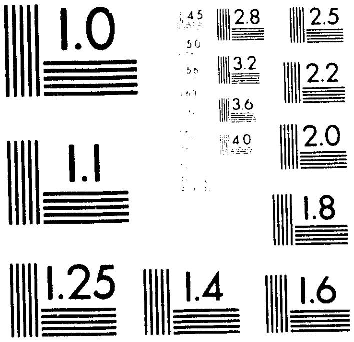
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Collision avoidance during teleoperation using whole arm proximity sensors coupled to a virtual environment

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ABSTRACT

This paper describes a collision avoidance system using Whole Arm Proximity (WHAP) sensors on an articulated robot arm. The capacitance-based sensors generate electric fields which completely encompass the robot arm and detect obstacles as they approach from any direction. The robot is moved through the workspace using a velocity command generated either by an operator through a force-sensing input device or a preprogrammed sequence of motions. The directional obstacle information gathered by the WHAP sensors is then used in a matrix column maximization algorithm that automatically selects the sensor closest to an obstacle during each robot controller cycle. The distance from this sensor to the obstacle is used to reduce the component of the command input velocity along the normal axis of the sensor, allowing graceful perturbation of the velocity command to prevent a collision.

By scaling only the component of the velocity vector in the direction of the nearest obstacle, the control system restricts motion in the direction of an obstacle while permitting unconstrained motion in other directions. The actual robot joint positions and the WHAP sensor readings are communicated to an operator interface consisting of a graphical model of the Puma robot and its environment. Circles are placed on the graphical robot surface at positions corresponding to the locations of the WHAP sensor. As the individual sensors detect obstacles, the associated circles change color, providing the operator with visual feedback as to the location and relative size of the obstacle. At the same time, the graphical robot position is updated to reflect the actual state of the robot. This information, coupled with the selective constraints imposed by the WHAP control system, permit the operator to plan alternative paths around unmodeled, but sensed, obstacles.

1. INTRODUCTION

Much of the current robotics effort at the US Department of Energy is directed toward remote handling of hazardous waste. Some of this waste threatens the environment, requiring that active steps be taken to remotely stabilize, detoxify, or repackage the material. Because of the hazards involved, telerobotic systems are being developed to remotely inspect, characterize, and process waste and the containers. Sophisticated systems are being developed to permit sensor mapping of the environment, building of world models, and graphical programming of the robot system[1].

An important tenet of this waste handling scheme is that the act of processing the waste must create no additional hazards and do no damage to the containment structure. Collision-free paths for robot manipulators are calculated using world models generated from sensor information. To provide the required degree of safety, however, it must be assumed that the information contained in these world models is inaccurate due to errors such as sensor noise or incorrect assumptions. This mandates the use of an independent collision avoidance system incorporating both sensors for detecting the approach of obstacles, and a control system that gracefully overrides commands which would result in collisions.

An excellent technique for preventing collisions, especially along the length of a robot link, involves the use of proximity sensors spaced over the robot surface. Cheung and Lumelsky[2] use a system of infrared emitters and detectors on flexible printed circuit boards. These sensors are directional and can provide information useful in mapping obstacles. However, large numbers of these devices would be required to completely protect the surface of a robot arm. A capacitive sensor, termed the Capaciflector, was developed at NASA for collision avoidance[3]. This sensor design uses active electrical guarding techniques to allow sensors to measure the capacitance between the sensor and electrical ground. Merritt Systems, Inc. has developed a multi-mode sensor architecture that combines infrared and ultrasonic sensors for collision avoidance[4]. In all these systems, information from the sensors is used in a variety of control and planning schemes to permit collision-free motion in the presence of obstacles. Additionally, since it is desirable to continue purposeful motion in the presence of obstacles, these sensor systems can deliver spatially-resolved proximity data that reflects the distance to the obstacle, as well as the location along the robot and corresponding robot surface normal. This vector information can then be used to modify trajectories to permit path replanning and (if possible) subsequent progress toward the final destination.

