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VISION TECHNOLOGY/ALGORITHMS FOR SPACE ROBOTICS APPLICATIONS

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Abstract

The thrust of automation and robotics for space applications has been proposed for increased productivity, improved reliability, increased flexibility, higher safety, and for the performance of automating time-consuming tasks, increasing productivity/performance of crew-accomplished tasks, and performing tasks beyond the capability of the crew. This paper provides a review of efforts currently in progress at the NASA/Johnson Space Center and at Rice University in the area of robotic vision. Both systems and algorithms are discussed. The evolution of future vision/sensing is projected to include the fusion of multisensors ranging from microwave to optical with multimode capability to include position, attitude, recognition, and motion parameters. The key features of the overall system design will be small size and weight, fast signal processing, robust algorithms, and accurate parameter determination. These aspects of vision/sensing will also be discussed in this paper.

I. Introduction

The Space Station, a major goal of our spoace program over the next decade, has been planned as a multipurpose facility in which missions of long duration can be conducted and supported. These missions will include science and applications, observation, technology development and demonstration, commercial laboratories and production facilities, operational activities such as servicing/maintenance, repair of satellites, support of unmanned platforms, assembly of large space systems, and as a transportation node for transfer to other orbits and planetary missions. An important technology area foreseen to increase productivity and enhance astronaut safety is *automation and robotics* (A&R). The use of A&R for the Space Station can be viewed in two major areas: teleoperated/robotic systems for servicing, maintenance, repairs, and assembly; and computerized systems to reduce the manpower requirements of planning, monitoring, diagnosis, control, and fault recovery of systems/subsystems. In addition to increase in the productivity through autonomy, A&R will result in increased operational capability, and flexibility. Robotic operations for the Space Station will involve maintenance/repair of the entire structure including various subsystems, orbiter/satellite servicing, astronaut assistance, equipment transfer, docking and berthing, inspection, remote monitoring, rocket staging, telescience, and assembly of the Station and large structures. To aid the astronauts in various tasks and replace him/her from some activities, robots must perform beyond the current state of the art by responding to a high degree of environmental uncertainity and operational flexibility. In order to accommodate various performance goals in robots, design concepts have been proposed by many organizations [1,2,3,4,5,6]. One approach advanced by the NASA/Johnson Space Center (NASA/JSC) involves using the Shuttle Remote Manipulator System (RMS) for Space Station Assembly (Figure 1). The next step in the use of A&R would be the Space Station Mobile RMS (now known as Mobile Service Center (MSC)). With the MSC tasks such as the final Station assembly, Station/satellite maintenance and repair, and routine inspections could be accomplished. The Orbital Maneuvering Vehicle (OMV) could similarly be used for the retrieval and repair services. As a final step, robots could be made autonomous and free-flying for inspection, retrieval, and repair tasks. A simplified schematic which shows the functional elements of an automated system is presented in Figure 2. One of the key elements of the system is *sensing and perception*. Its primary function is to provide information regarding the position of the object in its environment relative to the system's effector. This function involves isolation, description, identification, location, and data transmission. In a broader context a class of object properties which include geometric, mechanical, material, optical, acoustic, electric, magnetic, radioactive, chemical, and weight may be needed. The type, volume, and precision/accuracy of the data needed will depend on the nature of the task to be accomplished.

As the robotics era dawns in space, vision will provide the key sensory data needed for multifaceted intelligent operations. In general the 3D scene/object description along with location, orientation, and motion parameters will be needed. Sensor complements may include both active and passive microwave and optical with multifunction capability. The fusion of the information from these sensors, to provide accurate parameters for robots, provides by far the greatest challenge in vision. Furthermore, the compression, storage, and transmission of the information associated with multisensor capability require novel algorithms and hardware for efficient operation.

In this paper, the vision data requirements are discussed from the standpoint of various applications. A review of the advanced systems technology for space applications is provided. The progress in the area of algorithm development fo parameter estimation is summarized. Future concepts in bo sensor and algorithm development are elaborated.

II. Vision Requirements

The vision requirements for space robotics are characterized by environmental factors and tasks that the robot has to perform. The natural space environment consists of intense light and dark periods. At a nominal Space Station altitude of 270 nmi, the sunlight intensity will fluctuate between about sixty minutes of extreme brightness (13,000 footcandles) and thirty minutes of nearly darkness [7]. Furthermore, due to the absence of atmosphere, light is not diffused/scattered. Consequently, the unenhanced images have large contrast with intensity changes of the order of 10. The intense specular reflections combined with camera performance can cause bloom and Fraunhofer/Airy rings resulting in scene obscurity. Further complexity results from other objects, such as stars, moon, sun, Earth, and other satellites in the field of view(FOV). Object reflectivity can also pose problems for the vision systems. Most space systems are painted white or finished with smooth, specular materials to provide highly reflective materials. The ubiquity of white surfaces intensifies the problem of relying on photometric data for object identification/discrimination. A secondary source of concern affecting vision is the absence of gravity. For free flying and tethered objects there would be an increased number of positions and orientations in which the objects may improve due to the lack of disturbances caused by aerodynamic and gravitational forces.

Many tasks have been proposed for robotic operations in the Space Station era. The most significant tasks include assembly of space structures, maintenance and repair, inspection, and aid/retrieving of astronauts during Extra-Vehicular Activity (EVA). Assembly can include mating structures, bolting, locking, and forming joints in the structure itself. For the Space Station assembly initially the Shuttle Remote Manipulator System (RMS) controlled by astronauts in the cabin or EVA can be used. This can be followed in the later stages of assembly by the Space Station Mobile Service Center (MSC). As time proceeds, the assembly processes could involve Orbital Maneuvering Vehicle (OMV) or a free flying robot with robotic arms and various sensors for vision (Figure 3).

In the case of Space Station the maintenance and repair tasks can include structural damage, failure of systems and components, cleaning and storage of space debris, and environmental effects on the spacecraft. Inspection is the first significant part of the maintenance and repair activity. The inspection can include low velocity encounters with solar array, thermal radiator, hulls, windows, TV cameras, heaters, fluid containers, aging composite materials, printers, recorders, and door mechanisms. The unpredictable nature of maintenance and repair tasks creates a problem in the development of the capability/design of space robots. The vision capabilities must be adaptive/versatile to accommodate these uncertainties. A detailed comparison of data using computer stored scenes/identification parameters with data from distorted/damaged systems, structures, or components yields the failure or absence of the parts. Another crucial application of the space robot is the retrieving or aiding of EVA or Man Maneuvering Unit (MMU) seated astronaut. This task can be thought of as a special one belonging to a class of retriever and repair of spacecraft/orbiting objects. The robots/manipulators (such as RMS, MSC) can be operated by humans using teleoperation. The commands and other vital data are transmitted using communications systems. In more advanced concepts, the humans act as supervisors, setting schedules, tasks, and evaluating the performance of the robots. When this interaction is neglegible, the robot can act autonomously.

For a direct control teleoperator systems, the primary function of robotic vision is to provide information about the position of the object relative to the system's effector. In a direct controlled teleoperator system, some subfunctions may be allocated to the humans. In particular, the object identification can be delegated to humans. In a goal-directed teleoperator system, reliability and flexibility has to be incorporated so as to allow it to search, identify, and locate parts based on existing data base. In the absence of the vision system the required object identification and position data has to be entered manually. In general, for the autonomous robotic systems, three levels of information are needed. These levels pertain to the scene/world in which the objects are located, the objects themselves, and the specific parts of the objects. In most tasks an envelope of paramenters can be preprogrammed into the system. For example, in docking and berthing applications the robotic vision/sensing may be needed within a cone of thirty degrees to a distance of fifty meters. Beyond this spatial zone, a radar system may be used for tracking/monitoring the object motion.

