Reflexive Obstacle Avoidance
for
Kinematically-Redundant Manipulators

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Abstract

Dexterous telerobots incorporating 17 or more degrees of freedom operating under coordinated, sensor-driven computer control will play important roles in future space operations. They will also be used on Earth in assignments like fire fighting, construction and battlefield support. A real time, reflexive obstacle avoidance system, seen as a functional requirement for such massively redundant manipulators, was developed using arm-mounted proximity sensors to control manipulator pose. The project involved a review and analysis of alternative proximity sensor technologies for space applications, the development of a general-purpose algorithm for synthesizing sensor inputs, and the implementation of a prototypical system for demonstration and testing. A 7 DOF Robotics Research K-2107HR manipulator was outfitted with ultrasonic proximity sensors as a testbed, and Robotics Research's standard redundant motion control algorithm was modified such that an object detected by sensor arrays located at the elbow effectively applies a "force" to the manipulator elbow, normal to the axis. The arm is "repelled" by objects detected by the sensors, causing the robot to steer around objects in the workspace automatically while continuing to move its tool along the commanded path without interruption. The mathematical approach formulated for synthesizing sensor inputs can be employed for redundant robots of any kinematic configuration. The work described in this paper was funded by NASA Langley Research Center.

1.0   INTRODUCTION

The National Aeronautics and Space Administration (NASA) has identified a number of promising applications for advanced robots and telerobots in future space operations. The most sophisticated of these robots will be required to perform complex tool-handling tasks with dexterity approaching "man-equivalence", while operating with a minimum of human intervention.

One class of NASA telerobots will be designed for EVA operations in high vacuum, zero-G or micro-G environments. Prototypical of this class is the Flight Telerobotic Servicer (FTS), a general-purpose tool-handling robot that will be used by Astronauts to assist in the assembly and servicing of the U.S. Space Station. (An illustration of the Grumman-Robotics Research-TRW team concept for FTS is shown in Figure 1.) Transported by NASA's Orbital Maneuvering Vehicle (OMV), the FTS and derivative models will eventually be deployed for remote servicing of the polar orbiting platform and the growing fleet of civil and military satellites in geosynchronous orbit. EVA servicing robots like the FTS also may become standard integral maintenance and repair subsystems on board large unmanned space probes and manned interplanetary vessels.

Robots with capabilities similar to the Flight Telerobotic Servicer will play important roles in initial exploration of the surface of other planets and moons in the Solar system. Designed to operate in the local gravity field and atmosphere, these units will naturally be built with somewhat different physical proportions, materials and sensor systems than high-vacuum, zero-G telerobots like FTS. They will also,

by necessity, be capable of considerable local intelligence and autonomy, since transmission delays preclude real-time control from remote human operators. In the planned Mars Rover mission, for instance, mobile robots will be used to survey Mars autonomously, examining the surface at close range and retrieving geological samples for analysis on Earth. Other devices of this type will be used to resume exploration of the surface of the Moon, and to survey the satellites of Jupiter and Saturn.

A third class of dexterous tool-handling robots are being planned by NASA for use in micro-G, IVA operations. These devices will operate inside Space Station laboratory modules, initially performing routine material-handling functions such as those required in semiconductor processing and liquid pharmaceutical processing operations which exploit the micro-G environment. Very general-purpose mobile servicers may ultimately be developed to handle "housekeeping" chores within the crew modules of the Space Station and manned interplanetary vessels.

Figure 1:
Grumman-TRW-Robotics Research
Concept for NASA Flight Telerobotic Servicer

The specific physical configurations of NASA's dexterous telerobots will differ from one application to another, and one working environment to another. Some may have a single tool-handling arm. Some may have two dexterous arms mounted on a torso/waist assembly. Others may utilize "spider" configurations to provide mobility on a truss, including several arms, each with a dexterous end-effector, plus a number of legs and peripheral camera and light positioners. The control system capabilities of these robots will also differ from one application to another. Some will function primarily in a teleoperated or shared control mode, with the "man in the loop", while others will operate autonomously for long periods of time. Nevertheless, the basic missions established for NASA's dexterous manipulator systems impose certain common requirements for their physical designs and control architectures. One can reasonably foresee the following:

The Need for Kinematic Redundancy   In order to perform their assigned tool-handling tasks, NASA's dexterous telerobots will generally have more than six joints operating under simultaneous, coordinated control. Seven axes are the minimum required in a mechanical manipulator to emulate the basic motions of the human arm, from the shoulder to the wrist. Like the human arm, a 7 degree of freedom (DOF) manipulator can assume any number of different joint configurations, or arm poses, for a given position and orientation of the "hand" (or "toolpoint"). With one "redundant" degree of freedom, the manipulator arm has the freedom, for example, to reach around and avoid collisions with objects in certain locations in its workspace while it performs its programmed task. In principle, the more redundant degrees of freedom incorporated in the manipulator system, the more versatility it has. To perform extremely complex tasks with skill approaching "man equivalence", future space telerobots will eventually incorporate hundreds of degrees of freedom operating under coordinated control.

The Need for Sensor-Driven Computer Control of Redundancy   A computer will be required to coordinate the actions of the joints in these redundant manipulator systems. In the limited number of mission scenarios in which such telerobots might be commanded in a teleoperated mode by nearby Astronauts, it is unlikely that many of the manipulator configurations could be slaved to a "replica" master (a device whose geometry matches that of the slave which permits the human operator to directly and continuously control the individual joints in the slave manipulator). Obviously, in massively redundant manipulator systems and ones which assume non-anthropomorphic configurations, this would be entirely impractical. Instead,

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one can reasonably predict that the human operator will share the control of the dexterous manipulator with a computer, where, at most, the human essentially "flies the hands" of the manipulator system by specifying a 6 DOF goalpoint, while the local computer decides how to move the manipulator joints to execute this toolpoint trajectory. (In this mode, the human operator will also need the ability to control the position of the hand in some tool axes and the forces applied in the others.)