This paper expands upon previous work[5,6] with the Whole Arm Proximity (WHAP) sensor and collision avoidance system. First, the principle of operation and advantages of the Whole Arm Proximity (WHAP) sensors are discussed and compared with other types of sensors. Next is a description of a new control algorithm that is tailored for collision avoidance in teleoperated or preprogrammed motion. This control system automatically perturbs operator or preprogrammed robot commands to actively avoid collisions. A virtual environment has been developed to provide the operator with a graphical representation of the current state of the robot and the world model. This allows the operator to interact with the robot system in order to respond to unmodeled obstacles and replan robot paths.

2. CAPACITIVE PROXIMITY SENSORS

Capacitance-based proximity sensing for collision avoidance offers many advantages. The distribution of the electric field allows broad coverage of a robot without large numbers of sensors. Changes in the electric field due to obstacles are sensed instantaneously, unlike sound-based systems which require listening for a return echo. A capacitance measurement is also insensitive to the color, texture, and surface orientation of an approaching obstacle. Capacitive sensors are inherently simple, consisting of two conductive plates with minimal supporting electronics located near the sensing site. This greatly increases sensor reliability—an important consideration in hazardous environments with extremes of temperature, radiation, and corrosives.

Capacitance-based proximity sensors may be divided into two classes based on whether or not the obstacle forms one plate of capacitive sensor. The most common capacitive sensors consist of a single plate on the sensor itself and use the obstacle or a distant ground as the second capacitor plate. This configuration works well in environments in which obstacles are nearby and coupled to ground through relatively small impedances[3]. However, parasitic capacitances to ground are problematic and require the use of driven-guard shielding techniques which add to the complexity of the electronics located near the sensor as the number of sensors increases.

The Whole Arm Proximity (WHAP) sensor described in this paper measures a mutual capacitance between two conductors patterned on the sensor substrate itself[6]. The two electrodes can be designed with precisely defined geometries to generate a spatially-resolved fringing electric field. Conductive or dielectric obstacles disturb the electric field through a shielding effect and alter the measured mutual capacitance. Since the electric field between the two plates is well-defined by the conductor arrangement, it is possible to reconstruct the obstacle surface and range more accurately. Because this configuration does not measure displacement currents to electrical ground, stray capacitances to ground (such as between the sensor and a metal robot surface) do not affect the measurement. No active shielding is required, and this type of sensor is insensitive to the electrical potential of the obstacle.

3. WHAP SENSOR PRINCIPLE OF OPERATION

A schematic 2D model of the WHAP sensor is given in Figure 1. One electrode is driven by an oscillator, while the other is connected to an amplifier for sensing capacitor charge. For a fixed oscillator drive voltage, this charge output signal is proportional to the sensor capacitance. The sensor capacitance is altered by the presence of obstacles within the electric field. Under the assumption that the wavelength of the oscillator is much larger than the dimensions of the sensor, the analysis becomes an electrostatic problem containing two conductive electrodes and obstacles of unknown composition. Using this technique, both conductive and nonconductive obstacles may be sensed, although the sensor output depends on the composition, as well as the geometry of nonconductive obstacles.

The obstacle is assumed to be a conductive plate oriented parallel to the sensor. This assumption is reasonable for collision avoidance purposes if the WHAP sensor is smaller than the obstacle and the obstacle is relatively far away. This model with the three capacitances and one impedance of concern is given in Figure 1. The charge amplifier configuration of the WHAP circuitry (discussed later) senses changes only in C_{12}, so the problem consists of relating the obstacle geometry to this capacitance. In a previous paper[6], finite element analyses (FEA) have been used to calculate the variation of C_{12} with distance, d, for different sensor geometries. This FEA technique permits more general analysis of sensor response to nonconductive or poorly grounded obstacles, as well as obstacles of arbitrary shapes.