The levels of information depend on the application involved. As an example in the satellite servicing area, the vision/sensing system may have to provide the necessary information to guide a robot/astrobot to a particular area, say an antenna feed. The satellite could be rotating and translating simultaneously. Furthermore, the antenna could be gimbaling with a certain motion. In this scenerio, the data would not only include a 3D dynamic description of the target/object but also its position and rotational parameters with respect to the satellite. To accomplish this, algorithms are needed for the parameter estimation. The vision/sensing instrumentation in this case would not only involve fixed field of view video systems, but laser/millimeter wave radars which could be slaved to the antenna feed motion. Doppler signal processing at microwave or optical frequencies can be used to sense moving parts within a scene. The implication on the vision/sensing systems is clear, several sensors are needed to complete the basic information needed for an autonomous robot. Clearly, for space applications the size, speed, and weight parameters are of paramount importance. Autonomous robot performance depends crucially on the vision capabilities. In certain operations, humans can be surpassed by robots due to memory and vision. Robotic vision can allow more precise measurements and faster response during time-critical situations. Other limitations of humans include fatigue, a limited spectrum, and inaccurate color and grey scale resolution. Robotic vision provides an opportunity to utilize active and passive sensors in microwave, and optical/infrared bands. Furthermore, polarization and lookangles can be optimized to accurately measure scene parameters of interest. The vision extension to shadowed and occuluded regions is important in many applications. The illumination intensity variations along with shadows can be used to determine the relative motion between the camera and the object. Structured multispectral illumination can be used to derive the 3-D description of the target. Mathematical models coupled with real-time imagery/data can be used to derive the motion and shape parameters. Associated with the sensory data is the need for computer architectures which provide high-speed processing, parallel computations/algorithms, associative memories, and intelligence. The transfer and reduction of the sensor data requires an efficient communications subsystem [8].

Moving objects in space need to be recognized and defined in terms of their position, orientation, and velocities for proximity operations. Soft docking is an important operation for many robotic activities. A detailed analysis of docking for robotic manipulations shows many benefits can be entailed with accurate tracking sensor data. The perturbations of the target/object position and attitude can be minimized by using accurate measurements of distance/range and velocity. The relative velocity and maximum shuttle RMS tip force for the docking of Shuttle to Space Station were analyzed by Mission Planning and Analysis Division of NASA/Johnson Space Center (JSC). The capture stopping distances and the relative velocities for various forces are shown in Figure 4. With the knowledge of very accurate relative velocity (0.1 ft/sec) the perturbation force can be minimized at a particular stopping distance. The same result holds for a robot docking with a satellite, etc. Based on these considerations a laser docking sensor is now under development at JSC to provide performance goals as stated in Table 1. This is an illustrative example of the type of vision data needed in addition to the imagery. The overall scope of the vision data needed for the proposed JSC EVA Retriever project is depicted in Figure 5. A multi-sensor vision system has been proposed for this application. To achieve independence of the sunlight and to enhance accuracy, a multiple structured illumination source with controllable intensity, wavelength, polarization, field of view, and angles of incidence can be incorporated to alleviate limitations in vision systems being proposed by many organizations [9,10,11]. In the development of the space vision systems cost effectiveness, speed, small size, lightweight, high reliability and flexibility, and ease of operation must be considered.

III. Vision System Concepts/Technology

The initial use of vision for the Space Station could be to provide feedback to the human operator of the robotic structure. In the initial vision systems, NASA anticipates the use of stereo televisions for label/feature based object recognition [12]. Color and 3-dimensional imagery will be important to both telepresence and robotic vision. NASA's television program from Apollo through the Space Shuttle programs has been one of high crew and ground participation and control. Several limitations of these earlier video systems have already surfaced. One notable one was during the Solar Max Satellite repair when the shadowed surface could not be approached, and the grappling of the Solar Max was severally restricted because of limitations with the manual camera light level controls. For robotic application, several features must be added to the presently available space television system. Specifically, predictive auto focusing, programmable predictive scene control with auto zoom, gamma, and iris, automated or voice controlled pan, tilt, pointing, and scene tracking capability. Illumination affects the scene definition and is, therefore, critical to the robot's performance. The lighting technique should involve a combination of artificial lights and natural sources (Figure 6). The parameters/performance for the artificial light should include programmable wavelength, polarization, intensity, and angle of incidence, as well as the number and positioning of these light sources. The natural incident light from sun, moon, Earth, and stars should be characterized in terms of both color and intensity on the surface of the scene/object which is being viewed. For Space Station, a light intensity of 100-foot candles at the working surface is considered desirable [7]. For limiting glare, polarized filters can be used for both lights and cameras. The modes of lighting can include strobe lighting to eliminate motion blurring, infrared/ultraviolet illumination to reduce glare, and structured lighting to achieve 3-dimensional robotic vision [7].

Articulation mechanisms for cameras and lighting should incorporate flexibility. These mechanisms would form a significant part of the closed-loop control for endeffector tracking, stereo camera adjustments, and autonomous operations. In the case of stereovision, the focal length, intercamera distance, and inter-camera angle must be automatically adjusted to provide optional stereo acuity. In the case of moving objects/scenes, the vision articulation should provide the feedback to determine the trajectory to a particular point on the object/scene.

Several technology innovations are envisioned for making television's multi-features highly reliable [13]. Solid-state cameras, based on charged coupled device (CCD) or charge injection device (CID) technology with variable spatial resolution, with panels in the order of 1024×1024, can feature automatic zoom and ability to detect objects as small as 2 millimeters at a distance of 1 meter. Furthermore, the density of the sensing elements can be patterned after the eye with high resolution in the middle and low resolution in the peripheral vision. Brightness filters, automatic iris, and automatic gain control can be incorporated to allow handling of high intensity sunlight. Intensities of sun can range up to 13,000-foot candles necessitating bloom protection, large dynamic range, and protection from burn-in [7]. Similarly, sensitive night/dark vision modules with nonblooming characteristics are needed. In particular, very high quality and resolution imagery is needed to meet robotic vision requirements. In certain applications, large format cameras capable of precise image mensuration at the pixel level may be required. In some applications, design features favorable to telerobotic vision applications may be incorporated to identify and determine aspect/attitude of various objects. Object shapes, color, and markings are some of the parameters useful for this purpose. Color vision offers an additional capability for the recognition of objects. The levels/shades of colors used in robotic vision can be substantially higher than can be distinguished by the human eye. Its immediate effect on the design of the video system is added complexity, data processing, and resultant cost. Furthermore, the rate of data transmission increases significantly. Infrared cameras may be extremely beneficial in the location of objects in the dark and occluded areas. Although inherently low resolution, infrared imagery can provide gross identification of the objects.

The accuracy of television-based measurements is adversely affected by the presence of the earth, sun, moon, and/or stars directly in the field of view (FOV) of the camera system. CID video implementations can allow reduction of image blooming and removal of the limited area in the FOV corresponding to the sun, moon, and/or stars. In the case of the extended background provided by Earth, selection of appropriate operating optical wavelength for the video system can reduce or eliminate this backgrouund radiation. A wavelength of 0.94 m provides an attenuation of 21.6 dB due to water absorption in the earth's atmosphere [14]. Video systems have been developed at JSC in this band for future use in space robotic applications [13].