The local computer system which is charged with real-time, coordinated control of manipulator joints will decide how to employ the redundancy in the system based on sensory inputs about its internal condition and its environment, using a set of rules which seek to optimize the situation. The NASREM architecture, developed by Dr. James S. Albus, et al, at the U.S. National Institute of Standards and Technology (formerly National Bureau of Standards), has been adopted by NASA as its standard reference model for advanced telerobot control systems[32]. NASREM utilizes a hierarchical architecture in which each successively higher level has a broader purview with respect to space and time, and is equipped with sensory feedback, memory and logical functions appropriate to its level of responsibility. In this context, authority over how to use the kinematic redundancy in the manipulator will not reside within any single level of the control system, but will be affected by decisions made at all levels.

Robotics Research Corporation is principally concerned with those levels of the telerobot control system responsible for making "reflexive motion control" decisions based on local, kinesthetic sensors mounted on the manipulator. These might be viewed as "brainstem" functions, analogous to the autonomic or sympathetic divisions of the central nervous system in biological models. (They are encompassed by Levels 1, 2 and 3 in the NASREM model-- "Servo", "Primitive", and "Elemental Move".)

Investigators at Robotics Research believe that this reflexive motion control system will employ a hierarchy of competing rules, or objective functions, in making a balanced decision each clock cycle about how best to dispose manipulator redundancy. We propose that, in general, the robot should attempt to execute the commanded toolpoint trajectory,
1.   while avoiding collisions with itself, and
2.   while avoiding collisions with objects that are detected in the telerobot's working envelope, and
3.   while recognizing singularities intrinsic to its mechanical geometry and using them appropriately,
        a)   to produce energy-efficient, graceful motion, or
        b)   to increase leverage (mechanical advantage), or
        c)   to control "impedance" at the toolpoint, and
4.   while "favoring" any joints that are sensed to be closer to their thermal limits than others.

Obviously, a higher level in the hierarchical control system may elect to override or reprioritize these objectives based on its broader view of the situation.

Robotics Research Corporation introduced its first products in 1984-- the K-Series line of Dexterous Manipulators and the Type 1 Motion Controller, a motion control system based on the National Bureau of Standards hierarchical architecture and designed specifically to provide real time control of the company's kinematically-redundant arms. The 16-bit Type 1 Motion Controller, and the newer, 32-bit Type 2 model, employ proprietary algorithms which coordinate the joint motions of a redundant system using a set of weighted objective functions and which solve these equations in an extremely computationally-efficient manner[30,31]. Original algorithms accomplish 3a, above, i.e., they recognize singularities intrinsic to the manipulator's mechanical geometry and use them appropriately to produce efficient, graceful motion. Robotics Research has subsequently been developing new objective functions compatible with these algorithms.

The goal of the research described in this report was to implement objective function 2, above-- a means for real-time control of manipulator redundancy using arm-mounted proximity sensors to provide reflexive collision avoidance. While this effort aimed primarily at avoiding collisions with external objects detected in the workspace, in fact, it is clear that the principle devised applies equally well to function 1, above, i.e., detecting and avoiding collisions between different members of the manipulator itself.

2.0 TECHNICAL OBJECTIVES

The research effort described in this report had four specific objectives:

1.   To survey alternative proximity sensor technologies that could be used on dexterous manipulators to accomplish real-time, reflexive obstacle avoidance, with particular emphasis on sensor systems that could be employed in the space environment;

2.   To develop algorithms which translate arm-mounted proximity sensor data into appropriate penalty functions representing obstacles in the robot workspace;

3.   To modify Robotics Research Corporation's existing software to synthesize a set of motion commands which automatically cause a kinematically-redundant manipulator to avoid obstacles while accomplishing a prescribed end-effector path;

4.   To implement such a reflexive obstacle avoidance system which controls the redundant degree of freedom of an available Robotics Research K-2107HR 7-axis manipulator (Figure 2) and to demonstrate the ability of this system to execute prescribed toolpoint paths while automatically keeping the elbow clear of obstacles placed within its workplace.

3.0 SURVEY OF APPLICABLE PROXIMITY SENSOR TECHNOLOGY

3.1 Functional Requirements for Arm-Mounted Proximity Sensors

For the general problem of reflexive obstacle avoidance using arm-mounted sensors, a system is needed that effectively creates a "field" around the entire manipulator assembly capable of detecting the presence and measuring the coordinates of objects anywhere close to the surface of the unit (Figure 3).

We established the following specific guidelines in evaluating alternative sensor technologies:

1.   The system must have the ability to detect objects of a wide variety of physical sizes, geometries, materials, surface finishes and temperatures;

2.   Candidate sensor hardware must permit compact mounting on the manipulator in array configurations which, given the intrinsic beam geometry, provide full coverage (i.e., no blind spots);

3.   Candidate sensor hardware must be capable of reliably detecting and measuring the distance of objects normal to the manipulator surface at a minimum range of one inch to 12 inches with a minimum accuracy of +/-10% (a zero to 24 inch range is considered to be ideal for the obstacle avoidance application);

4.   The proximity sensor array covering the entire manipulator assembly should operate with an update rate of less than 20 milliseconds (50 Hz), including transmission delays and computation;

5.   Sensor-emitted energy must not cause injury to personnel or damage to equipment within or without its effective sensing range;

6.   The system should not have moving mechanical parts (e.g., no scanning mechanism should be used to generate a useful field of view).

