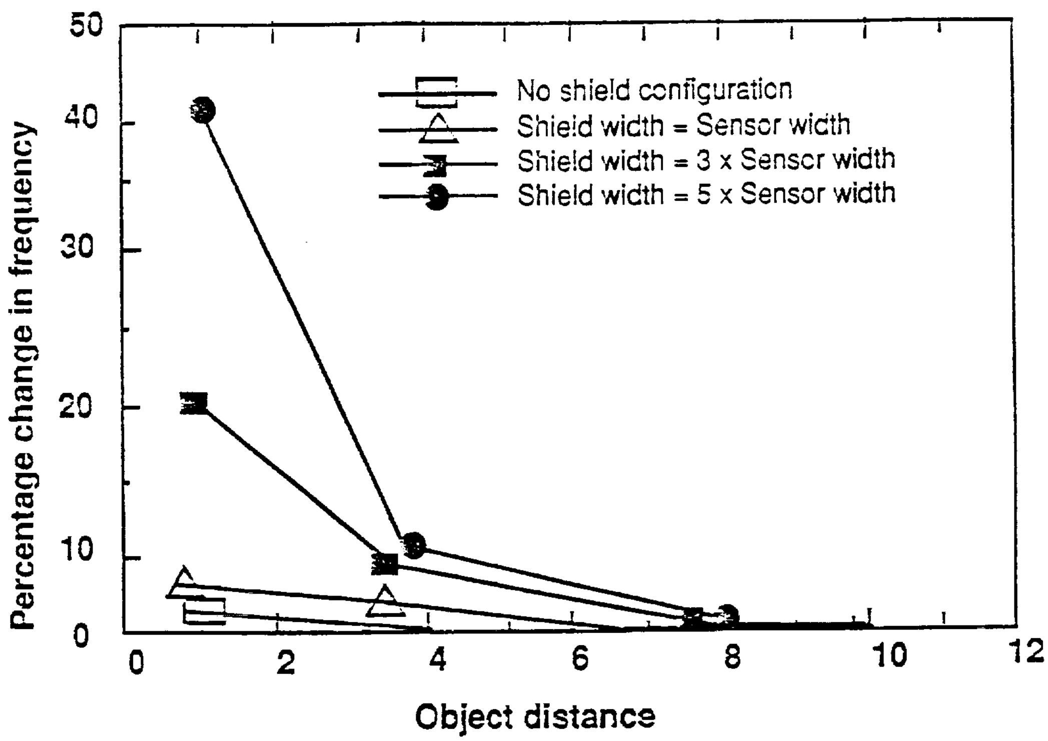

Fig. 4: Modeling results,
% Frequency change vs Object distance From Sensor.

As can be seen, calculated frequency change is inversely proportional to the object distance from the sensor. Sensitivity increases significantly as the shield width increases, especially at small object distances.

5.2 Experimental Results

The experimental set-up consisted of a sensor approximately six inches long with the reflector approximately fourteen inches long. The object was one inch in diameter and thirty six inches long. The reflector was made from strips of copper foil that could be connected in several configurations. Testing has shown that the sensor must be shorter than the reflector to reduce the end effects which substantially reduce sensitivity. It appears that the reflector must totally surround the sensor to contain the field. Otherwise, the flux lines from the sensor will simply shift to the lower field strength and return to the ground at the ends of the sensor, thereby reducing the coupling to the object. The results of the experiment are shown in Fig. 5.