Automation in TV operations can be incorporated by processing the imagery to determine parameters which are needed in the feeback loop. One such parameter is a particular object in the scene to be tracked as it moves. Recognition of the object, along with position of its centroid as a function time, are needed to point the TV to this object. Accurate algorithms for such parameter estimation in presence of rotation/motion and multi-object environment are presently under development at many institutions. A complementary and independent automation feature in space TV operation can use voice control. Such an implementation has been developed at JSC [15,13]. This voice control system (VCS) allows hands-off control of TV functions including: (1) monitor selection, (2) camera selection, and (3) pan, tilt, focus, iris, zoom, and scene track. Future use of voice has been projected to include the EVA astronaut. In this application, the astronaut can ask for Heads Up Display (HUD) of vital data from the Shuttle computers. The data can include system parameters, orbital parameters/location, system status, and particular subsystem data. The technology innovations for future VCS include speaker independence/user-trained, very large vocabulary, and isolated and continuous speech recognition.

The need for video data to be able to interface with digital processors/computers has given impetus to digital TV technology. For the solid state implementations using VLSI/VHSIC, recognition/prepro- cessing algorithms can be implemented on the same electronics chips making the size of these video imagers small. As this technology is rapidly moving forward, the need for handling and transmission of high data rates is becoming obvious. For a video system at 5 MHz baseband, an 8-bit digitization would generate 80 MBPS data stream. For color TV implementations and multiple systems, this bit rate can multiply significantly. For real-time processing of this data, compression techniques have been proposed which can also be implemented by innovative chip designs. The compression algorithms should be automatic and transparent to users, not destroy or discard any relevant information, and compress/ decompress data at speeds significantly higher than the associated device data transfer speeds.

Fourier optical processing offers a method of high speed parallel processing of data needed to support automation and robotics applications (Figure 7). The inherently parallel nature of optical processing, coupled with the easy and natural optical Fourier transform and the programmable masks, can obviate numerical processing for many applications. The masks are used to modulate the optical Fourier transform of the input scene. An optical retransform then allows direct detection of, say, the mathematical correlation between the viewed scene/data and the reference image/data. This scheme allows correlation or convolution computations in a rapid manner; the speed essentially controlled by the recalling of computer-memorized data and transfer of the input scene to the programmable masks. Texas Instruments, under NASA/JSC sponsorship, has fabricated an early prototype of this processor. Many improvements in the performance of these processors are envisioned for operational use. Designs are needed for Deformable Mirror Device (DMD) high spatial resolution, accuracy, and reduction of nonlinear effects caused by diffraction/scattering. The phase-only nature of these processors results in loss of correlation due to rotation and translation of the object/scene. Work is in progress at JSC to incorporate rotation-invariant filtering (directional filtering) for compensating the phase-only correlation effects.

Another rotation-invariant methodology is the use of a transformation such as the logarithmic spiral grid for picture digitization to make it to correspond to the human eye [16,17]. This spatial mapping from a high resolution imager to the input modulator in the correlator results in insensitivity to scale and rotation of a viewed object. Changes in scale and rotation of the input image become displacements in the correlation plane (Figure 8). Continued development of various mappings will result in the design of VLSI cameras whose receptor patterns are best suited to drive a subsequent optical correlator.

Another processing technology can be based on neural networks. Neural networks are patterned after the human neurons in the brain and can be termed as the learning networks. Hardware implementations of neurocomputers has already made it to commercial markets. For example, the TRW Mark III has 8100 processing elements and 417,000 interconnections. As a coprocessor to the VAX computer, it speeds operations by a hundred times. Analog electronic neurons have been assembled and connected for the analysis and recognition of acoustical patterns, including speech [18]. To recognize speech/sounds at the phoneme or diphone level, the set of primitives belonging to the phoneme is decoded such that only a neuron or nonoverlapping group of neurons fire when the sound pattern is present at the input. The output from these neurons is fed into a decoder and computer which then displays the phonetic representation of the input speech. Similarly, neural network architectures/algorithms have been proposed to provide anthromorphic framework for analysis and synthesis of learning networks for correlation, identification, and tracking applications [19]. The current technology allows 100-million processing elements along with 100-million interconnects. By late 1990's one billion neuron networks, with 10 billion interconnects, can be projected as technology in this area advances rapidly. Increases of the number of neurons on a single chip are projected to ten thousand. These analog neuro-network processors can then be directly used for video/scene recognition and mensuration. Images of space scenes/objects in certain aspects can be memorized on the neural networks. Based on this data, new aspect object views of the incoming data can be recognized using interpolation and extrapolation techniques.

For 3-D vision, range information to each pixel can be added to the video imagery. Laser scanning devices capable of giving angles/position and ranges to each pixel within the field of view provide the depth/height profile of the object. Included in these measurements can be the laser reflectance of the pixel. Two technologies of the solid-state laser vision devices currently available are those using mechanical motion of mirrored surfaces, and those that involve an inertialess change in the optical properties of the transparent medium. The latter class includes diffraction of light from an acoustically generated periodic structure. Phased-arrary solid-state scanning devices are also currently under development. These devices have the promise of providing fast, accurate, and lightweight laser vision. Another application of the laser range data can be in the automatic zoom/focus of video systems. The laser vision measurements are dependent on the intensity of reflected radiation. If coherent radiation is used in order to generate an image of the object information from the amplitudes, as well as the phases of the scattered radiation, a 3-D reconstruction of the object can be made. Such devices are known as holographic devices. The source of coherent radiation can be a solid-state laser that can, in principle, provide a resolution of the order of about 1 m. Part of the radiated beam is deflected toward the detector (Figure 9), where it interferes with the backscattered light from the object. The hologram can then be generated using known reproduction processes, or a 3-dimensional description of the object such as a Fast Fourier Transform (FFT). Several applications of holographic scanners have been discussed by Sincerbox [20]. Some of these are directly applicable to space robotics systems.

Microwave systems have been used to detect relative speed of objects and their range in many applications. Their use in space robotics applications is being studied at NASA/JSC. In particular, millimeter wave radars provide attractive performance parameters in addition to their small size. The possiblity of broader beam than laser systems makes these sensors attractive for initial acquisition of moving objects. A radar at the frequency of 100 GHz has been developed at NASA/JSC [21]. This particular system is for use on a Man Maneuverable Unit (MMU) to provide relative range and velocity to the object. The radar is designed to operate over the range of speeds from 0.1 to 2.0 fps. This type of radar operating at several carrier frequencies can be used to measure backscattering coefficients for various polarization combinations. These coefficients are object structure dependent. There is also the possibility of penetration through thermal protection and obscuration caused by nonmetallic objects. This data can be utilized in an interactive manner with that of the video systems to provide scene definition/parameters in certain situations/scenerios.

Another promising microwave technique is the time-domain imaging, the synthesis of the scattered electromagnetic field distribution over an object plane. The transmitted pulse is an impulse source offering higher instantaneous signal-to-noise ratio, higher resolution, and option for echo time gating. Technology advances in the fast pulse generators and sampling devices allow the fabrication of time-domain imagers in picosecond region with measurements and recording of both phase and amplitude of the returned/transmitted signal. The scattered signal can be formulated as the convolution of the source with the transmitter, receiver, and scatterer responses [22]. From a set of time-domain responses obtained from different viewing directions, the two-dimensional field distribution is synthesized using a technique similar to the one in tomography [23]. The resultant image closely resembles the object geometry [22]. Thus, time-domain impulse imaging is another tool in extracting physical information about the object.

Space telerobotic and autonomous robotic operations have to be monitored and controlled remotely without the availability of hardline power and data services. The robots/end effectors must reach small, crowded, or restricted space. The communications system on the robot has to be able to transmit multiple channels of high-quality video and high rate data from other sensors. In most implementations, it should be able to receive high-rate data from the control and monitoring station. The coverage for the robot/end effector should be spherical without blockage/interference from the system. Furthermore, the time delays through processors, prime power, size, and weight should be minimized. In view of these desired performance goals, higher wavelengths would be attractive for communication systems. The bands could include millimeter wave and optical/infrared. Infrared/Laser communications offer unique advantages which are being explored at JSC. The design features include multi-access, packetized, high-rate, broad-beam links.