Arrays of ultrasonic acoustic sensors might be devised which meet these qualifications for Earth use, as discussed in a subsequent section of this report. In space, candidate sensors obviously must employ some frequency in the electromagnetic spectrum, but a number of other requirements must also be considered:

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1. The sensor hardware must have the ability,
   a) to withstand the space environment (i.e., to tolerate high vacuum, ambient radiation, thermal extremes, and shock and vibration), and
   b) to function properly in that environment (i.e., not to be confused by solar radiation and EMI from other sources);

2. Sensor-emitted radiation must not interfere with other spacecraft systems;

3. The sensor system must consume little power;

4. Any "blanket" of proximity sensors must not adversely affect the manipulator's ability to reject waste heat to space.
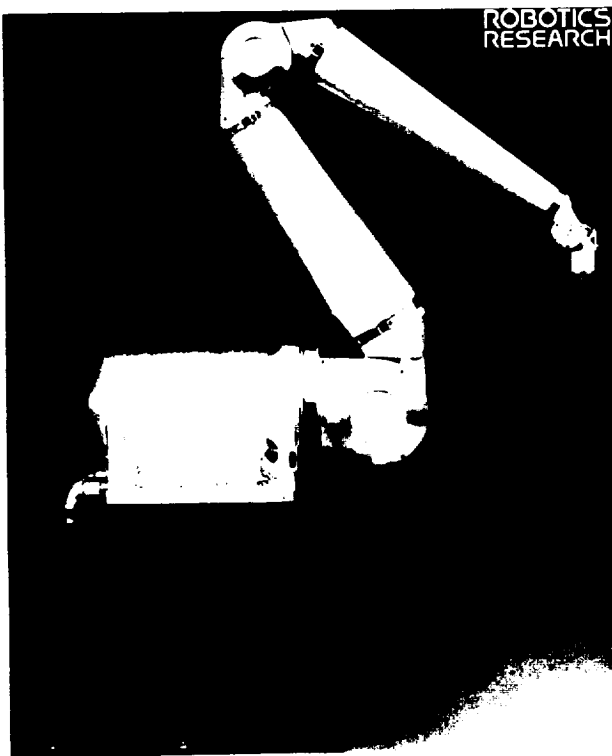
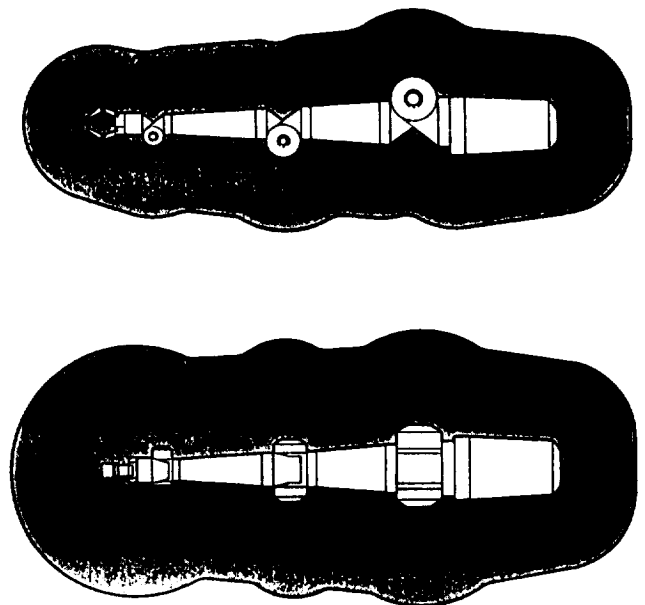Figure 2:
Robotics Research K-2107HR
7 DOF Manipulator Arm

Figure 3:
Idealized Proximity-Sensing "Field"
Surrounding Manipulator

3.2 Proximity Sensor Principles of Operation

In order to drive the reflexive obstacle avoidance algorithms, the sensor system must provide information that describes the location of the obstacle relative to the manipulator. Location can be reduced to components of bearing, azimuth and range. Means of deducing the bearing and azimuth are, as follows:

1. A dense blanket of simple transmitter/receivers, radially mounted, each dedicated to sensing a sector of bearing and azimuth (Figure 4);

2. A system of numerous emitters and one-dimensional sensor arrays, radially or laterally mounted, each

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equipped with an optical system which couples each sensor pixel to a particular sector of space (Figure 5);

3. A system of a few emitters and two-dimensional sensor arrays, radially or laterally mounted, each equipped with an optical system which couples every sensor pixel to a particular sector of space (Figures 6 and 7).

Independent of the means employed to determine bearing and azimuth, the sensors and emitters of illumination can utilize a variety of techniques to deduce range.

1. **Echo Intensity** Pulsed or continuous radiation is transmitted and the intensity of the return echo reflected from an object is measured. Since the intensity of the reflection for a point source diminishes at the inverse square of the distance, a range can be calculated. Due to variations in reflectivity of different targets (size, geometry, surface finish), echo intensity is not a reliable general-purpose ranging system.

2. **Time of Flight** The time delay between the transmission of a signal pulse and the return echo reflected from an object is measured. Distance is directly proportional to time delay.

3. **Amplitude Modulation** Continuous amplitude-modulated radiation is transmitted (its intensity is varied cyclically) and the phase shift of the return echo is compared with that of the emitted reference signal. Phase shift is a function of distance. The significant advantages of the phase shift approach are that the electronics required for continuous emission are relatively simple compared to pulse-type systems and it is a superior technique for use in measuring distance at very short ranges. A factor that must be taken into account with phase shift systems is the ambiguity which arises when signals are returned from a distance that exceeds one-half the speed of light divided by the modulation frequency. The intensity may be employed to resolve this problem by the use of an appropriate intensity threshold (below which the signal is disregarded) and the choice of a reasonably long ambiguity distance.

4. **Frequency Modulation** Continuous frequency-modulated radiation is transmitted (its frequency is varied cyclically) and the phase shift of the return echo is compared with that of the emitted reference signal. Phase shift is a function of distance. Ambiguity is again a factor.

5. **Triangulation** Bearing and azimuth information to the same object from different points of known location and separation can be used to determine range. If the angular information is discretized into sectors, the range information must be discretized as well.

3.3   Candidate Sensors for Space Applications

A number of available sensor technologies might serve the purpose in a reflexive obstacle avoidance system for space applications. The most promising band of wavelengths for the system ranges from the near-infrared (1100 nM) to the near-ultraviolet (200 nM). Silicon-based photosensitive devices, in particular, are suitable for this part of the spectrum. Gallium arsenide-based devices also could be employed and would be desirable if the telerobot were subjected to an intense radiation environment. However, gallium arsenide-based devices are expensive and offer fewer options for large scale integration with local signal conditioning, logic and multiplexing electronics.