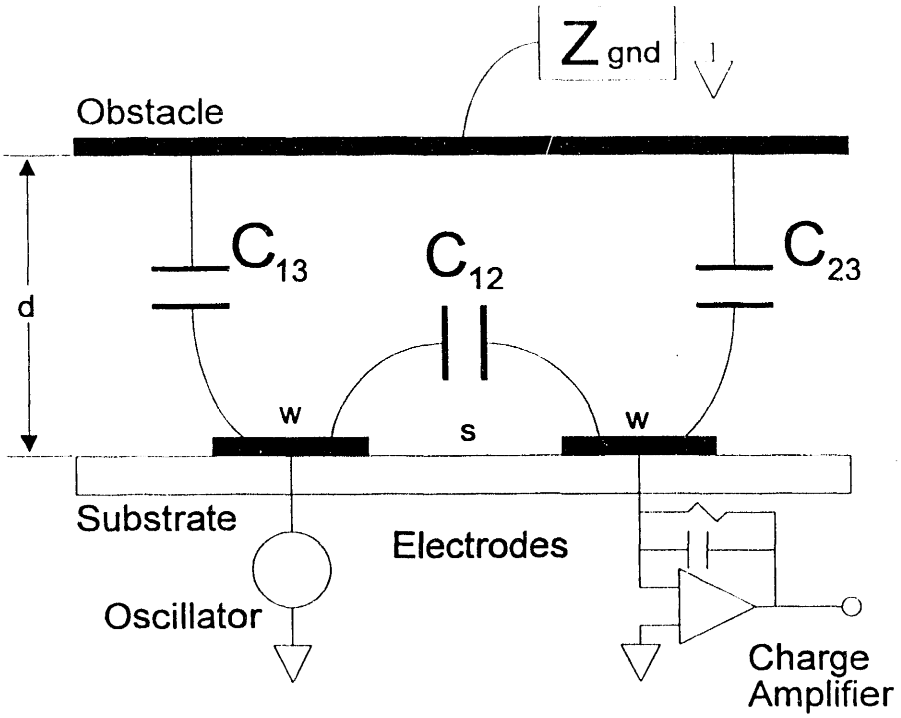

Figure 1. Schematic 2-D Model of the WHAP Sensor.

4. EXPERIMENTAL METHODS

The WHAP sensor "skin" for the PUMA was fabricated using a three layer printed circuit board. Each sensor consists of a 20 mm diameter disc surrounded by a 30 mm i.d. ring that is 4 mm wide. A total of 41 of these sensors has been mounted on the robot. Fourteen sensors are mounted on the third link, and 27 are mounted on the large planar region of the second link (Figure 2). The sensors were positioned to provide enough overlap of the sensing fields to provide redundant information. Center-to-center distances ranged from 50 to 120 mm, depending on the location on the robot arm.

The bottom layer of the sensor circuit board (nearest the robot) was used for power, drive signals, and the charge amplifier components, while the middle layer was grounded for isolation. The top layer was patterned to provide the disk and ring sensor configuration discussed above. The sensor receiving plates (right electrode in Figure 1) from two adjacent sensors were electrically connected to a single charge amplifier input. By driving the sensors at two different frequencies, the single charge amplifier output lead can be used for both sensors. This configuration can be extended to further reduce the number of signal lines by increasing the number of unique operating frequencies. Recent changes to the sensor design allow WHAP sensors to be fabricated using two-layer boards, significantly reducing complexity and cost.

An important feature of this configuration is that only the charge amplifier integrated circuits and associated passive components and connectors need to be on the sensor board (Figure 1). As mentioned earlier, no driven electrical guard electrode is necessary in this design since the charge amplifier configuration is insensitive to parasitic capacitances to ground. Synchronous detection circuitry was used to measure the amplitude of the corresponding frequency component in the charge amplifier output. These circuits provided an extremely low noise signal output by phase- and frequency-locking onto the input drive signal. Because of this, no shielding was required on the signal leads. Only the cables leading to the drive electrodes must be shielded to minimize stray coupling to the charge amplifier inputs. This electrical configuration significantly reduces the number of components that must be in a hazardous environment, facilitating the environmental and radiation hardening of the sensors. The use of unshielded cabling also significantly reduces the weight of the system.

