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A Survey and Experimental Evaluation of Proximity Sensors for Space Robotics

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Abstract

This paper provides an overview of our selection process for proximity sensors for manipulator collision avoidance. Five categories of sensors have been considered for this use in space operations: intensity of reflection, triangulation, time of flight, capacitive, and inductive. From these categories, the most promising commercial and mature laboratory prototype sensors have been selected and tested. After reviewing the selection process and the experimental results, conclusions are drawn about which sensors are best and why.

1 Introduction

The safety of flight hardware in the workspace of a robot manipulator can only be guaranteed through robust collision avoidance control that treats the spacecraft hardware as obstacles, around which to navigate. Previous research addressing this problem has been broadly divided into two classes of methods: *global* and *local*. Global methods rely on the description of the obstacles in the configuration space of a manipulator [6]. Local methods rely on the description of the obstacles and the manipulator in the Cartesian workspace [4, 1].

Local methods employ the use of artificial forces, expressed in the Cartesian workspace of the manipulator as a function of the shortest distance between the manipulator and the obstacles [4, 1, 9]. Collisions are prevented by making these forces repulsive. If a goal point is specified, it will impart a similar attractive force on the robot end effector. Actuator torques equivalent to the sum of these specified forces cause the motion of the real manipulator.

The main advantage of local techniques is that they are less computationally demanding than global ones, permitting their use in real-time control [4]. Further, they provide the necessary framework to deal with changing environments and real-time collision avoidance. When used with a teleoperated manipulator, local artificial forces also provide low level collision avoidance, while high-level path planning of the manipulator is performed by the human operator.

A large problem with using artificial forces is the need to determine the distance between the robot and its environment. If this is to be calculated, an accurate geometric model of the arm and the environment must exist a priori or be created from sensor information, such as computer vision. But even if a very accurate model exists, it is computationally expensive to calculate the three dimensional distances between the modelled arm and its environment.

The alternative is to use sensors to directly measure the distances between the robot and its environment. If perfect measurements can be made from each point on the robot's surface, along the normal to the surface, then unexpected contact with the environment can be eliminated. Obviously, there are no perfect sensors, and no way to provide complete coverage of the robot. The key issues then become, the quality of the sensor data and coverage that the limited set of these sensors may provide.

This report address the first of these issues, the quality of proximity sensor data, in terms of accuracy and robustness to different environmental surfaces. We have investigated the available proximity sensing technologies, all of which utilize five physical principles of operation: intensity of reflection, triangulation, time of flight, capacitance, and inductance. From these categories we have selected and performed initial experimental evaluation of the most promising commercial products available. We have also obtained and tested mature laboratory prototype sensors from two of these categories. These initial tests were performed on black, white, and aluminum surfaces. (In preparation for more extensive testing we have also selected and prepared a spectrum of spacecraft surface material samples.)

This report is organized as follows. Section 2 provides an overview of commercial and mature laboratory prototype sensors that utilize the five physical principles to detect distance to the environment. A discussion provides the reasoning behind selection of particular sensor models for experimental testing. Section 3 presents the results of the experimental testing of these selected sensors. Finally, Section 4 reviews our results and draws conclusions about individual sensor efficacy.

2 Sensor Selection

To avoid the time and cost of sensor development, this study has been interested in acquiring and testing commercial or mature laboratory technology only. In some cases, the sensors were modified slightly to increase their performance, adjust their range, or make them more amenable to direct comparison with other sensors.