This sensor system must be able to function reliably independent of the background radiation. Intense solar illumination, Earthlight and moonlight, reflections and emissions from nearby spacecraft, and the extreme contrast against the blackness of space make this a challenging problem. Photosensitive devices will almost certainly have to extract a usable return signal from background noise by employing controlled illumination. Two techniques, in the opinion of the investigators, offer the most potential: notch pass filtering of the detector, and amplitude modulation of the emitted lighting. Well-known techniques exist for
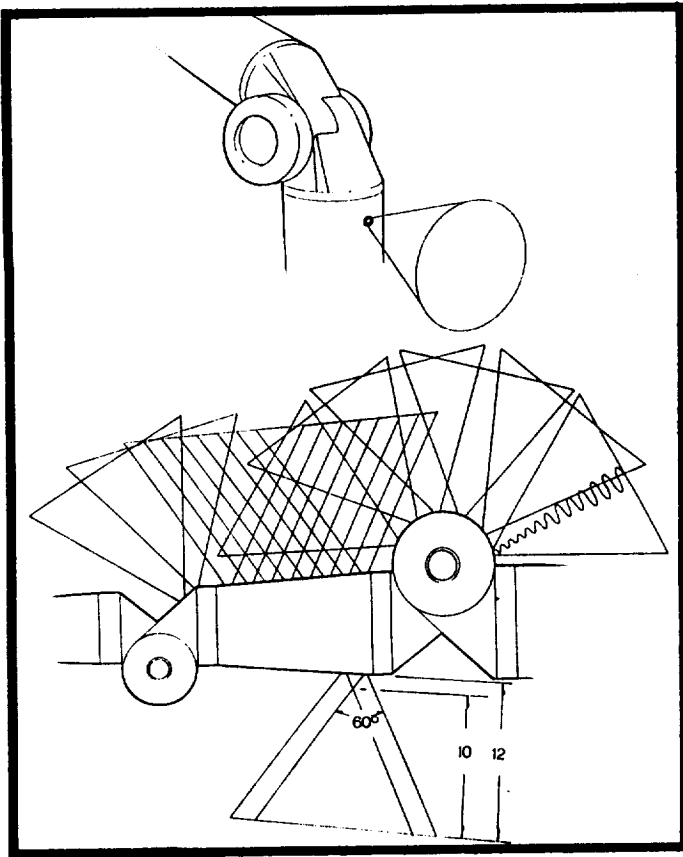
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Figure 4:
Blanket of Transmitter/Receivers
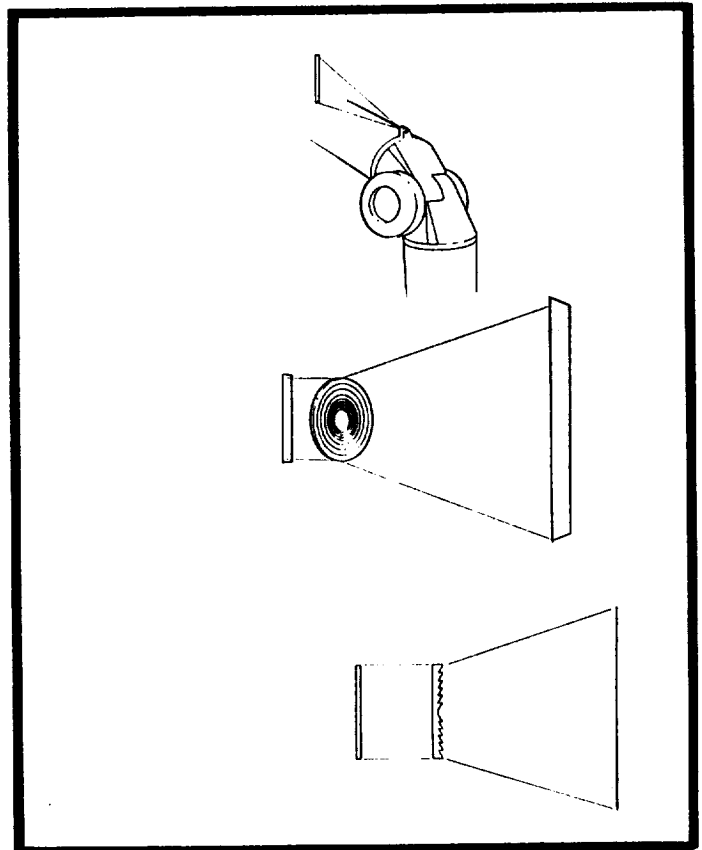Mounted Radially