This section has dwelt on a broad set of concepts for system implementations for robotic vision. Active and passive sensors in microwave, optical and infrared bands, along with high-rate communications systems, are needed for various vision applications. Superconductivity devices/systems will have a significant impact on the vision systems design and performance. Examples of systems benefiting from this technology would be: (1) millimeter wave high efficiency distributed antennas with broadband and large beamwidth performance, (2) microwave power switches, networks, and distribution circuits resulting in substantial reduction in power loss, and increase in bandwidth and sensitivity, (3) development of optical and infrared detector cameras for low level/dark sensing, and (4) development of programmable signal processors, neuro-networks for speech and scene recognition, and communications monitoring/ control processors.

IV. Information Processing Algorithms

The processing of video data at various information levels, spanning from the data level to the intelligence level, is driven by *algorithms*. As mentioned earlier, the result of this processing is to provide a human operator or a robot with the parameters needed to control a mechanism. In other instances the processing leads to a high level description/interpretation of the observed scene for consumption by a human or robotic supervisor.

In a given application the set of vision algorithms may be grouped into three stages, depicted *in* Figure 10 and explained in detail in [24]. These three stages provide a meaningf rationale for a *CAD-based vision* under current developm at Rice.

(1) The *first stage* is an Image Preprocessing Stage (which sends the noisy pixel data into a set of *labeled fea* Typically, there are three types of features, namely, *corr*

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vertices, *edges*, and *shaded regions* corresponding to surface patches on the imaged object. In a given application one may use any one of these types of features or a combination of some or all of them. For example, a common set of features is the *wireframe* W_f of an image f of an object O_m. The wireframe W_f consists of the set of edges and corners present in the image f. The wireframe of the image of a cube is shown in Figure 11a. >From now on, we will assume that the output of the IPS is a labeled wireframe. A typical sequence of algorithms constituting the IPS would be algorithms for Gaussian filtering, Sobel operation, thresholding, median filtering, and contour thinning. Other sequences of image processing algorithms can be selected, depending on the type of the image data used. The wireframe of a mock-up of the Space Shuttle of Figure 12 extracted using these operations is shown in Figure 13.

(2) The *second stage* is what we call a *Symbolic transformer* (ST) (see Figure 10) which maps the labeled wireframe W_f into an attributed graph $G(W_f)$. One way of converting W_f into $G(W_f)$ is to map each face F_i (the region enclosed by a mesh in the wireframe) into the node N_i of the attributed graph $G(W_f)$ and the edge defining the boundary between two adjoining faces, say F_i and F_j, into the link l_{ij} of the graph. Referring to Figure 11, the graph $G(W_f)$ corresponding to the wireframe W_f of the visible surface of the cube of Figure 11(a) is mapped into the subgraph within the dotted curve (consisting of the nodes N_1, N_2, and N_3 and the links joining these nodes to each other) of the graph of Figure 11(b). The whole graph of this figure corresponds to the wireframe of the entire surface (visible and occluded) of the cube. In such a symbolic representation, we assign an attribute (feature) vector to each node and each link in the graph. Thus, let an m-vector $I^i = col(I_1^i, ..., I_m^i)$ represent a set of attributes (features) associated with the face F_i which are *invariant* under 3D translations, scalings, and rotations. Examples of such I^i are the sets of numbers expressing the Gaussian curvature or mean curvature of F_i. We call the attributed graph $\tilde{G}(\eta)$ obtained from $G(\eta)$ by assigning to the nodes N_i, $i = 1, ..., n$, respectively, the attribute vectors I^i, the FIAG (Feature-Invariants/Attributed-Graph) [25] representation of the object η. A special case of this representation is the MIAG (Moment-Invariants/Attributed-Graph) representation of polyhedral objects proposed in [26], in which I^i constitutes a set of 2D moment invariants of F_i (these being invariant with regard to 3D translations, scalings, and rotations).

(3) The *third* and final *stage* (see Figure 10) is a set of High-Level-Processors (HLP's) that map the attributed graph into appropriate symbols or vectors giving the information that the vision system is required to provide to the human operator or robot. Thus, in Figure 10, HLP1 identifies the object being viewed as being the object O_m of the objects present in the computer library. In other words, HLP1 is embodied by an *identification algorithm*. HLP2 and HLP3 constitute implementations of algorithms for determinant of the position and orientation of the object respectively, etc.

Having outlined the general framework for the various algorithms constituting the vision system, we now focus attention on some of the algorithms making up the indiv[illegible] HLP's mentioned above.

(a) Object Identification/Recognition. The Moment-Invariants/Attributed-Graph (MIAG) algorithm [26] for recognition of 3D objects from a single picture has been successfully developed and tested [27]. The algorithm works for polyhedral objects, and its generalization for nonpolyhedral objects has been indicated [25]. Each face of a polyhedron can be considered to be a rigid planar patch (RPP). Motion of the object can be considered to be motion of its constituent RPP's. In the case of parallel projection, if an RPP undergoes rigid body motion in 3D, its image undergoes affine transformations. So the method which tries to identify an object in 3D motion should use features of images which remain invariant under affine transformations. General moment invariants introduced in [26] are such features. These are invariants of 2D (rigid planar patch) moments which remain invariant under 3D translations, rotations, and scalings. Identification of an object is achieved by matching the attributed graph of its image (see Fig. 11(a)) to a subgraph of one of the graphs corresponding to the models stored in the computer library. The algorithm matches a pair of nodes by comparing the Euclidian distance between their feature vectors. Thus, if $I = (I_1, I_2, I_3, I_4)$ is the feature vector of a node consisting of four moment invariants of its corresponding face, and $I' = (I_1', I_2', I_3', I_4')$ the feature vector of the node to which it is being matched, the distance between them is taken to be

$$d = \sqrt{\rho_1(I_1 - I_1')^2 + \rho_2(I_2 - I_2')^2 + \rho_3(I_3 - I_3')^2 + \rho_4(I_4 - I_4')^2} \quad (1)$$

where ρ_i's are appropriate weighting factors. The driver algorithm arbitrarily picks a node N_j in the image attributed graph; then it looks for a node O_j in the model graph with the same feature vector. If matched, these nodes are marked as a pair, and an adequate node in the image graph is chosen, and the nodes adjacent to O_j are scanned to see if it matches one of them. In practice, after a few node matchings, a unique identification is achieved.

(b) Motion Parameter Estimation. Using appropriate camera calibration, all the motion parameters (position, velocity, attitude, and attitude rate) except for a scaling factor, can be determined by means of a single high precision camera. For this purpose, there are basically two model-based methods available: One, based on the contraction of the moment tensors of a surface patch of the model and its image, determines the attitudes vector $\underline{\theta}$ (raw, pitch, and yaw) and attitude velocity $\dot{\theta}$. (See [25] and [26] for details.) The other, based on the correspondence (assumed known) of eight points on the image f and eight points on the model η^i (assumed located and oriented in a standard position), yields all the motion parameters except for a scaling parmeter. This second method has been extensively discussed by Longuet-Higgins [28], Tsai and Huang [29], Haralick, et al. [30], and others, and recently extended to the case in which both the object and camera are moving by Fotedar, et al. [31].

(c) CAD-Based Vision. What we have described above constitutes a framework for CAD-based vision (see [24] for details). The current CAD-based systems are driven by 3D geometric modeling procedures originally developed for the representation and manipulation of objects in a design or computer graphics environment [32-34]. The system under development at Rice, based on the representations described

above, will be fully compatible with the requirements of a vision system.

There are three other areas of algorithmic development related to vision which are of special interest and the work on which is being actively pursued. These are described below.