Type			
Company	Model	(laser type)	range (cm)
Laser Triangulation			
Keyance	LB-041	IIIa	(4.5-5.5)
	LB-081	IIIa	(6.5-9.5)
	LB-301	IIIb	(20-40)
	LB-11	IIIb	(6-14)
	LB-12	IIIb	(3-5)
	LC-2320	II	(4.2-5.8)
	LC-2220	II	(2.7-3.3)
Cyber Optics	RRS-1600		(5.3-6.9)
Adsens Tech	LAS-5010		(4.5-5.5)
	LAS-8010		(6-14)
Selcom	2201	IIIb	(7.9-11.1)
	2203	IIIb	(13-22)
Aromat	LA40	I	(3-5)
	LA75	I	(5-10)
	S10	IIIb	(10-20)
	ANL1651	IIIb	(8-18)
Idec	MX1A/B-A		(3-5)
	MX1A/B-B		(5-13)
	MX1C	IIIb	(6-16)
Photo-Electric Triangulation			
SunX	DSA series		(8-12)
Idec	SA1D-LK4		(20-50)
Optical Reflection Intensity			
Eaton	E67LXL2N		(100-340)
			(40-160)
			(30-70)
	E67LXL2W		(60-300)
			(30-150)
			(30-110)
SunX	RS120HF4SAS		(2-9)
	RS120HF1SAS		(10-70)
	RS720H1SAS		(60-300)
	RS120HF8SAS		(8-17)
	RS120HF2SAS		(5-40)
	RS820H1SAS		(50-150)
Banner	OASBD		(23-92)
Tritronics	SAL01		(-130)
	SA01		(-100)
	SAL02		(-14)
	SA02		(-12)
STI	307		(45-600)
	304		(45-300)
	306		(0-7.6)
	303		(0-30)
	L303		(0-60)
Fiber Optic			
Banner	OASBFX		(3-15)
	OASBF		(1-7.5)
Optical Time of Flight			
Sick	DME-2000	II	(10-200)
Microwave Time of Flight			
AM Sensors	MSM10500		(15-1500)
Inductive			
Eaton	E56		(0-10)
Pepperl+Fuchs	NJ50		(-5)
	IA		(-3)
Electromatic	DJ		(-4)
Radio Shack	Micronta		(-20)
Capacitive			
Capacitec	410SCBNC		(0-15)

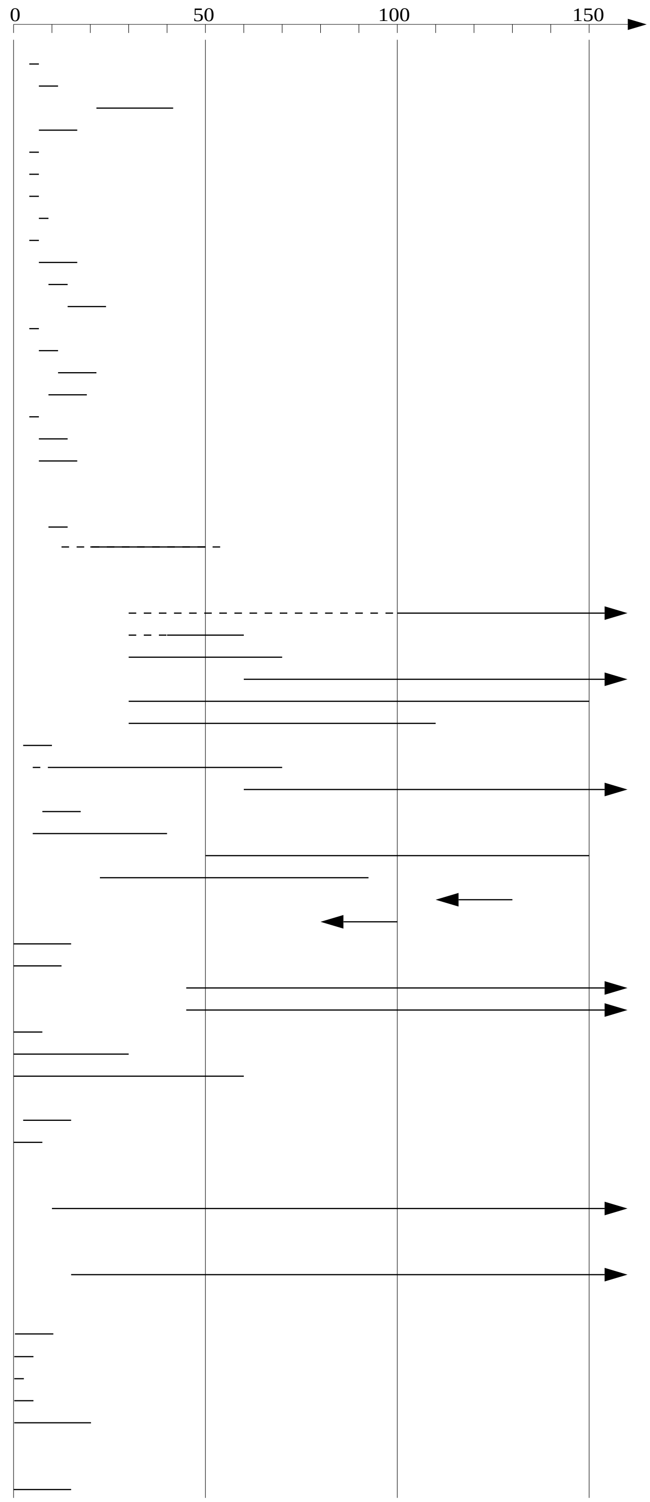

Figure 1: *A table of many of the commercially available sensors considered in this study. The right hand side of the chart graphically shows the advertized sensor range in centimeters.*