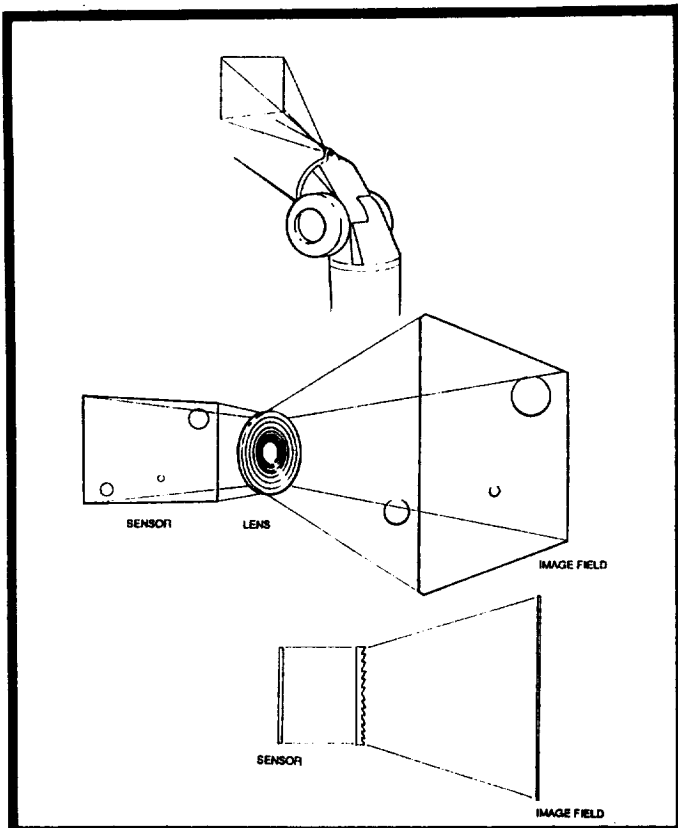Figure 5:
One-dimensional Sensor Array

Figure 6:
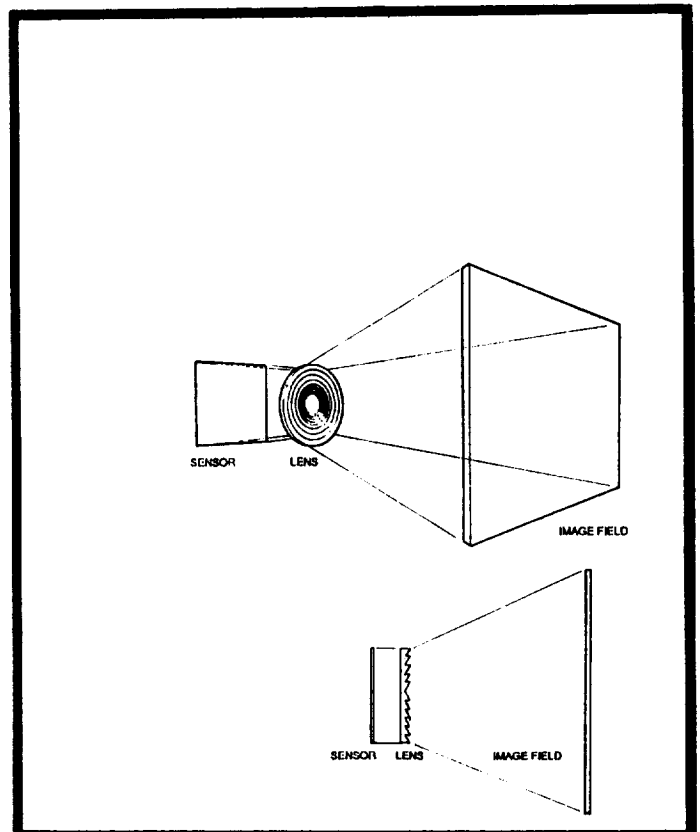Two-dimensional Sensor Array

Figure 7:
Fresnel Lens Implementation

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filtering the light incident on the detector to allow only a relatively narrow slice of the spectrum, centered on the wavelength of the emitted light, to fall on the detector. This is helpful in limiting the DC response and saturation of the detector when exposed to intense background noise. Likely devices for generating the light for illumination of the objects have very narrow emission spectra and can provide usable levels of illumination relative to the energy content of the incident light at that wavelength.

A second enabling technique for enhancing the general signal-to-noise ratio is amplitude-modulation of the emitted illumination, also a convenient method for determining range. (The frequency corresponding to a fifteen foot ambiguity of range is about 3.4×10^7 Hz.) The receiving electronics can be AC-coupled and responsive only to detected signals varying in amplitude at that frequency, providing complete rejection of ambient light signals. Range deduction is accomplished by phase comparison with the emitted illumination.

This general implementation of an arm-mounted proximity sensor system promises to satisfy the key functional requirements for a reflexive obstacle avoidance in space applications. Utilization of the amplitude-modulation technique definitely favors a sensor with fast response and low hysteresis. The significant changes in background lighting, even with filtering, favors a sensor with linearity over a wide dynamic range and relatively low internal gain. Since relatively low voltages are advantageous (consistent with highly integrated, semiconductor electronics), the sensor of choice becomes the silicon photodiode.

To obtain the best linearity and dynamic range, photovoltaic operation is preferred. Photovoltaic operation also minimizes the noise perceived from several sources. Given the need for high speed operation with an amplitude-modulated light source, the proposed implementation of the photodiode is in a photoconductive mode with a reverse bias applied to the photodiode. This system, with a transimpedance amplifier, provides high speed operation with a wide dynamic range. The reverse bias causes a significant reduction in the junction capacitance, the major impediment to high frequency response.

Silicon photodiodes are available in all of the physical arrangements previously discussed (single element sensors of various sizes, linear arrays of discrete photodiodes and rectangular discrete arrays). In addition, silicon photodiode technology can be used to make position sensors. This implementation can be used to determine both analog intensity of perceived light and analog position of the center of the spot of light on the sensor surface, with both one dimensional position on a linear element or both x and y positions on a square or rectangular element. These devices are most commonly employed in laser triangulation probes (refer to Figures 6 and 7). The relatively coarse measurement resolution required in this application favors the use of discrete element arrays, since they provide sufficient resolution (discrete photodiode elements are available as small as 0.004" on a side) and can be fabricated in a IC fashion with amplification, local logical processing and multiplexing components on a single chip.

Such a chip could be designed to report over any suitable network a message that an object has been detected in a particular direction (the chip/element address, corresponding to a particular sector in bearing and azimuth relative to a known point on the manipulator) and at a particular range, deduced locally by comparing the perceived amplitude modulation phase with the emitted light reference signal. This approach would permit the obstacle sensing systems to be placed on a flexible circuit board with a minimum number of electrical connections for power, communications and ground/common. (A higher speed communication system might also be implemented with sync lines or a parallel structure.) In this configuration, all of the high speed operations are resident on the individual chips.

The best candidates for providing amplitude-modulated illumination are solid state laser diodes and light emitting diodes. Both of these devices, closely related, are commonly utilized in fiber-optic communications systems operating at extremely high modulation frequencies. The effective detection of objects and safety of Astronaut vision are both enhanced by using relatively diffuse beams of illumination. Further investigation and design by those skilled in the art will be necessary to choose the intensity of illumination and detailed characteristics of the detectors, amplifiers and other elements of a practical sensor system of this type.