(1) *Shape Extraction Based on Illumination.* As pointed out earlier, the fact that near vacuum prevails in space scenarios makes the scattering of light by a surface strongly dependent on the surface properties. Thus, by using appropriate mathematical models for the surface and for the 3D illumination conditions, it is possible to design algorithms that precisely determine the shape of the surface by the shadowing caused by illumination as well as any changes that have occurred on the surface conditions.

We note that a variety of methods have been developed for extracting shape based on camera data, each working under a different set of conditions and using different clues for reconstructing the surface. Thus, *Stereo Vision* uses the disparity between two images of the same object from two cameras to reconstruct the surface. Methods based on *Structured Lighting* project a known pattern of light on the surface and reconstruct the surface by looking at the distortion of this pattern. *Shape from Shading* is based on the premise that surfaces reflect different light intensities depending on the relative orientation of the surface to the light source and the observer. In principle, knowing the form of this dependence and the amount of light actually reflected back, the surface orientation can be calculated (see [35] and references therein).

Two methods have emerged for extracting shape from shading. One is called the proper *"Shape from Shading"* method while the other is termed *"Photometric Stereo."* Classical shape from shading techniques reconstruct the object from a single photograph of the object when the light source is placed in a known position. Photometric stereo involves reconstructing the object from multiple images of the object taken by moving the light source to different positions, while the position of the camera remains fixed. Some of the advantages that these methods offer are *high resolution* surface reconstruction as typically needed on assembly line operations. Handling of new parts, object testing for tolerance, estimating and repairing structural damage are some tasks which need a high resolution surface reconstruction front end. Another possiblity is the design of a front end visual system for feeding in surface models of real world objects to a CAD system.

Stereo vision and structured lighting methods have an inherent matching problem (used in generating the disparity map and the line matching) that is as yet unsolved. This problem is absent in shape from shading methods. Furthermore, in comparison with the structured lighting methods, shape from shading methods offer the advantage that the whole surface of interest is imaged. No shadows are willfully projected on it.

In shape from shading algorithms, the characteristic strip expansion methods [35] have several shortcomings, including sensitivity to measurement noise and a tendency of adjacent characteristic strips to cross over each other, due to accumulation of small numerical errors. Finally, the procedure is not amenable to implementation in parallel form. The variational method [35] that uses an object's occluding boundaries as cues to the recovery of its shape from shading alleviates these limitations. The blending of concepts from variational calculus with those from the best approximation theory can lead to spline-based solutions for the gradient functions determining the local surface shape orientation, as obtained in [36]. Research is also under way at Rice [37] to investigate certain aspects of Photometric Stereo such as completeness of illumination, optimal light placement, and robustness with respect to noise.

(2) *Shape Extraction from Sparse Range Data.* Our second set of algorithms for the extraction of shape of 3D objects are the ones based on sparse range data. A new methodology for surface reconstruction from such data was recently developed by Kehtarnavaz, et al. [38]. Such a reconstruction is formulated in terms of three separate subproblems: (i) 3D contour segmentation, (ii) segment matching, and (iii) surface patch formation. This framework is based on a *syntactic/semantic criterion* which incorporates the shapes of the contours in creating the surface. First, the contours are divided into sets of 3D curve segments in order to distinguish local shapes or substructures in the contours. Then, the curve segments are found on adjoining contours with similar shape characteristics. Finally, parametric surface patches are formed between the matched pairs of curve segments on adjoining contours by appropriately blending them. Typical reconstruction obtained by these results are illustrated in Figures 14 and 15.

(3) *Shape Extraction by Sensor Fusion.* Although radar scattering cross-sections alone cannot provide a complete description of a scattering surface, they are very useful when used to complement optical images, providing information in those regions of the object where a camera is blind due to phenomena like specular reflection.

The specular point on a curved surface is a point at which the angle of reflectance equals the angle of incidence. In traditional shading models, highlights occur at these points. In space, these highlights are so disproportionately intense that they tend to obscure the surrounding details of the surface. This phenomenon can be traced to two causes: the *Airy disk* , and *blooming*.

The *Airy disk* , or ring, is an optical term for the first diffraction fringe surrounding the image of a point source transmitted through an aperture. Because lenses constitute finite apertures, these rings are present to some degree in all imaging systems [39]. Usually, when dealing with incoherent light emanating from curved objects, the Airy disks of a distribution of point sources tend to cancel each other out and are not visible in the resulting image. However, intense specular reflections become point sources which are orders of magnitude more intense than the surrounding reflections. The resulting diffraction fringe is highly visible and can wipe out the shading information in adjacent areas of the image.

Blooming occurs at points of high intensity in a television image. If the distribution of intensities is relatively even, this phenomenon is not a problem. If specular points occur whose intensities contrast sharply with their surroundings, the effect is noticeable. The anomalously high grid voltage in the camera cathode ray tube causes the electron beam to spread. The result is specular points which are smeared over several pixels. Blooming can obscure small features surrounding specular points in the image of a highly reflective surface.

Space images also suffer from *indistinct edges*. Because of the complete lack of illumination on the shadow side of space objects, their edges are invisible against the dark background. This can result in false edges for curved objects, or the absence of one or more edges on polyhedrons.

The sensor fusion algorithm under development at Rice [40] reconstructs 3D space objects (whose images may be degraded as described above) given observations taken by a microwave radar system from a solitary remote point. Since microwave or millimeter-wave radar systems are currently found on a variety of space vehicles, radar scattering information would seem to be a logical addition to a space robot's sensory data. The unknown portion of the scattering surface is parametrically approximated with splines so that the microwave scattering equations can be used to derive the unknown surface. In this way the radar cross-sections are used to reconstruct those portions of optical images which are destroyed by high intensity specular reflections (see Figure 1). Edges which are lost in shadows can be inserted in a similar fashion. The solution procedure is an *iterative non-linear least squares* algorithm [41], using the incomplete optical surface to provide a first approximation to the actual surface parameters. A surface model is generated at each step in the algorithm and approximations to the co- and cross-polarized scattering cross-sections are computed from this model. A Physical-Optics approximation to the Jacobian is then used to update the unknown surface parameters for the next iteration. When the best possible surface is obtained, the least-squares algorithm is terminated and the new surface, with the degraded portions filled in, may be passed back to the optical shape-from-intensity algorithm for further refinement. Thus, we are fusing the optical image sensors with polarized microwave radar cross-sections to arrive at a target object characterization which is more complete than either of those derived from the image or radar separately.

V. Proposed Future Developments

As was mentioned earlier, the interaction of natural light with the objects in space has to be accounted for in the vision algorithms. Furthermore, artificial light(s) arrangements have to be developed which can provide structured (known distribution) light across the object. The pronounced shadows and specular points due to the vacuum and smooth parts of the object, provide a large dynamic range of the reflected/scattered signal. The intensity changes can be in the 10 range. The addition of artificial illumination provides the opportunity to control intensity, wavelength, polarization, and orientation with attendant advantages of increased recognition. Additionally, color will be another discriminant involved in the recognition. Analytical studies in these areas should lead to the design of illumination systems for space applications.

The use of laser vision and microwave scattering instruments creates another area of future development. Fast scanning/holographic lasers provide a depth perception of objects, which is quite complex. This depth data can be utilized to iteratively provide a 3-D image of the object by weighting video-aquired image data appropriately. These weights will depend on the surface curvatures as they project in the incidence direction of the laser beam. Both empirical and analytical studies are needed. The microwave backscattering can provide another independent set of data. The shape of certain objects can be directly deduced from this data. In many inspection tasks in which a nonmetallic shielding has obscured the view, such sensing will be mandatory. In other situations, the microwave data can be iteratively used with that of TV to arrive at more definitive description of the object. At the expense of complexity, doppler processing of microwave and laser data can be used to discriminate moving parts of a distant object. The advantage of such a vision is that it is independent of sunlight and it provides a direct measure of range and relative velocity of various parts of the object.