Selected Proximity Sensors			
type	*model*	*range/cm*	*cost/$*
Reflection	SunX RS120H1SAS	5-70	160
	SunX RS120HF1SAS	5-70	160
	SunX RS120HF2SAS	5-40	170
	SunX RS720H1SAS	30-300	250
	SunX RS820H1SAS	50-150	140
Laser Triang.	Aromat LA75	5-10	1300
P-E Triang.	Idec/Izumi SA1D-LL4	20-50	225
Optical ToF	Sick DME2000	10-200	3900
μwave ToF	AMSensors MSM10500	15-1500	500
Inductive	Micronta Metal Det.	0-20	170
Capacitive	Capacitec 410SCBNC	0-15	1900

Figure 2: *The selected commercial proximity sensors and their costs.*

2.1 Commercial Sensors

By far, the majority of the sensors considered and tested in this study are commercially available products. Figure 1 provides a list of most of the sensors that were investigated. (Acoustic sensors were not considered because they will not function in the vacuum of space.) The chart is divided horizontally into the sensing technologies, and vertically by company name, model number, laser type, and range in centimeters. The laser types are: (I) eye safe, (II), eye safe but do not stare into the beam, (IIIa) not eye safe but visible, and (IIIb) not eye safe and invisible. The sensor range is also displayed graphically for easy comparison. An arrow on the range indicates an unknown bound, or a bound that does not fit on the chart.

Figure 2 provides a summary of the sensors that were selected, purchased, and experimentally tested. Also included in the table is the price per sensor (that we paid). While none of these sensors is designed for use in space, the underlying physical principles, as well as the simple design of many of the sensors, would readily lead to the creation of flight qualified versions. Given this assumption, we have used other criteria for making the sensor selections. A discussion of this selection process is provided below.

2.1.1 Intensity of Reflection

Optical intensity of reflection sensors are probably the most widely available in the number of manufacturers, the number of models, and the ranges of operation. (However, there is some repetition, such as the Eaton E67LXL2W, which is the same sensor as the SunX RS720H1SAS.) Many of these sensors have adjustable ranges, which are set by turning a potentiometer on the sensor housing. Therefore, the ranges listed for some sensors may not be attainable by one sensor setting. Also, some sensors (such as those by Tritronics) did not have a minimum value specified by the company. Finally, there are versions of these sensors which have fiber optic light guides which carry the emitted and received light to and from a location up to several meters away. While this technique effectively collocates and shrinks the emitter and receiver, it suffers from fiber transmission losses and a corresponding reduction in sensing range.

To fully test the range of intensity of reflection sensors, a spectrum of five models from SunX were selected (all of those listed except RS120HF4, since it is designed for short range operation). All of these sensors were comparable in price to each other and other sensors not selected. During tests with these models, their potentiometers were set to maximize the span of distances that provide usable sensor output.

2.1.2 Triangulation

Triangulation sensors typically project a narrow beam of light and measure the location of the reflected light when viewed from an angle. While this technique gives accurate readings independent of signal strength, Figure 1 indicates the problems with those sensors which are commercially available. The majority have a very limited range, and increase their range by employing more powerful lasers which are not eye safe. We consider eye safety an important issue for robot proximity sensing system that will be used near ground crews and astronauts, and potentially reflective spacecraft surface materials. Therefore, the Aromat LA75 laser triangulation sensor was chosen because it has the most range of Class I models.

Alternatively, there is a smaller set of photo-electric triangulation sensors available. These have less resolution, but much greater range and eye safety. Further, they are significantly cheaper than the laser sensors. The Idec/Izumi SA1D-LK4 was selected.

2.1.3 Time of Flight

We are only aware of two commercial time of flight sensors available at reasonable cost. The first is a laser time of flight sensor, the Sick DME2000. At approximately $4000 and weighing 1 kilogram per sensor, we considered it to be at the limit of acceptability for a robot proximity sensing system. However, it was selected since its accuracy/range combination is the best amongst all sensors available.

The second time of flight sensor is the AM Sensors MSM10500 microwave sensor. Operating at 10.525 GHz, it has a resolution of 15 cm. Also, the sensor electronics are designed to only output a measurement when the environment is moving toward the sensor, and only above an unspecified threshold speed. Finally, sensor readings are updated at a rate proportional to the approach speed. These characteristics did not bode well for its performance, but the sensor was selected anyway since no alternatives were found.