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3.4　Selection of Proximity Sensors for Experimental Purposes

Several commercial ultrasonic sensor systems were identified which operate over the range required for our laboratory use in algorithms development and demonstrations. After review, sensors and a multiplexing system were selected which operate in a 5"-to-36" range at 225 kHz with an accuracy of +/-0.004". The sensor head measures 1-5/16" long by 5/8" in diameter. The sensor produces an average beam angle over the range of approximately 18 degrees. The multiplexing electronics provide a sequential scanning mode operating at 12 mS per sensor, enabling us to mount a number of sensors close together as an array without interference. Eight multiplexed ultrasonic proximity sensors were mounted in a hemispherical array on either side of the elbow joint, scanning a large "conelike" region around the manipulator elbow (Figures 8 and 9). Each sensor responds to objects in the range of approximately 5" to 26" from the manipulator.

The selected array configuration has gaps in the sensing zone due to the rather narrow field of view of each sensor. An attempt was made to increase the field of view of these sensors by using a concave surface aligned to one side of the beam angle. Although this did increase the beam angle (at the expense of the sensing distance), the approach also had a significant adverse effect on the sensitivity and accuracy of the measurements. In experiments, these gaps ultimately proved to have no significant effect on performance.

4.0　CONTROL SYSTEM

## 4.1　Robotics Research Corporation Motion Control Algorithms

A 7 degree of freedom Robotics Research K-2107HR Dexterous Manipulator and Type 2 Motion Controller were utilized as a testbed for algorithm implementation (Figure 2). The Type 2 Motion Controller is an open-architecture, 32-bit multiprocessor position control system designed to coordinate the motion of a redundant manipulator. A set of weighted objective functions are used to determine the joint motion commands. Algorithms previously implemented by Robotics Research produce graceful, singularity-free motion by treating the redundant system as a spring-loaded mechanism which can deform elastically according to how the end effector is positioned.

Robotics Research's approach to obstacle avoidance employs a similar conceptual model, creating a repellant "force field" in which the manipulator senses obstacles as repellent forces that push on the springs to achieve equilibrium. The intensity of these forces varies with the distance of the object from the arm. The moments generated by these forces cause the system to employ its redundancy to escape the force field.

In the case of the K-2107 Dexterous Manipulator used as a testbed for this development program, we have a seven jointed linkage effectively pinned at both ends (fixed at the base and maintaining a commanded position at the tool tip) in which elbow attitude is the only variable (Figure 10). While maintaining a specified tool position and orientation, this "extra" degree of freedom can be used to revolve or "orbit" the elbow in a direction along the centerline of the elbow pitch joint (J4). This capability exists whether the toolpoint remains fixed during the orbit move or is in transit from one goalpoint to another.

It is important to note that a more highly redundant system, such as Robotics Research's new K/B-2017 Dexterous Manipulator, provides for considerably greater freedom of action in avoiding obstacles. The K/B-2017 is seen as prototypical of many future space servicing robots. It incorporates 17 degrees of freedom operating under coordinated computer control, with two 7 DOF arms mounted on a 3 DOF torso/waist. In this system, five independent "orbit" modes can be brought into play simultaneously, one for each elbow and three for the torso. This level of redundancy begins to approach "man-equivalent" versatility and maneuverability when performing complex tool-handling operations in crowded worksites without unintended collisions.
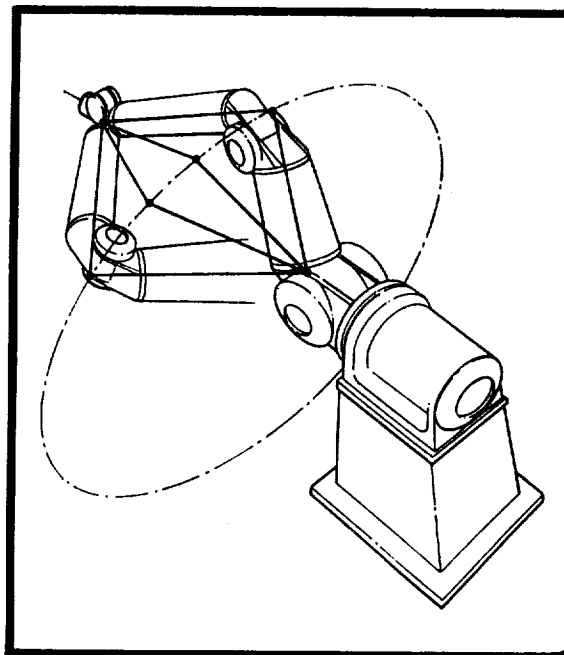
In our laboratory implementation of the proximity sensors system on a 7 degree of freedom arm, signals transmitted by each sensor in the elbow-mounted arrays to the control unit are processed to add vectorially

