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Grasping Objects Autonomously in Simulated KC-135 Zero-G

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ABSTRACT

The EVAHR (Extravehicular Activity Helper/Retriever) robot is being developed to perform a variety of navigation and manipulation tasks under astronaut supervision. The EVAHR is equipped with a manipulator and dexterous end-effector for capture and a laser range imager with pan/tilt for target perception. Perception software has been developed to perform target pose estimation, tracking, and motion estimation for rigid, freely rotating, polyhedral objects. Manipulator grasp planning and trajectory control software has also been developed to grasp targets while avoiding collisions.

Flight experiments have been scheduled aboard NASA's Reduced Gravity Laboratory (KC-135 aircraft) in 1994 to attempt grasps of free-floating objects. A software simulation of the EVAHR hardware, KC-135 flight dynamics, collision detection, and grasp impact dynamics has been developed to integrate and test the EVAHR software. This paper describes the EVAHR system, with emphasis on the robotic and KC-135 simulation software.

1. INTRODUCTION

Much work has been done on autonomous grasping of stationary, complex objects, e.g. in bin-picking and pick-and-place problems[1,2]. However, very little work has been devoted to autonomous grasping of moving, complex objects. This is probably due in part to the difficulty of the problem and to a lack of applications for such technology. There exists an abundance of applications for this technology at NASA, however, as recent Shuttle-based satellite recovery attempts have amply demonstrated. STS-49 required 3 astronauts to grasp the ailing INTELSAT VI satellite - an autonomous mechanism would have spared the astronauts hazardous EVA activity. The difficulties encountered on 41-C in 1984 rescuing the Solar Max satellite and the failure to recover the Leasat 3 during 51D in 1985 provide further evidence of such a need. The recent ROTEX experiment onboard the Shuttle mission STS-55[3] demonstrates that the German Aerospace Research Establishment (DLR) considers this a key piece of robotic technology for space. The ROTEX system combined a tele-operated manipulator and camera system to grasp a free-floating object, among other tasks.

The EVAHR (Extra-Vehicular Activity Helper/Retriever) project has been developing robotic technology, hardware and software, for navigating among and grasping free-floating objects since 1987. The EVAHR project was originally conceived as an autonomous device for retrieving personnel or objects which had become detached from Space Station Freedom (SSF). At the conclusion of Phase II in 1990, the following autonomous robotic capabilities were demonstrated on a precision air bearing floor (PABF): a) navigation among stationary obstacles and b) grasping arbitrarily located and oriented, cylindrical targets. At this time, a simulation of the EVAHR in an 6 degree-of-freedom (DOF) orbital environment[4] was developed for use in the next phase. It would provide a testbed for development of 6 DOF navigation and grasping software. Models initially developed included orbital dynamics, plume impingement effects of the Manned Maneuvering Unit (MMU) (a compressed-gas-based propulsion system), and a laser scanner range/intensity image simulation[5]. Six DOF body motion control and orbital state estimation algorithms were developed and tested for navigation purposes. Phase III then took as its primary goal the development and demonstration of an integrated system for grasping free-floating, complex objects.

The EVAHR team chose the KC-135 zero-gravity aircraft as the hardware testing and demonstration platform for this phase[6]. The KC-135 aircraft flies a series of parabolas, free-falling over the hump of each parabola, simulating zero-gravity or weightlessness for objects and personnel free to float inside the plane. Each of these periods lasts 20-25 seconds. The EVAHR, attached to the floor of the KC-135 throughout the experiments, will attempt to grasp targets released in its envelope during the simulated zero-gravity period . While the KC-135 is a difficult environment for such testing, it provides the only direct means of testing the contact dynamics of free-space grasping short of a Shuttle flight experiment.

Prior to flight, software to grasp free-floating, complex objects in a 6 DOF, orbital environment was developed and integrated. Software for an orbital environment was developed first and testing was conducted to determine the performance of the system[7]. Dynamics and state estimation software was then developed to represent the KC-135 environment.

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2. OBJECTIVES

Essentially, the integrated EVAHR grasping software must be capable of **autonomously grasping a variety of polyhedral objects, each in less than 15 seconds, where the object is freely but slowly translating and freely rotating at up to 30 deg/sec**.

A maximum time-to-grasp of 15 seconds was initially chosen as a conservative estimate of the zero-gravity period provided by the KC-135. While recent data gathering flights on-board the KC-135 have shown that the time available is actually less than 8 seconds, most of the testing presented here was conducted with the 15 second per grasp attempt time limit. One might speculate that in order to be considered useful in real applications, the robot would have to perform these grasps much more quickly, but this consideration did not affect our requirements.

The maximum rotational rate is taken from a Crew and Equipment Retrieval Study (CERS) conducted by NASA[8], which estimated the likely maximum separation rates of objects which might become detached or untethered from the SSF. The CERS maximum translational rate of 2 feet/sec was ignored because the EVAHR, as a free-flying vehicle, would rendezvous with and stationkeep at the target with nearly the same velocity. From on-orbit navigation tests in the EVAHR simulation, a rate of 2 in/sec during stationkeeping was found to be the maximum. However, it would be impractical for the EVAHR vehicle to match the CERS rotational rates.