Sensor noise levels of 2.5 mVrms were measured during motion of the robot. It is important to note that the analog signals are carried approximately 8 meters on unshielded ribbon cable immediately adjacent to the robot motors which generate large amounts of electromagnetic interference. The synchronous detection circuitry rejected most of the interference and allowed low noise measurements to be made. Other techniques, including rectification and oscillator frequency variation, were found to inadequately reject the interference. The dynamic range of the sensors was approximately 330 mm (13"), using a flat metal plate as the obstacle.

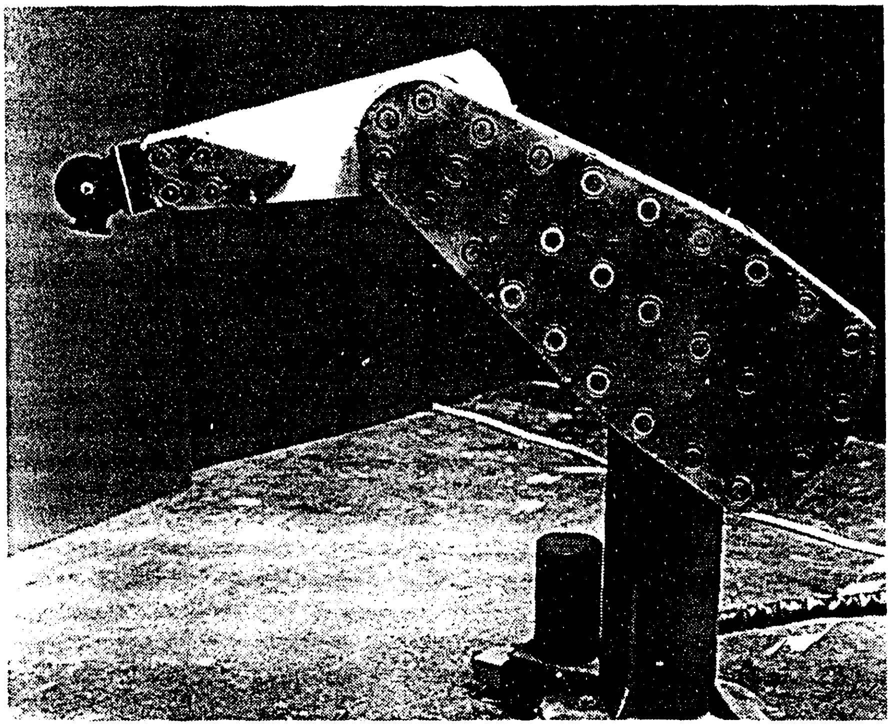

Figure 2. WHAP Sensor Skin on PUMA Robot. The WHAP sensors are visible as disks surrounded by light-colored rings.

5. APPLICATION TO A PUMA 560

Current laboratory experiments consider the use of WHAP sensor information to gracefully prevent collisions by perturbing commands provided by an operator through a six degree of freedom force input device, called the Force-Torque Ball (FTB). The control system for the teleoperated PUMA configuration is given in Figure 3. The operator gives velocity commands, $\dot{x}_d$ in the world coordinate frame. These commands are transformed into joint space to result in the desired velocity trajectory, $\dot{q}_d$. This command vector is scaled by the WHAP filter prior to being communicated to the robot controller as command velocity $\dot{q}_c$.

The WHAP filter reduces the desired velocity based upon the direction and magnitude of a joint perturbation vector, Δq. This perturbation vector is controlled by the perturbation calculated using a column space maximization technique. For m sensors on link n,

$$\Delta z = J_s J_q \Delta q = J \Delta q ,$$

where

Δz = m - dimensional vector of perturbations in the z direction of the sensor

J_s = $m \times 6$ constant matrix representing the differential transformation from sensors to the link coordinate frame

$J_q = 6 \times n$ matrix representing the differential transformation from link coordinate frame to the joint angles
$\Delta q = n$ - dimensional vector of robot joint perturbations.