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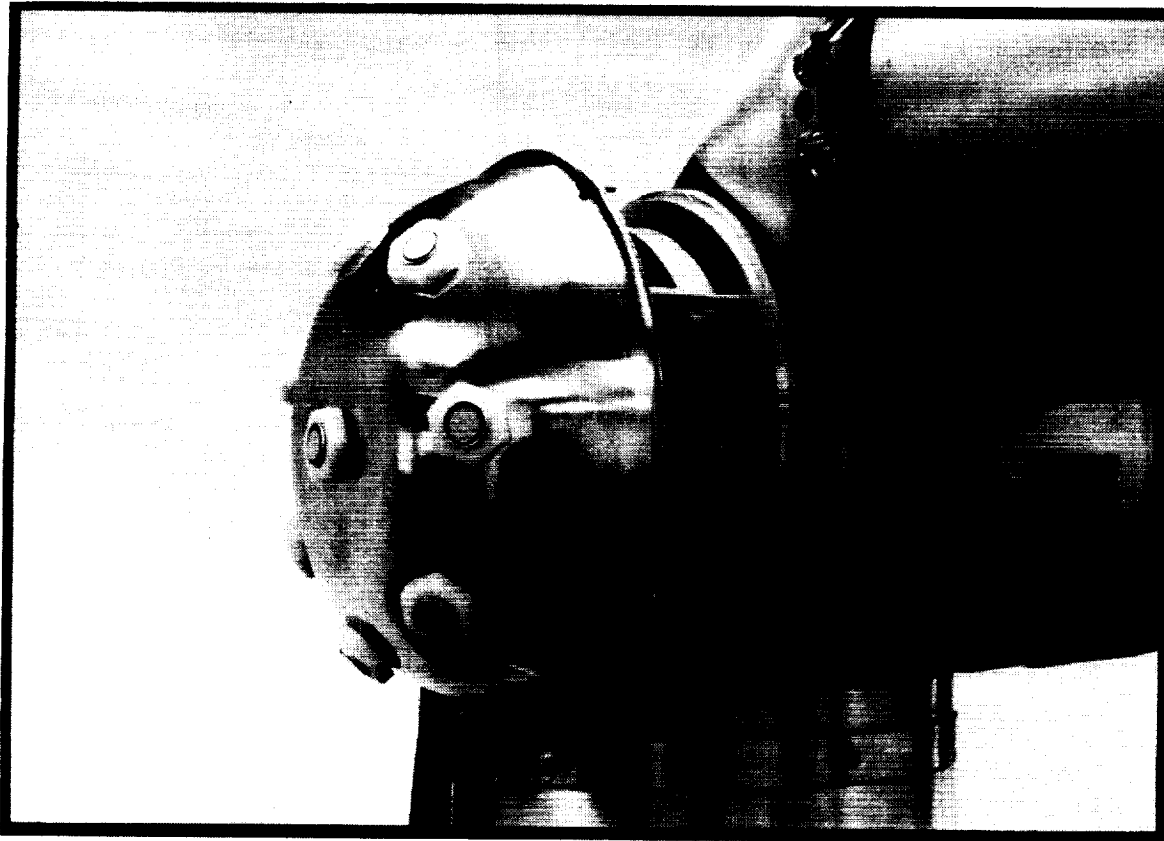
Figure 8:
Elbow-mounted Proximity Sensor Array
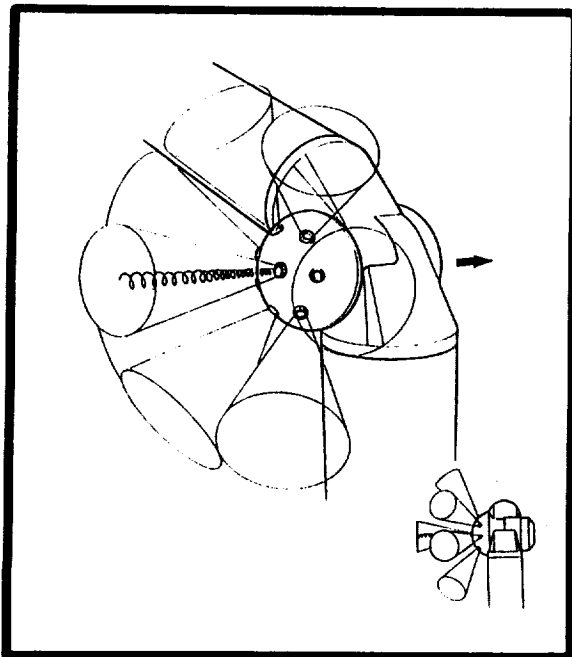
Figure 9:
Sensor Array Effective Geometry

Figure 10:
Elbow "Orbit" Move
with 7 DOF Arm

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the largest forces (as reflected by the closest objects) on either side of the manipulator and to apply the resultant force along the centerline of the elbow (J4). This scheme enables the arm to center itself between objects detected on either side of the elbow joint or on both sides simultaneously. In addition, the forcing function varies exponentially with distance, so that objects detected at close range cause a much more rapid movement of the arm away from an impending collision. This factor can be easily adjusted to increase or decrease the sensitivity of the arm to an object in its working space.

5.0   CONCLUSIONS

The concept of a reflexive, proximity sensor-based, real-time obstacle avoidance system is seen by Robotics Research as one of the key enabling technologies required to exploit fully the intrinsic advantages of redundancy. This NASA-sponsored research project has afforded us the opportunity to demonstrate that concept. The system we have developed, while experimental, works quite well and was implemented without any significant difficulties. Our general conclusions are, as follows:

1.   Technology appears to be available today to produce proximity sensor hardware for use in a space environment to support reflexive obstacle avoidance. The practicality of such a system will depend heavily on clever systems integration. It appears to us that a key requirement is the development of a small, rugged, highly integrated emitter-sensor package with local processing.

2.   Ultrasonic sensor systems are also available today that could be effective in this application for terrestrial/atmospheric use. Again, the practicality of such a system will depend upon careful systems integration.

3.   The placement and coverage of the sensor array used to update the control, in combination with the "spring constant" established for a perceived object, are judged to be the most important design variables affecting the behavior of the obstacle avoidance system.

4.   The mathematical approach employed by Robotics Research to translate proximity sensor inputs into additional redundant control criteria is extensible to massively redundant systems of any topology. The more redundant the system in question, the more valuable sensor-driven reflexive obstacle avoidance becomes.

5.   We believe this work establishes a theoretical basis for a practical reflexive obstacle avoidance system for future telerobots used both in space and in ground applications. In the case of complex space and nuclear servicing robots, it may, indeed, be impossible to perform the planned operations without some type of reflexive system. Also, real-time collision avoidance is a critical safety subsystem. We further anticipate that opportunities for the application of redundant robots in industrial factory-automation would also be substantially expanded if a reflexive obstacle avoidance system became commercially available. Off-line programming for redundant manipulators and associated workcell design time would be greatly reduced were an obstacle avoidance system to select arm pose dynamically, and without explicit programming or operator intervention.

6.0   REFERENCES

1.   Millard, D.L., "Animate Sensing for Industrial Automation Safety", Proceedings from ROBOTS 11, 17th International Symposium on Industrial Robots, pp. 9/23-9/43, April 26-30, 1987, Chicago, IL.
2.   Helmers, Carl, "Active Remote Sensing", SENSORS, July 1987, p.89.
3.   Graham, James H., Millard, D.L., "Toward Development of Inherently Safe Robots", Proceedings from ROBOTS 11, 17th International Symposium on Industrial Robots, pp. 9/11-9/21, April 26-30, 1987, Chicago, IL.
4.   Alpha Industries, Inc.,"Theory, Operation, and Application of Microwave Motion Sensing Modules", SENSORS, December 1987, pp.29-36.