2.1.4 Inductive and Capacitive

While many companies make inductive and capacitive sensors, most are designed to be switches for very short range (< 1 cm) assembly-line part presence detection. Amongst inductive sensors, slightly longer range models exist and are listed in Figure 1. The most sensitive of these is the Radio Shack Micronta, which is actually designed for buried metal detection. However, because of its larger coil size it has a range twice that of the nearest industrial model.

Amongst capacitive sensors, the same lack of long range sensors prevails. While primarily selling standard short range sensors, Capacitec was found to sell long range sensors by special order. As a compromise between size and range, we selected a capacitance sensor diameter of three inches, on a six inch reflector. The electronics which accompany the sensor were tuned at the factory for a maximum sensing range of six inches. Unfortunately, the special order creation of the capacitance sensor is relatively expensive ($800). Use of Capacitec sensor electronics, with homemade capacitor plate sensors, is a possible cost-saving alternative for the future.

2.2 Mature Non-Commercial Sensors

There are several sensors developed in non-industrial research labs which need to be mentioned. We will review four sensors which fall in the categories of laser triangulation and capacitance sensing. Two of these sensors have been tested and the results are presented later.

2.2.1 Laser Triangulation

Two experimental laser triangulation sensors promise extended range and less sensitivity to environmental surface properties. The first has been develop for use in the ROTEX flight experiment [2]. Integrated into the end-effector of this experimental robot, are several short range proximity sensors and one long range (3-50 cm) laser triangulation range sensor. We attempted to obtain a version of this sensor for testing, but were informed that no spares existed. Later discussions revealed the possibility of a forthcoming commercial version of the sensor.

The second triangulation sensor is called the Hexeye, being developed at USC in conjunction with JPL [5]. This sensor projects one beam which is viewed by an array of six linear photosensors with 12 pixels each. The output signals are averaged and passed through a neural net trained on specific environmental surface types. The training eliminates errors due to the peculiarities of the surface, the sensor components, and ambient environmental lighting. Some experimental results with a prototype of this sensor are provided in Section 3.2.

2.2.2 Capacitance

Two capacitance sensing methods are being studied at NASA Goddard Space Flight Center (GSFC) and Sandia National Laboratory [11, 8]. The GSFC sensor is similar in design to that sold by Capacitec. In Section 3.4, an experimental comparison will be made between these two sensors.

The Sandia capacitance sensor utilizes side by side capacitance plates, one of which is driven, and the other connected to a charge amplifier. The presence of an environment modifies the total capacitance of the system, and therefore the charge and resultant signal. One of the stated advantages of this design is that it eliminates the need for a driven shield behind the sensing capacitor, as is used in the GSFC and Capacitec designs. We were unable to obtain a sample sensor from Sandia for testing in our lab. Researchers at Sandia are in the process of commercializing their design, so testing of it may be possible in the near future.

3 Experimental Data

To evaluate the selected sensors, initial tests were performed with simple environments and variation in the normal distance of the sensor from the surface. For the optical sensors, black and white paper (8.5 by 11 inches) were used as the environmental surface. For the capacitive and inductive sensors, a six inch square aluminum plate was used. For the microwave sensor, both types of environments were tried.

3.1 Infrared Intensity of Reflection

The five different SunX sensors listed in Table2 were tested using black and white paper. The sensors are designed to have different distance sensitivity, selectable by adjustment of a potentiometer on each unit. While not as important to these tests, the sensors also have variable beam widths. For instance, the RS120HF1 has a narrower beam than the RS120H1. (The SunX catalog should be consulted for a comprehensive description of beam geometries.)

Figures 3–4 show the measured outputs of these sensors set at maximum range. All five have a good response for the white environment, utilizing most of the maximum voltage range and responding fairly linearly in the span of their respective operating distances. However, for the black surface, the results are very degraded. Not only are the responses less intense, but they are not linear with respect to distance, the worst example being the 720H1 in Figure 4. This degradation of the response from intensity of reflection sensors for non-white surfaces is well known. Unless the environment is guaranteed to be nonspecular and light colored, reliance on the sensed distance values is not advisable. However, these sensors may effectively be used as simple noncontact switches, instead of full range proximity measurement devices.

In this latter case, simple emitter/receiver diode pairs may be considered [7]. They are more compact and cheaper than the above tested sensors. However, their output is not linear, and they can be susceptible to confusion from ambient light sources (unless they are modulated).