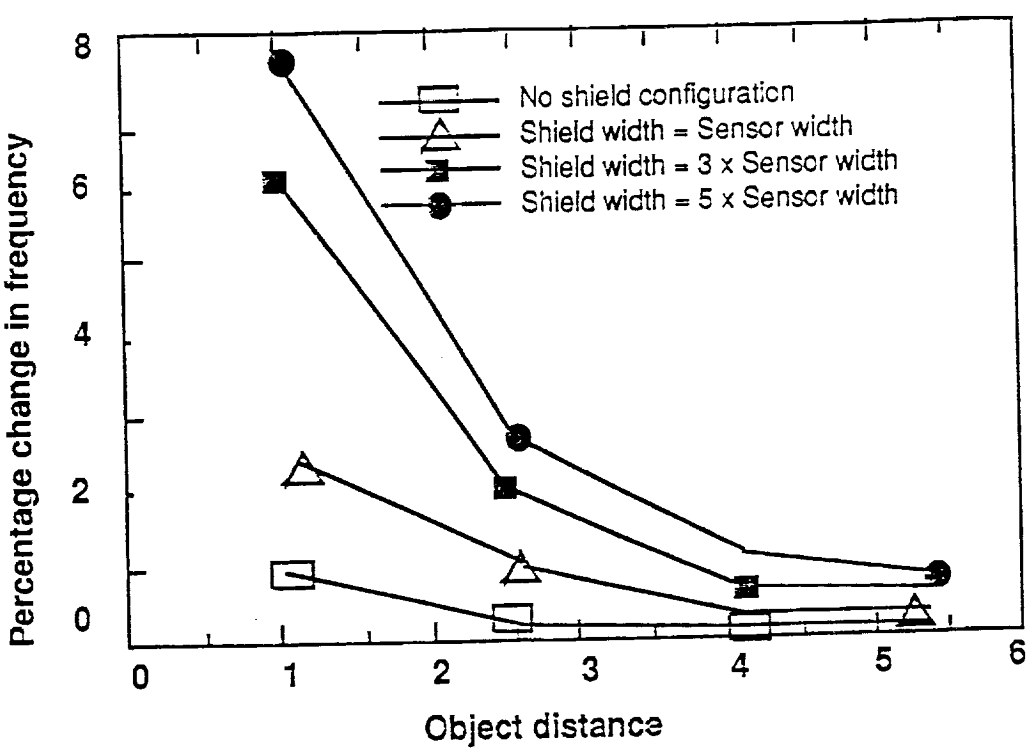

Fig. 5 : Experimental Results

The experimental results are quite similar to the simulations. Both show the frequency change is inversely proportional to the object distance from the sensor. They both show that the sensitivity increases dramatically as the shield width increases. However the simulations predicted a greater frequency change than the measured values.

The substantial difference may be due to the primitive models used to date. The model program assumes infinitely long strips for the sensor, shield and object, while the experiment used a six inch sensor with fourteen inch shield. End effects or the short sensor may account for the differences which the model may not be able to determine. The rate of variation between the curves is also different. The model shows almost no difference between the curves for no-shield and shield = sensor width, while the experimental results show a substantial difference. This result may be entirely due to inaccuracies in the model. Similarly, there is a difference between the rate of change between the upper two curves on the graphs. The model shows an increasing rate of change difference while the experimental result shows almost a constant difference. We cannot presently account for this result, but it may be due to either the model or to electronic circuit limitations. This latter conjecture comes from the fact that the frequency changes are substantial and nonlinearities my limit the frequency shift. Additional studies will be needed to answer these questions.

6. CONCLUSION

It is widely accepted in NASA that a capacitive array would make an excellent basis for a collision avoidance sensor if its range (typically one inch) and sensitivity could be extended far enough for the robot to react to an intrusion, if the sensor could detect ungrounded objects (especially a human) and if all this could be accomplished at no penalty in bulking up the robot arm. Preliminary results of this study have shown that the range and sensitivity of the capacitive sensor can be dramatically extended by providing a shield or reflector to isolate the sensor from the underlying ground of the robot arm and direct the electric field towards the object. In this configuration, the stand-off of the sensor is eliminated so the sensing skin will be incidental to the robot arm. Experiments with the sensor mounted on the robot arm and interfaced with the robot controller show that the sensitivity is more than sufficient for practical applications; a human hand can be detected at more than twelve inches.

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