5. Everett, H.R., "Noncontact Ranging Systems for Mobile Robots", SENSORS. April 1987, pp 9-19.

6. Stefanides, E.J., "Mini Motion-Detector Senses IR With Piezo Film 'Retina'", Design News, April 18, 1988, pp 88-91.

7. Biber, C., Ellin, S., Shenk, E., " The Polaroid Ultrasonic Ranging System", Porceeds 67th Convention of Audio Engineering Society, October 31, 1980, New York.

8. Irwin, C.T., Caughman, D.O., "Intelligent Robotic Integrated Ultrasonic System", Proceedings from ROBOTS 9, Volume 2, pp. 19/38-19/47, June 2-6, 1985, Detroit, Michigan.

9. Jorgensen, C., Hamel, W.,Weisbin, C., "Autonomous Robot Navigation", BYTE, January 1986, pp. 223-235.

10. Everett, H.R., "A Multielement Ultrasonic Ranging Array", Robotics Age, July 1985, pp 13-20.

11. Campbell, Dean, "Ultrasonic Noncontact Dimensional Measurement,SENSORS, July 1986, pp. 37-48.

12. Damm, Lennart, " A Three Dimensional Fiber Optical Proximity Sensor System", Proceedings from ROBOTS 11, 17th International Symposium on Industrial Robots, pp. 2/1-2/18, April 26-30, 1987, Chicago, IL.

13. Thiele, A.W., Gjellum, D.E., Rattner, R.H., Manouchehri, D.,"Sensor Systems Testbed for Telerobotic Navigation", Proceedings from the Workshop on Space Telerobotics, JPL Publication 87-13, Volume II, pp. 19-22, July 1, 1987.

14. Amerace Corp., "Ultrasonic Sensor Solves Wire Mesh Transparency Problems", SENSORS, July 1987, pp 34-37.

15. Squire, Patty L., "Piezoelectric PVDF Ultrasonic Transducers", SENSORS, July 1986, pp 12-16.

16. Johnson, R.F., "A Refresher in Position Sensing", SENSORS, September 1987, pp. 18-24.

17. Drumheller, M., "Mobile Robot Localization Using Sonar", IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. PAMI-9, No. 2, pp. 325-332, March 1987.

18. Moravec, H.P., Alberto, E., "High Resolution Maps from Wide Angle Sonar", 1985 IEEE, pp. 116-121.

19. Beckerman, M., Oblow, E.M., "Treatment of Systematic Errors in the Processing of Wide Angle Sonar Sensor Data for Robotic Navigation", ORNL/TM-10763, CESAR-88/07,April 1988.

20. Crowley, J.L., "Dynamic World Modeling for an Intelligent Mobile Robot Using a Rotating Ultra-Sonic Ranging Device", 1985 IEEE, pp.128-135.

21. Burks, B.L., deSaussure, G., Weisbin, C.R., Jones, J.P., Hamel, W.R., "Autonomous Navigation, Exploration, And Recognition Using the HERMIES-IIB Robot", IEEE EXPERT, Winter 1987, pp 18-27.

22. Marioli, D., Sardini, E., Taroni, A., "Shape Determination and Robot Arm Control Positioning by Means of Ultrasonics", Proceedings of the 7th International Conference on Robot Vision and Sensory Controls, pp. 171-182, February 2-4, 1988, Zurich, Switzerland.

23. Warnecke, H.J., Langen, A., "New Ultrasonic Sensors for Robotic Application Based on Beam Forming", Proceedings of the 7th International Conference on Robot Vision and Sensory Controls, pp. 149-160., February 2-4, 1988, Zurich, Switzerland.

24. Rock, D., Redus, J., Marr, L., Gohlke, M., Hartnett, D., "Falcon Eye Forward-Looking Infrared (FLIR) System", Proceedings of SPIE-International Society for Optical Engineering, Volume 782, pp. 38-45, May 19-21, 1987, Orlando, Florida.

25. Pellegrini, P.W., Golubovic, A., Ludington, C.E., "A Comparison of Iridium Silicide and Platinaum Silicide Photodiodes", Proceedings of SPIE-International Society for Optical Engineering, Volume 782, pp. 93-98, May 19-21, 1987, Orlando, Florida.

26. Mooney, J.M., Silverman, J., Weeks, M.M., "PtSi Internal Photoemission: Theory and Experiment", Proceedings for SPIE-International Society for Optical Engineering, Volume 782, pp. 99-107, May 19-21, 1987, Orlando, Florida.

27. Aguilera, R., "256x256 Hybrid Schottky Focal Plane Arrays", Proceedings of SPIE-International Society for Optical Engineering, Volume 782, pp. 108-113, May 19-21, 1987, Orlando, Florida.

28. Kosonocky, W.F., Hughes, G.W., "High Fill Factor Silicide Monolithic Arrays", Proceedings of SPIE-International Society for Optical Engineering, Volume 782, pp. 114-120, May 19-21, 1987, Orlando, Florida.

29. Murguia, J.E., Ewing, W.S., "Statistical Characterization of a Large PtSi Focal Plane Array",

Proceedings of SPIE-International Society for Optical Engineering, Volume 782, pp. 121-127, May 19-21, 1987, Orlando, Florida.

30. J. P. Karlen, J. M. Thompson, J. D. Farrell, "Design and Control of Modular, Kinematically Redundant Manipulators", Second AIAA / NASA / USAF Symposium on Automation, Robotics and Advanced Computing for the National Space Program, March 9-11, 1987, Arlington, VA (Robotics Research Corporation).

31. J. D. Farrell, "Pragmatic Control of Kinematically Redundant Manipulators", 1988 American Control Conference, July 15-17, 1988, Atlanta, GA (Robotics Research Corporation).

32. J. S. Albus, H. G. McCain, R. Lumia, "NASA / NBS Standard Reference Model for Telerobot Control System Architecture (NASREM)", National Bureau of Standards, Technical Note 1235, June, 1987.