3.2 Triangulation

Two different types of triangulation range sensors were tested: infrared diode (Idec/Izumi SA1D) and visible laser (Aromat LA40). Both project a beam of light outward and look for the surface reflection with a position sensing device (PSD) located to the side of the light source. Figure 5 shows the response of these sensors on black and white paper environments. Unlike the intensity of reflection sensors, the triangulation sensors provide consistent readings independent of surface reflectance, over a limited range.

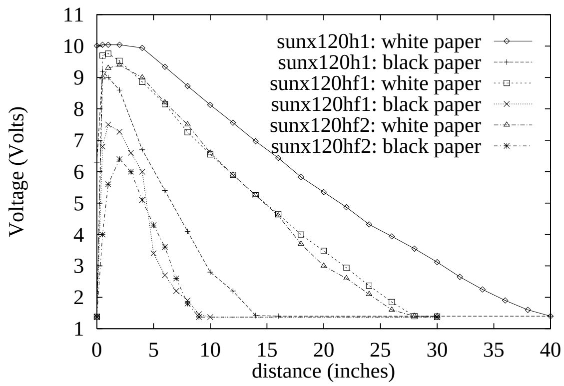

Figure 3: *Data for short range infrared light intensity of reflection on black and white test surfaces.*

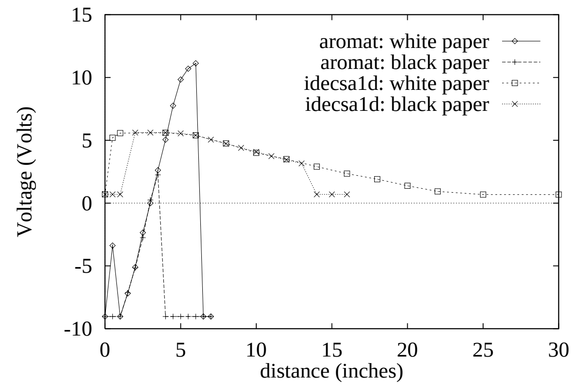

Figure 5: *Data for triangulation sensors on black and white test surfaces. The Idec/Izumi SA1D uses an infrared beam, and the Aromat LA40 uses a visible laser.*

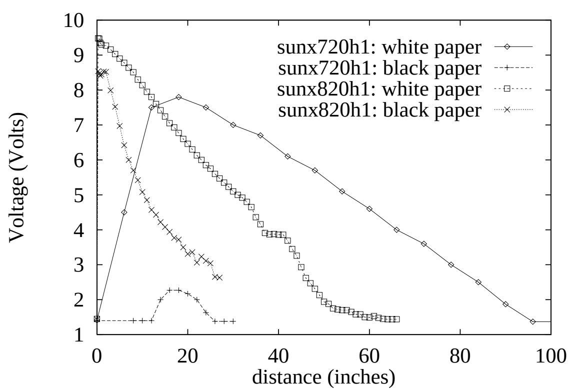

Figure 4: *Data for longer range infrared light intensity of reflection on black and white test surfaces.*

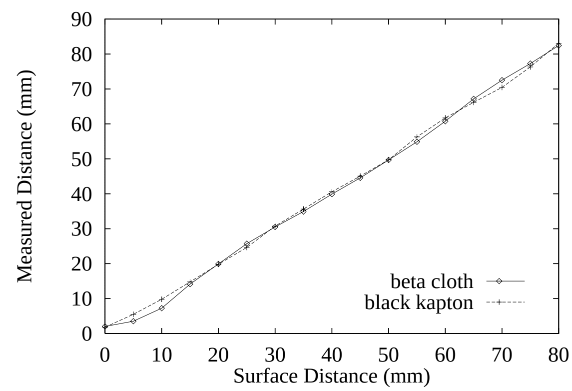

Figure 6: *Data from the Hexeye sensor on black and white space craft materials for which its neural net has been trained.*

For robot collision avoidance and distance servoing, we've selected the SA1D as the better sensor of the two. First, it has a range about four times greater than the LA40. Second, it does not employ laser light which may require eye protection. Third, it is about one fifth the price. Fourth, it may be used directly with conventional power supplies. Fifth, the LA40 has spurious peaks inside of its sensing range and drops down to its minimum value reading for far positions. The only possible advantage of the LA40 laser sensor is its visible, small diameter beam.

As indicated in Figure 1, laser triangulation sensors tend to be designed for a shorter sensing range with very high resolution. Longer ranges typically require lasers that are not eye-safe, and therefore undesirable for our purposes. This is because the target market of circuit board inspection typically requires short range and high resolution sensing. General purpose robot collision avoidance, however, requires greater range sensing.