To enable the EVAHR to meet these objectives, a metrically-accurate CAD surface model and mass properties (mass, center-of-mass, inertia matrix) are provided to the EVAHR describing each target object prior to runtime. The target's surface must be non-specular so that the laser scanner can image it.

Integrated software testing with the orbital simulation yielded information about the performance of the EVAHR software in its ultimate target environment, i.e. the success ratio for different target velocities, the required vision update rates, etc. The addition of a KC-135 dynamics model provided a means of integrating the KC-135 state estimation module and verifying continued, successful system performance.

3. EVAHR HARDWARE

The principal EVAHR hardware elements to be flown on the KC-135 flight experiments is shown in Figures 1 and 2. These elements are combined into a fictitious EVAHR body in the orbital simulation shown in Figure 3. A Perceptron LASAR laser scanner is mounted in a pan/tilt mechanism on top of the EVAHR body. The Perceptron provides 64x256 range/reflectance images at 9 Hz, 128x256 resolution at 5 Hz, or 256x256 at 2.5 Hz - switchable at runtime. The range resolution is approximately 1/7 inch, though noise can result in a range error of up to 3%. The pan/tilt motors are able to rotate the Perceptron at 180 deg/sec. A Robotics Research (RR) K807i 7 DOF manipulator is mounted as a left arm, with a 3-fingered JH4 dexterous hand as its end-effector. The RR arm has a maximum end-effector speed of 30 in/sec, static repeatability of .002 in, and may accurately support loads of 10 lbs. The dexterous hand was manufactured at JSC. It provides 3 joints per finger, though only 2 are active. The maximum finger joint speed is roughly 120 deg/sec so that the hand is able to close in roughly 1/4 sec. Proximity detectors are located on the palm and each finger tip.

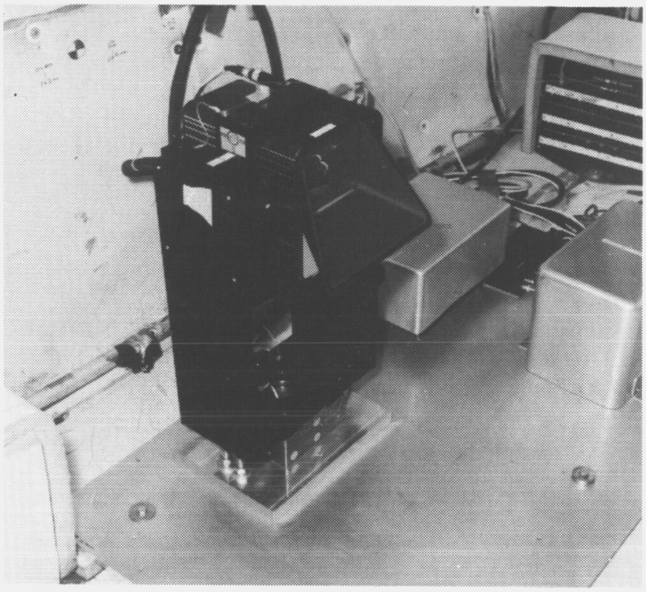


Figure 1. EVAHR laser scanner & pan/tilt

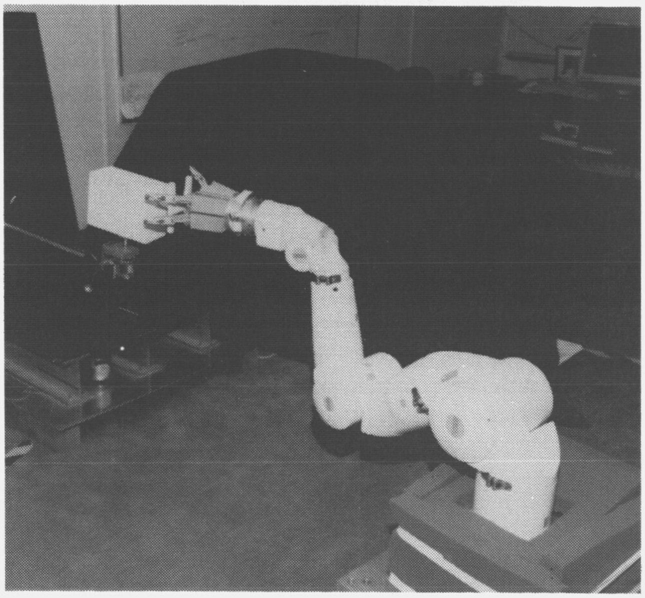
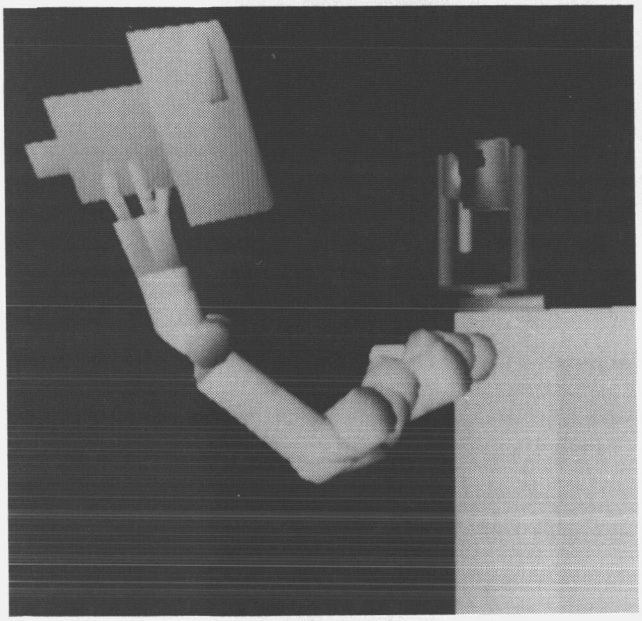