The most conservative joint perturbation, corresponding to the closest obstacle, is chosen by using

$$\underset{j=1,\ldots,n}{\Delta q_j} = \underset{i=1,\ldots,m}{\max}\left[\frac{\Delta z_i}{J_{ij}}\right] \quad \text{for} \quad |J_{ij}| \geq J_{\min} \geq 0.$$

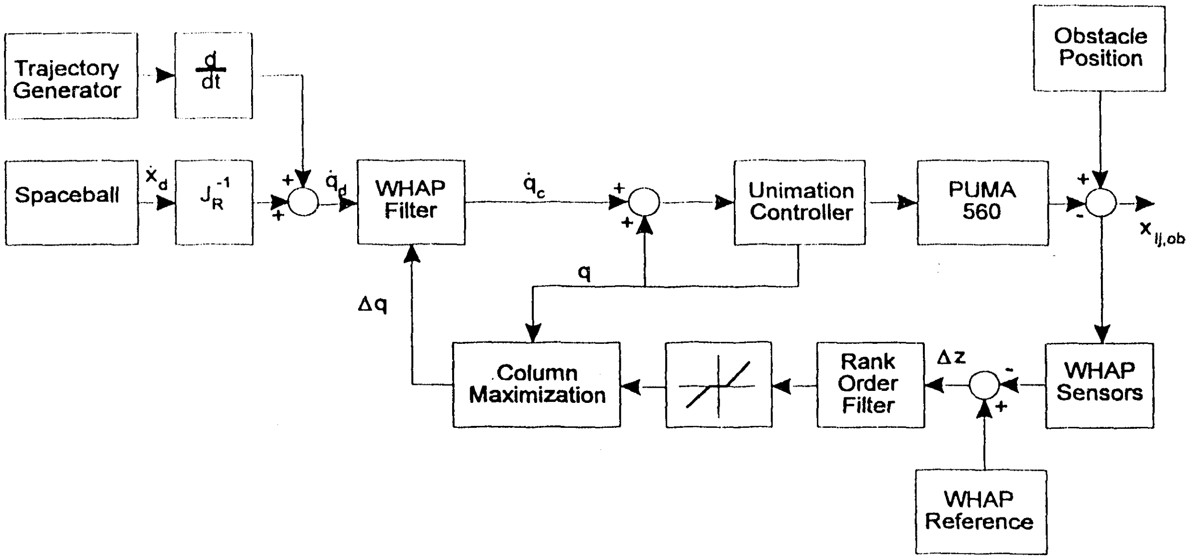

Figure 3. Control Structure for Obstacle Avoidance System.

This algorithm computes a linearized distance, in robot joint space, to a sensed obstacle along the z axis of each WHAP sensor. The column maximization operation makes the decision as to which sensor is providing the most important information during each controller cycle. Because the maximization algorithm is executed for each robot controller cycle, the "important" sensor can change smoothly as the arm is moved past an obstacle. This simple method of selecting a sensor works well because the overlapping electric fields of the WHAP sensors provide simultaneous sensing of an obstacle by a number of sensors. This seamless transition results in smooth motion past an obstacle, in spite of gross motion of the robot with respect to the obstacle.

The characteristics of the WHAP filter are shown in Figure 4. The filter operates on the velocity component, in robot joint space, which lies parallel to the z axis of the sensor determined in the column minimization procedure. It reduces the magnitude of the dot product of the velocity command and the "important" sensor normal vector based upon the estimated distance to the obstacle. The linear transition with two breakpoints was chosen for simplicity — other functions may be also be used. The breakpoints currently used in the system were chosen such that the WHAP filter begins to decrease at a distance of about 200 mm, and becomes zero (stopping all motion in the direction of the obstacle) at about 30 mm.