Another experimental laser triangulation sensor is the USC/JPL Hexeye [5]. It utilizes six linear sensors to detect the position of the projected laser illumination. The averaged sensor element readings are further processed by a neural network trained to eliminate range errors caused by the unique reflection patterns of specific materials. Figure 6 shows the response of the sensor system for white and black spacecraft materials (Beta Cloth and Black Kapton) for which it was trained. Figure 7 shows the sensor response to several materials for which it was not trained. Significant amongst these is the aluminized Kapton, which has a near-mirror surface. While the measured values are inaccurate, it is impressive that the sensor is not completely confused by this reflective surface. Currently, this sensor system suffers from limited range and large size, but the next version promises improvement in these areas.

3.3 Time of Flight

Two types of time of flight sensors were tested: laser and microwave. Interestingly, these sensors provided the best

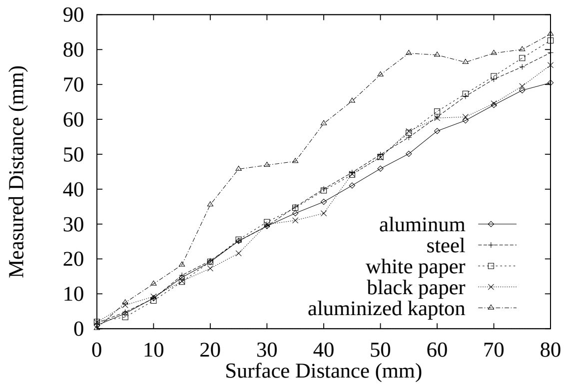

Figure 7: *Data from the Hexeye sensor on materials for which its neural net had not been trained.*

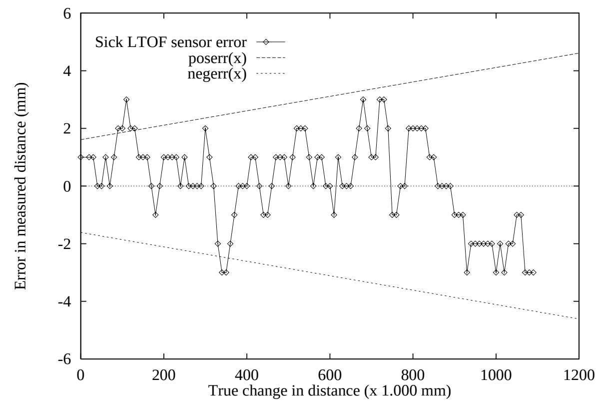

Figure 8: *Error for visible laser time of flight sensing on a white surface. (Model: Sick DME2000)*

and worst results of those tested.

The microwave sensor (AM Sensor MSM10500)) did not work well for the ranges, resolution, and static conditions for which we were testing. The results are not presented since we could not get consistent readings from the sensor. To be fair, the sensor is designed to determine range to a large environment, moving toward it. It has a maximum range of 50 feet, and a resolution of six inches. These values are probably too large for conventional sized manipulator arms. (The manufacturer, AM Sensors, has tentative plans to develop a model with a one inch resolution.) However, the greater problem with this sensor is that it requires motion between it and the environment for a distance to be measured. Also, the rate of sensor data output is proportional to the speed of approach. If the relative speed drops below the threshold, no sensed distance is available. For this reason, static measurements with the sensor were impossible. We attempted to obtain measurements while moving the sensor, but were unsuccessful in initial trials. However, even if the sensor worked perfectly while in motion, it would prove to be of little utility for robot collision avoidance. As obstacles approach, the robot should be slowed. But with this sensor, slowing the robot would cause the proximity readings to slow or stop. This situation would be extremely dangerous at best. Therefore, the microwave sensor has been removed from further consideration.

The second time of flight sensor (Sick DME2000) was the most accurate and precise proximity sensor tested. Because of this accuracy, a plot of the sensor measurement versus true distance appears as a straight line. Figure 8 instead shows the error of the distance measurement signal from its mean, versus the true distance from an arbitrary reference point. The true distance was established with a very precise coordinate measuring machine, capable of measuring micron increments in its change of position. Also, the manufacturer specified percentage errors are shown as negative and positive sloped dashed lines, for reference. Obviously, this sensor performs quite well, and is expected to perform equally well over its full operational range of 100-2000 mm. If a retro-reflective environment is used, the sensor can work out to 100 meters.