Another area of endeavor should be time-domain imaging. A sharp pulse transmitted yields a unique description of the object. This time domain reflectometery is evolving rapidly. Another mode of the system can utilize reflectivity data in the near-field. These techniques have not been explored for the robotic vision applications.

Finally, further research and development is needed in the area of multisensor coordination and fusion. The recognition algorithms are to be extended to include interrelating data from several cameras, laser scanners/holographic systems, and microwave sensors. These algorithms should include motion, rotation, and object changes as functions of space and time. In addition to this, "environmental" data pertaining to the events/objects and their status, has to be included. These aspects, along with rational models, incorporate expert and artificial intelligence techniques in the scene analysis. The goal should be a multisensor, multimode vision system capable of autonomous operation and self-calibration.

VI. Conclusions

This paper is aimed at providing a review of some of the efforts in progress at NASA/JSC and Rice University. The design and development of a vision systems for space applications needs several considerations which make them different compared to those used in ground applications. The concerns for space unique vision systems have been elaborated. Several efforts which need to be undertaken have been discussed. Considerable work has to be accomplished in order to provide robust, lightweight, small size, and autonomous vision systems for specific space applications.

Acknowledgement

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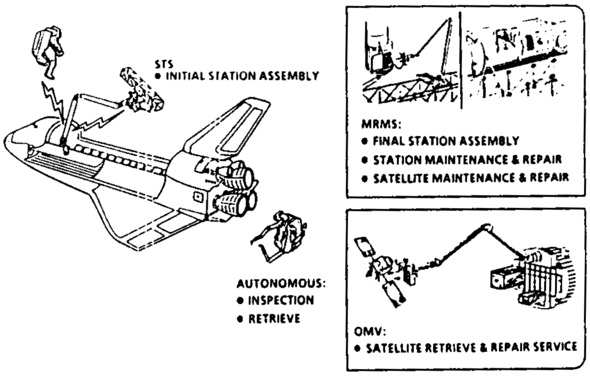


FIGURE 1. CONCEPTUAL SPACE STATION ROBOTICS/AUTOMATION

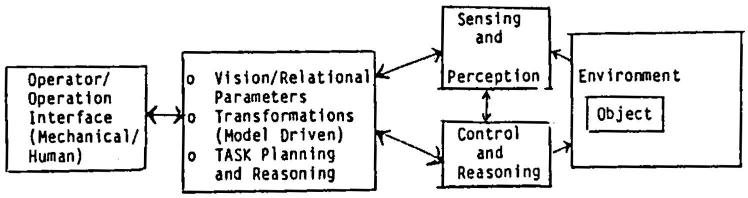


FIGURE 2.

FUNCTIONAL ELEMENTS OF TELEOPERATOR/AUTONOMOUS SYSTEM

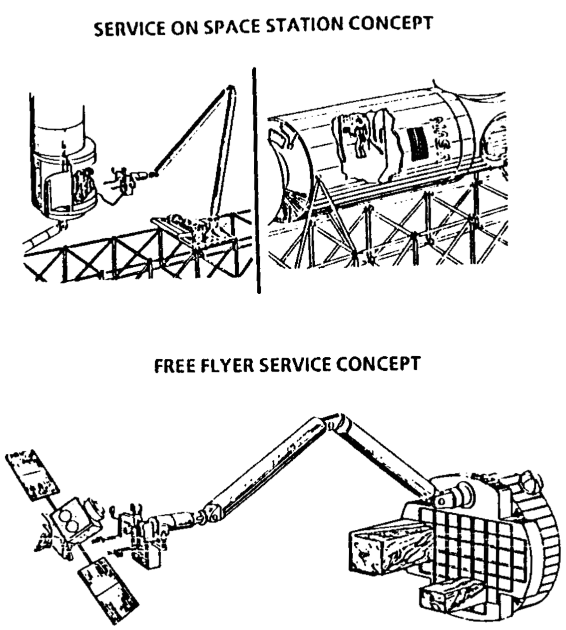
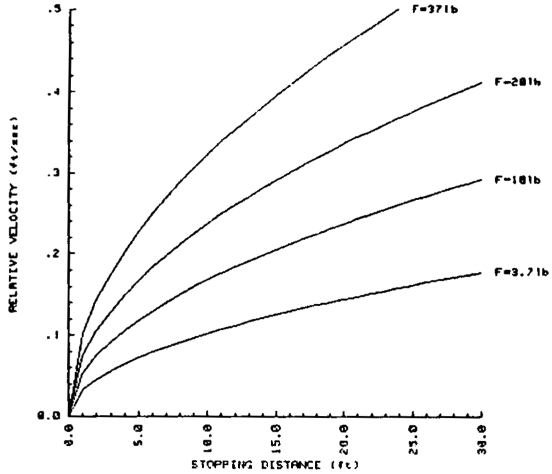


FIGURE 3. ROBOTICS SERVICING CONCEPTS



Braking Rule: $V(t) = (Vp/2)*(1+COS(\pi t/Tb))$

Orbiter Weight = 240k lbs; Station Weight = 373.2k lbs

FIGURE 4.

CAPTURE STOPPING DISTANCES AND VELOCITIES FOR VARIOUS FORCES

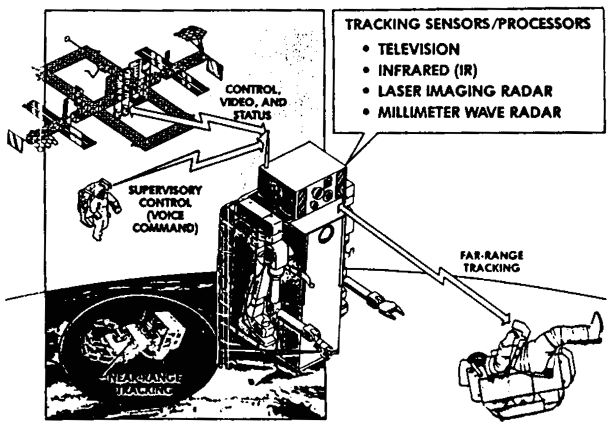


FIGURE 5. NASA/JSC EVA RETRIEVER VISION SYSTEM CONCEPT

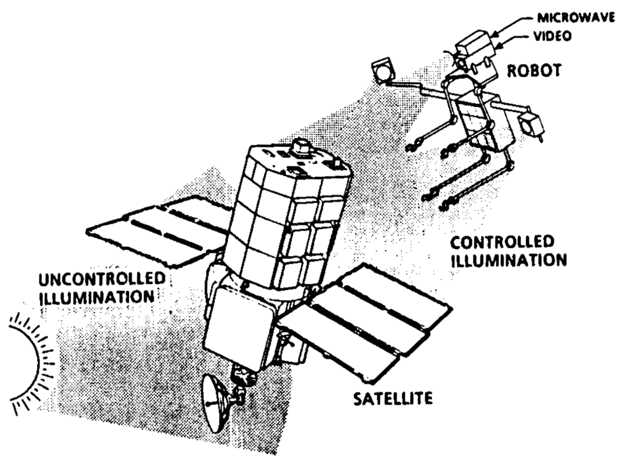


FIGURE 6.