This system has been implemented on a real-time VME-bus based computing platform. The WHAP sensor data is updated every 10 ms by a set of boards that perform the synchronous detection and analog-to-digital conversion. A 68030 CPU board running VxWorks© reads the sensor data over the bus and performs the Jacobian transformations from sensor space to robot joint space and the column maximization. A second CPU board reads the FTB input through a serial port, translates the input from world space to robot joint space, and uses the WHAP perturbation from the first CPU board to scale the desired velocity command, $\dot{q}_d$, to produce the command velocity $\dot{q}_c$. The Puma controller is running a SLAVE program which communicates serially with the VME system and exchanges the desired and actual robot joint positions every 28 ms.

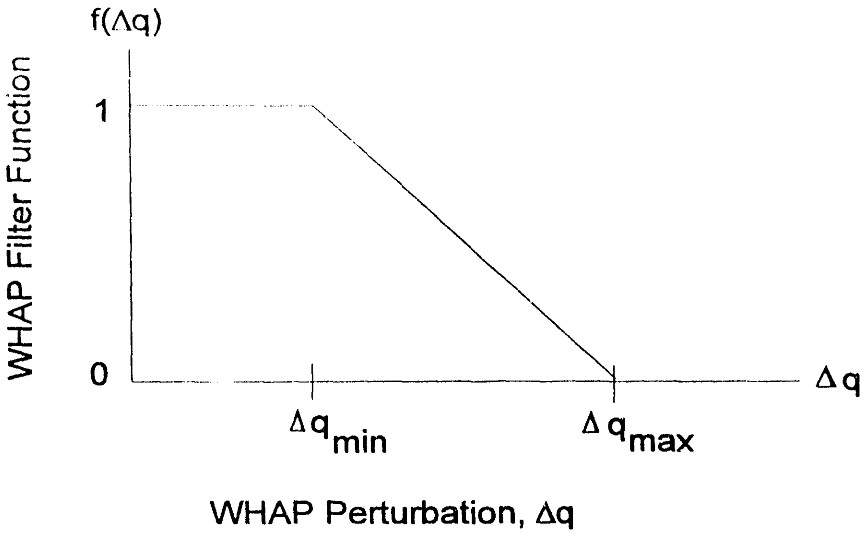

Figure 4. WHAP Filter Characteristic. The commanded robot velocity component along the direction of the 'important' sensor normal vector is scaled based upon the calculated joint perturbation, Δq.

6. VIRTUAL ENVIRONMENT

A virtual environment has been developed to enable the operator to interact with the robot system in an intuitive way. As the robot complexity and number of sensors in a robot system rise, it becomes increasingly important to communicate complex information to a human operator effectively. Through the virtual environment, the operator is provided visual feedback reflecting the actual motion of the robot and the state of the sensors. In the system described above, the WHAP sensors are used to automatically prevent robot collisions with unmodeled obstacles. However, unless the commanded trajectory is modified, the robot eventually stops and ceases to perform useful work. Through the virtual environment, the human operator views the WHAP sensor activation information in real-time, and is able to modify the robot motion to avoid unexpected obstacles.

The virtual environment consists of a 3-D graphical model of the kinematically correct robot and its environment, including modeled obstacles. Figure 5 shows the virtual environment with several sensors activated on the robot arm. The WHAP sensors are modeled as circles on the graphical robot. The size and location of the circles correspond to the respective position on the robot arm. The virtual environment model is generated using CimStation (Silma, Inc.) and is run on a Silicon Graphics workstation. The operator can be fully immersed in the virtual robot environment through the use of a 3-D stereo viewer. One of the advantages of full immersion in the virtual environment is that operator interactions are natural and intuitive. The view position of the operator is tracked by the Boom and the graphics are updated as the operator looks around and moves through the graphical model.

The communication between the virtual robot environment and the VME robot control platform uses a client/server protocol. During operation, the virtual model requests and receives real-time robot joint positions and WHAP sensor updates as the actual arm is moved via the FTB. The WHAP sensors on the graphical robot change color as the sensor readings indicate detection of an obstacle. While the VME robot control system keeps the arm from colliding with an obstacle by reducing the approach velocity to zero, the graphical display assists the operator in determining where the impending collision is occurring. The relative size and location of an obstacle can be determined by noting the number and location of the graphical sensors being activated. This feedback allows the operator to modify the trajectory to replan a path around the obstacle and continue performing the task.