3.4 Capacitance

Two different capacitive sensors were tested: the GSFC Capaciflector [11], and the Capacitec HPS3000/6000MCX capacitive sensor with a model 410-SC-BNC amplifier.

The GSFC Capaciflector was tested with six inch square aluminum plate environment, grounded and ungrounded. For these tests, the Capaciflector utilized the typical GSFC configuration of a 4 by 0.5 inch sensor on a 3.5 by 4.75 inch reflector [11]. Since the response of the Capaciflector drops very rapidly with distance, GSFC recommends using the logarithm of the sensor output, shifted to all positive values by a constant bias value [3]. Figure 9 shows the sensor output plot on a log-log plot to better reveal the sensor value changes. Notice that even in this representation of the sensor output, the values increase more rapidly for close proximity. This can be seen as an advantage of this sensing method when used with robotics, since higher resolution sensing is provided for very close proximity operations [10].

The second capacitance sensor tested was a very similar product from Capacitec. To provide range sensing comparable to the GSFC sensor, we selected the capacitive sensing area to be a three inch disk, shielded by a six inch disk behind it. The Capacitec electronics are different also, since they invert and linearize the output signal. (Therefore, the output voltage is proportional to the reactance, not the capacitance.) Figure 10 shows the output of this sensor for the grounded and ungrounded aluminum plate environment. Since the sensor was calibrated at the factory for a six inch range, we believe that further adjustment could pull the response curve down, out of saturation, and yield sensitivity to greated distances.

To draw a more legitimate comparison of the GSFC and Capacitec sensors, we attached the GSFC electronics to the Capacitec sensing capacitor and shield. Figure 11 shows the output of the sensor for the grounded and ungrounded

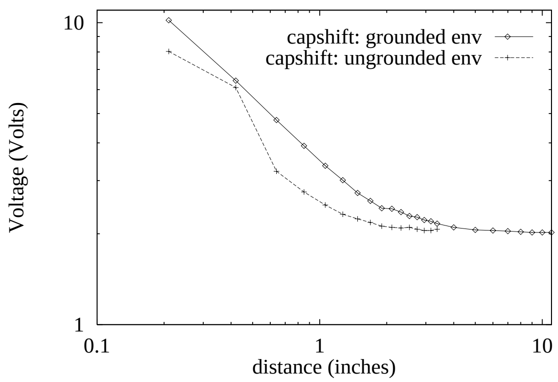

Figure 9: *Data from Figure 9, shifted by 15 V and plotted logarithmically.*

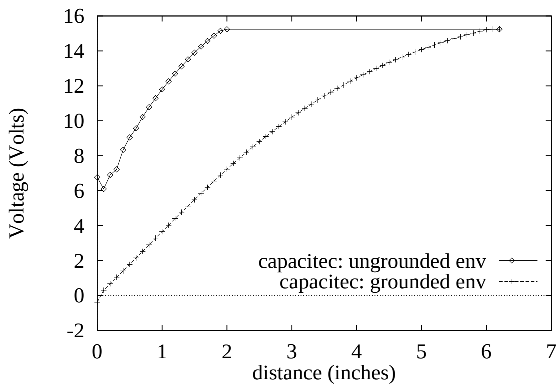

Figure 10: *Data from the Capacitec sensor and processing electronics. The voltage values are proportional to the measured reactance.*

aluminum plate plotted on a log-log graph for comparison with Figure 9. The curves have a similar shape, but the range has been extended by the larger Capacitec capacitor surface.

Finally, to compare the Capaciflector output with the Capacitec output, Figure 12 shows the normalized inverse ($min[x]/x$) of the data from Figure 11. Not only does this compare favorably with the original Capacitec data in Figure 10, but it appears to be a valuable way to generally represent the output from a capacitance sensor. While it diminishes the response at close range, the overall response is fairly linear with distance, and much more like an ideal proximity sensor.

3.5 Inductance

Most inductive proximity sensors sold commercially have very short range and are designed as near contact switches. However, metal detectors, commonly sold in hobby shops,

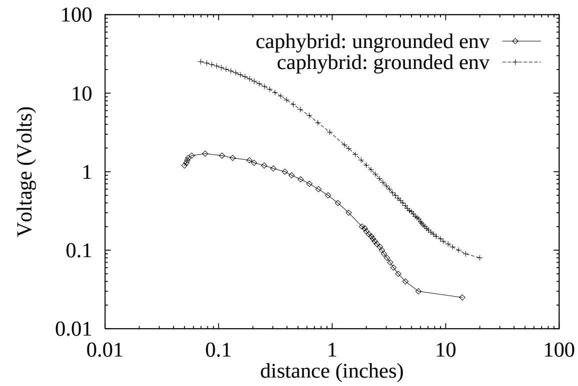

Figure 11: *Data from the Capacitec sensor with GSFC processing electronics, replotted with log-log scaling for comparison with Figure 9.*