SPACE ILLUMINATION FOR SHAPE DEFINITION/IDENTIFICATION

PARAMETER	LIMITS	ACCURACY (1σ)
RANGE (R)	0-1 KM (3280 FT)	.01 R; 2.5 MM ≤ 10 M
RANGE RATE	±3 M/S (± 10 FT/S)	.0001 R/S; 3MM/S ≤ 30M
POINTING	±π/2 RAD (±90°)	
BEARING ANGLE	±.2 RAD (±10°)	3 MRAD (.2°)
BEARING ANGLE RATE	±20 MRAD/S (±1°/S)	.03 MRAD/S (.002°/S)
ATTITUDE (P,Y)	±.5 RAD (±28°)	7 MRAD (.3°) AT R ≤ 100 FT
ATTITUDE (R)	±π RAD (±180°)	7 MRAD (.3°) AT R ≤ 100 FT
ATTITUDE RATE	±20 MRAD/S (±1°/S)	.03 MRAD/S (.002°/S) AT R ≤ 100 FT
R, $\dot{R}$ OUTPUT DATA RATE	1 Hz	
ANGLE OUTPUT DATA RATE	3.125 Hz	

TABLE 1. LASER DOCKING SYSTEM PERFORMANCE GOALS

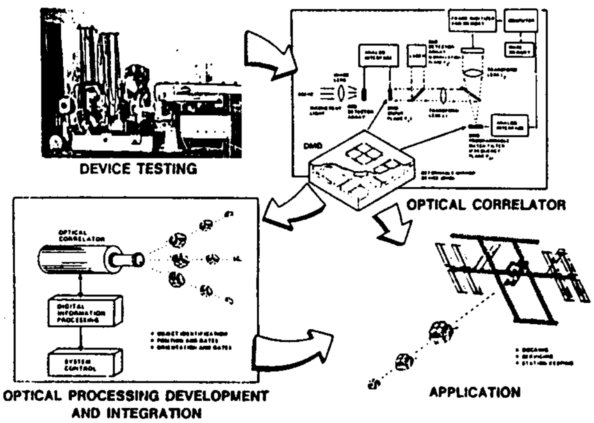


FIGURE 7.

OPTICAL PROCESSING FOR CONTROL APPLICATIONS

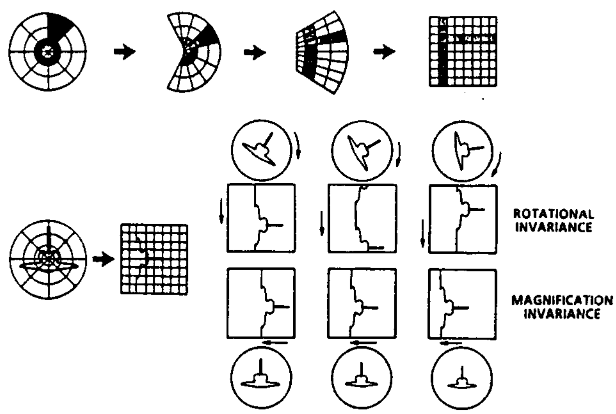


FIGURE 8.

COORDINATE TRANSFORMATION/MAPPING FOR ROBOTIC VISION

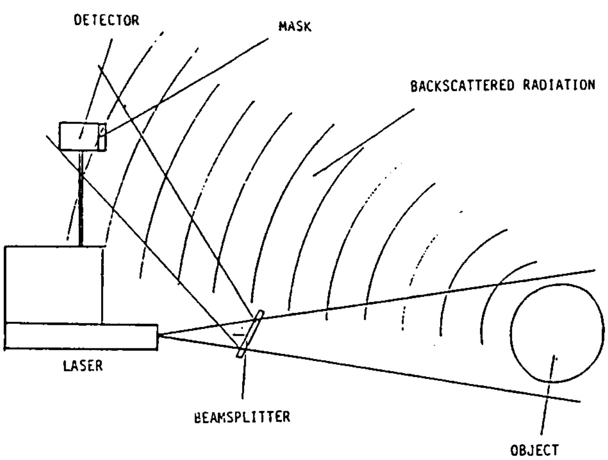
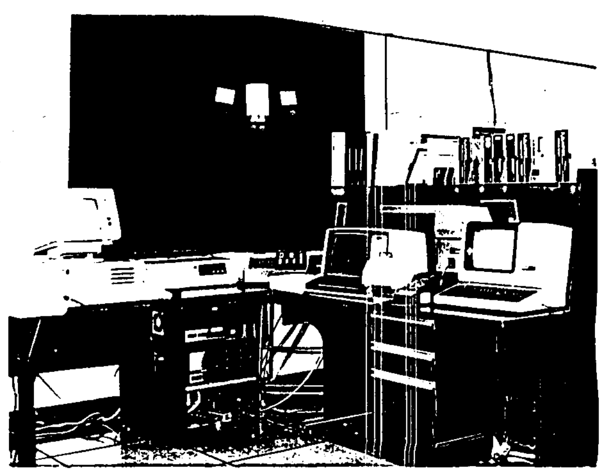
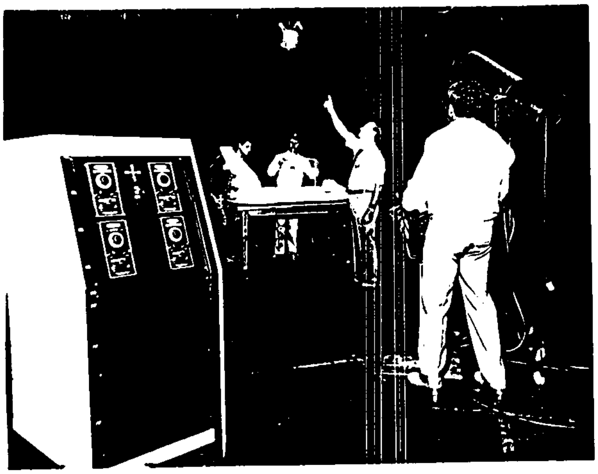


FIGURE 9.