DISCLAIMER

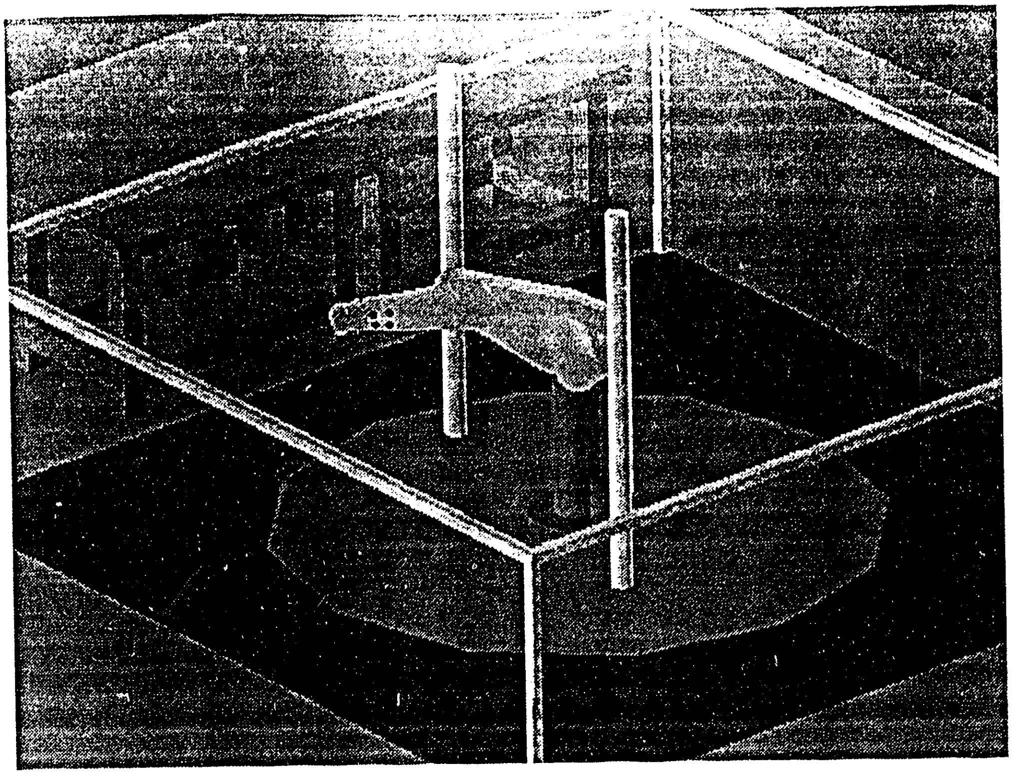

Figure 6. Graphical PUMA Robot and WHAP Sensors. On the color monitor, the WHAP sensors appear as circles on the surface of the graphical robot. Unactivated sensors are not visible in this figure. The robot has detected an unmodeled obstacle at the location of the four activated (dark) sensors.

7. SUMMARY

This paper presents a collision avoidance system using WHAP sensors on an articulated robot arm. The design of the sensor results in well defined electric fields that allow characterization of sensed obstacles. Appropriate placement of field based WHAP sensors can completely encompass a robot arm with a protective sensing field. The column maximization algorithm calculates the direction along which the closest obstacle is approaching. The system then reduces the component of the velocity command along this axis based upon the distance to the obstacle. Actual robot joint positions and WHAP sensor readings are communicated to a graphical operator interface, which consists of a graphical model of the PUMA robot and its environment running under CimStation on a Silicon Graphics workstation. Circles are placed at positions on the graphical robot surface corresponding to the locations of the WHAP sensor. The circles change color as the individual sensors detect obstacles, providing the operator with visual feedback as to the location and relative size of the obstacle. The graphical robot position is also updated in real time to reflect the actual configuration of the robot. This information permits the operator to monitor the approach of obstacles and plan alternative paths to continue a task.

8. ACKNOWLEDGMENTS

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