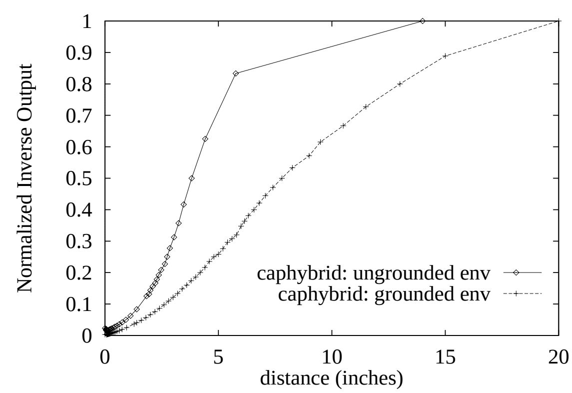

Figure 12: *Data from the Capacitec sensor with GSFC processing electronics replotted as a normalized inverse of the original data.*

work on the same principle to detect metallic obstacles buried many inches beneath a surface. Therefore, we selected and modified a commercially available metal detector to act as an inductive proximity detector.

The device selected is the Micronta Discovery 2 metal detector by Radio Shack. It has two concentric coils, with average diameters of nine and five inches. The inner one is driven and the outer is a receiver. For our tests, we bypassed the electronics provided, and supplied a driving signal at 6756.76 Hz, 11 V peak to peak. Figure 13 shows the peak voltage of the received signal as a function of the distance from the aluminum plate environment. The results were the same when the plate was grounded and ungrounded. While this sensor requires a large area, it works fairly well: the logarithm of the response is linear with distance, and it is capable of sensing to a range equal to its size. The main drawbacks are: it is completely blind to nonconductors, and the signal it generates may add noise to other sensor signals.

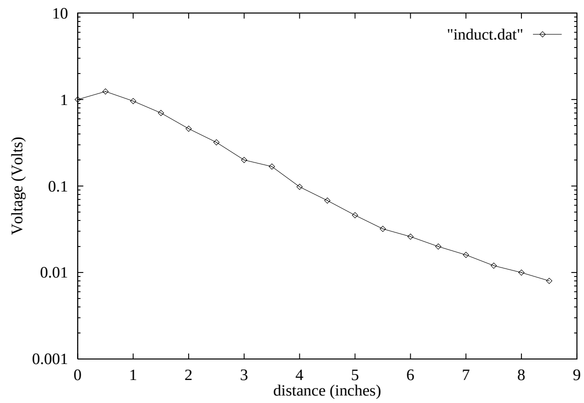

Figure 13: *Data from the Micronta inductive sensor for aluminum environment.*

Its large size is offset by the fact that it is flat and annular, so that it could effectively surround the end effector of a robot arm.

4 Conclusions

This report has detailed the selection of proximity sensors for manipulator collision avoidance during space applications. The sensors have been chosen from amongst the spectrum of commercial products and mature laboratory prototypes. Five distinct categories of sensing technology are represented: intensity of reflection, triangulation, time of flight, capacitance, and inductance. We have selected and performed initial experimental testing on several sensors of each type.

Based on the experimental data, three sensors stand out as most viable: the Idec/Izumi SA1D triangulation sensor, the Sick DME2000 laser time of flight sensor, and the Capacitec and GSFC capacitance sensor. While the DME2000 laser time of flight sensor is obviously the best performer, its cost and size make it prohibitive except for specialized applications. For instance, the cost and size would not be as large an issue if this sensor were to be used as an end-effector ranging device on the Space Shuttle Remote Manipulator System (RMS). However, for most applications, the smaller size and cost of the SA1D triangulation sensor make it more favorable. Within its operating range, it's accuracy is finer than the position control capabilities of most robot arms.

While the laser time of flight and triangulation sensors are adept at measuring distance to a point, they are much less useful for area coverage. Alternatively, the capacitance sensors promise complete area coverage if they are fashioned like a skin over the robot arm. While suffering in absolute accuracy, they can more reliably detect the presence of most obstacles. They can also be more easily incorporated into working surfaces, such as grippers. In these ways, capacitance sensing is a valuable complement to the more exact proximity measuring sensors.

5 Acknowledgments

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