CONCEPTUAL SCHEME FOR 3-D IMAGE PROCESSING BASED ON HOLOGRAPHY



TESTBED FOR SHAPE FROM SHADING ALGORITHM VERIFICATIO



SMART TELEVISION TESTBED

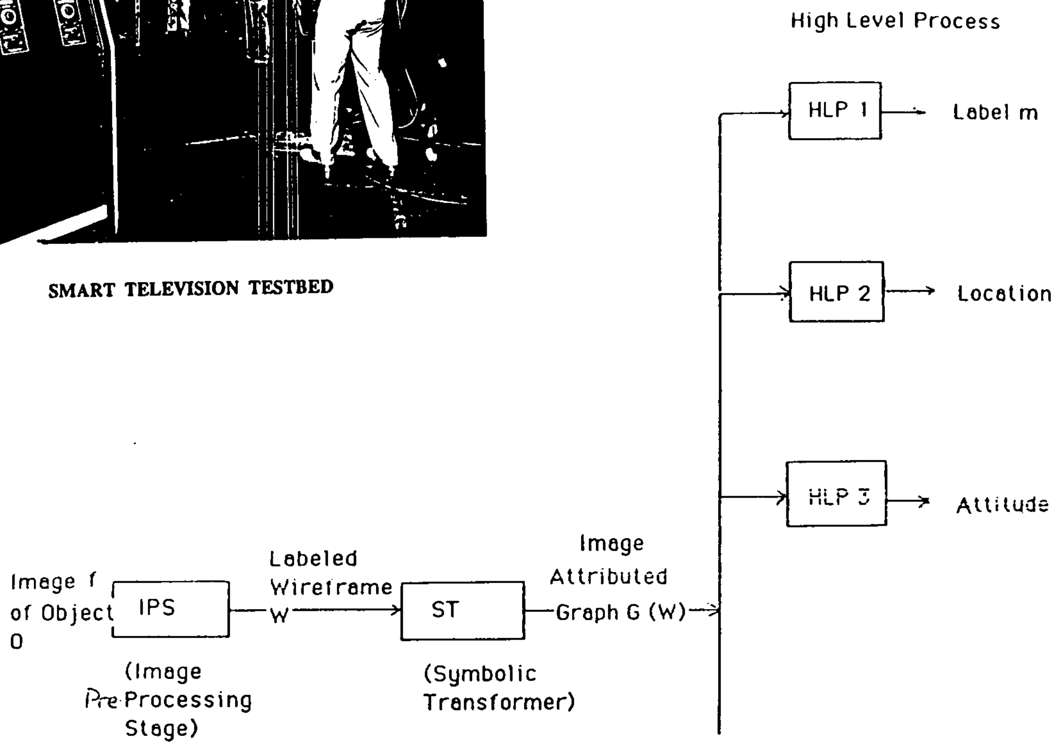


FIGURE 10. THE THREE STAGES OF THE VISION SYSTEM DESCRIBED IN THE TEXT

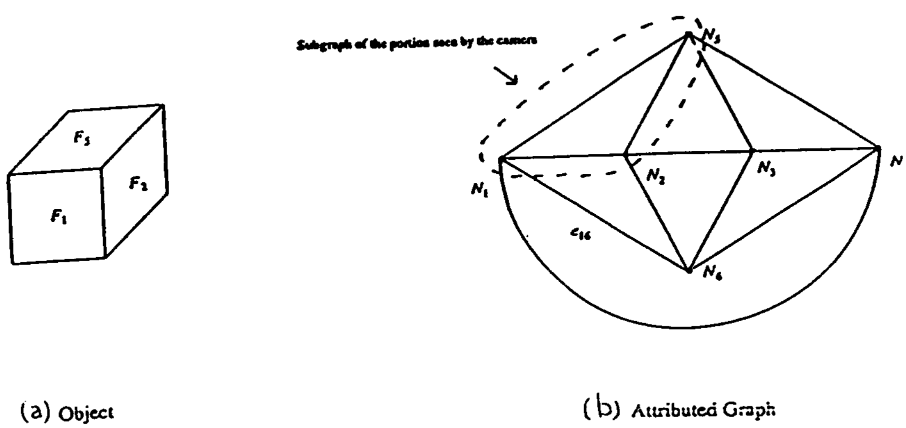


FIGURE 11. THE WIREFRAME OF A CUBE AND ITS ATTRIBUTED GRAPH REPRESENTATIVE

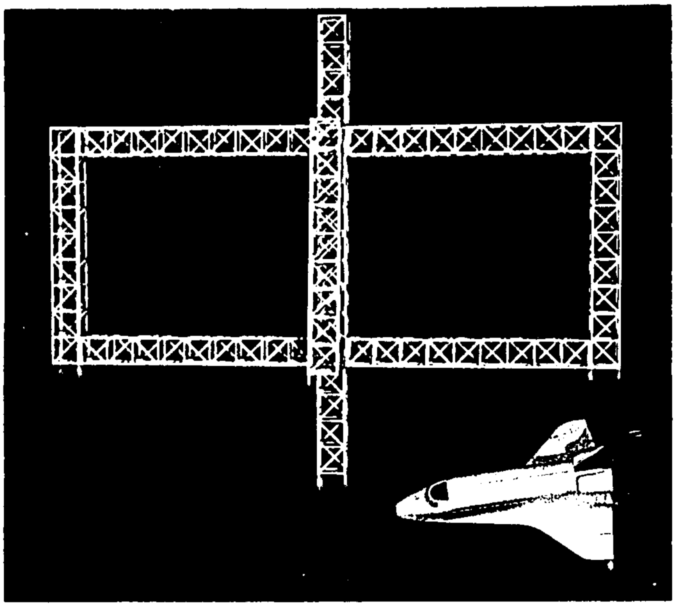
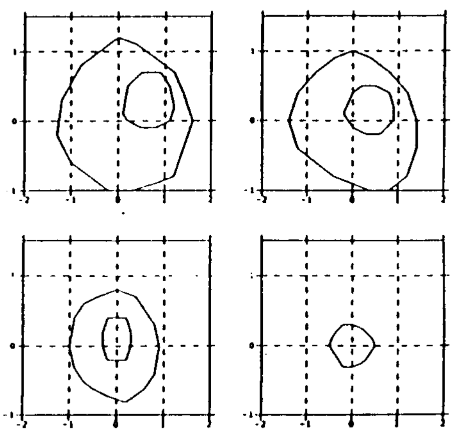


FIGURE 12.

LABORATORY MODELS OF THE SPACE SHUTTLE AND PART OF THE SPACE STATION



EDGES OF A TYPICAL SET OF LEFT VENTRICULAR PET

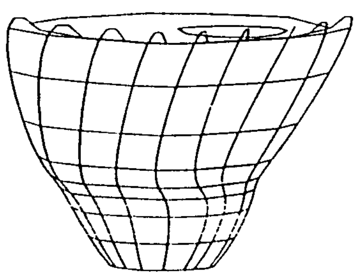


FIGURE 14.

(POSITRON-EMISSION-TOMOGRAPHY) SLICE AND THEIR RECONSTRUCTION BASED ON CARDINAL SPLINE BLENDING FUNCTIONS

Object ---> Edge Detector Output ---> Edge Thinning Output

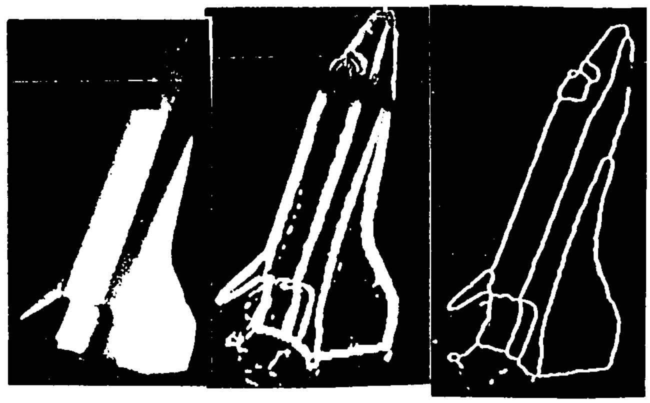


FIGURE 13.

PRE-PROCESSING OF A PICTURE OF THE SPACE SHUTTLE MODEL

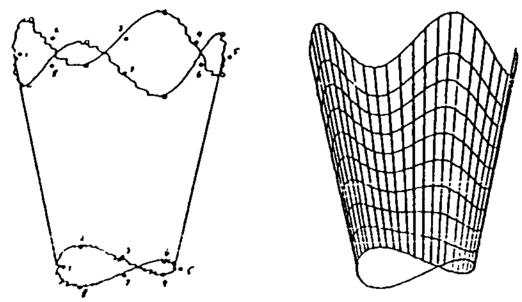


FIGURE 15. BOUNDARIES OF A BROKEN GLASS (NOISE ADDED) AND ITS SURFACE RECONSTRUCTION

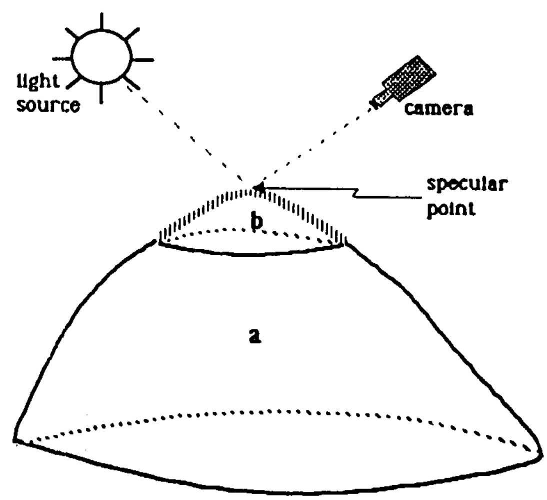


FIGURE 16. SURFACE RECONSTRUCTION BASED ON SENSOR FUSION (SURFACE A IS TO BE RECONSTRUCTED FROM IMAGE DATA WHILE SURFACE B FROM RADAR DATA)