Figure 2. EVAHR manipulator/hand

When the EVAHR is flown on the KC-135, the EVAHR hardware will be fixed to the floor of the aircraft - only the target will float free. In the orbital configuration, a 24-thruster Manned Maneuvering Unit (MMU) [9] is strapped to its back to provide 6 DOF propulsion. The MMU model was turned off during the grasping tests. Not shown in the figures is an inertial measurement unit (IMU) composed of 3-axis accelerometers and rate gyros, which provide acceleration and rotational velocity measurements of the EVAHR body. The EVAHR will use the following computers to grasp free-floating targets in real-time onboard the KC-135: 8 Intel i860 processors connected via crossbar, 14 Transputer T800 processors networked via synchronous Transputer links, and 4 68040 processors. A VMEbus will connect the processors/ networks and sensor/actuator electronics.



Figures 3. EVAHR grasping ORU in orbital simulation.

4. EVAHR SIMULATION

Figure 3 shows testing with the orbital simulation. The arm and laser scanner will be attached to the floor of the KC-135 in flight, as in Figures 1 and 2, rather than to the body. The KC-135 simulation includes models of the a) EVAHR hardware and b) dynamics of the KC-135 environment. Models of the EVAHR hardware required to test autonomous vehicle navigation were developed initially. One of these models, the laser scanner image simulation software, continues to play a major role in vision-guided manipulation. This simulation takes advantage of the z-buffering graphics hardware associated with Silicon Graphics workstations to provide fast range image generation for polyhedral-surface objects. The model was extended to provide configurations possible in the Perceptron laser scanner - 64x256 or 256x256 images and variable field of view. The laser scanner simulation model does not try to model noise or distortions, however, other than uniform pixel noise. Preliminary tests with the actual Perceptron hardware show a maximum error of 3% in the range pixel measurements. Unfortunately, the Perceptron produces more systematic noise which is not modeled by this simulation. Target CAD models (see Figure 6) along with CAD models of the EVAHR hardware (see Figure 3), are used by the laser scanner simulation to generate simulated images.

Additional models were developed expressly to support testing of the grasping software. These include models of: a) the RR manipulator and JH4 dexterous hand, b) collision detection, and c) grasp contact dynamics. Because dynamic models of manipulators are hard to obtain and compute-intensive, we opted for an acceleration-level model of the RR 7 DOF arm and JH-4 dexterous hand. This model has since been proven in tests with the actual arm. Collision detection software was developed to detect a) desired collisions between the JH-4 palm/fingers and the target and b) collisions that the manipulator trajectory control software is attempting to avoid. The collision detection software requires that the objects be convex or be composed of convex subparts. The dynamics of each body (e.g. EVAHR, target) is computed by summing the forces and moments on each orbiting body, computing the associated translational and rotational accelerations, then integrating (at 100 Hz) to arrive at each body's velocity and position. One such translational force is gravity. When collisions between the fingers or palm of the JH4 hand and the target are detected, additional forces and moments on the target are computed and "folded into" the (orbital) dynamics state propagation. To make the computation tractable, each finger is assumed massless relative to the target and stops on contact; however, its motion is resumed if the forces/moments on the target are such that the target moves away from the finger. The forces/moments are computed one contact point at a time, even when multiple fingers are in contact simultaneously. Assuming a loss of velocity after each contact due to friction, the motion of the target is considered "stopped" when the target's total velocity falls under a threshold. This simulation has not been validated except by visual verification of the results of random test cases. Numerous cases have shown the target slip out of the grasp of the closing fingers as well as the target being trapped by them - the behavior has appeared "reasonable".

5. EVAHR SOFTWARE

The EVAHR grasp software acts as a closed-loop control system (see Figure 4), where the simulation models just described act as the plant. The vision and grasping modules are as described in 7. All are implemented in C, as are the simulation models.

Measurements of the target's pose (3D position/3D orientation) are computed by the vision modules Tracking[10] and Pose Estimation[11, 12]. The Tracker processes each image to find a rough estimate of the target's location and, if the pose estimator is ready, the contour of the object. To avoid confusing the target with the arm/hand, which may be in the image or even partially obscuring the target, the arm/hand is removed from each image. The is accomplished by using a CAD model of the arm/hand. Pose estimates are computed by finding the best match of image features (edges/vertices) on the occluding contour to corresponding features in CAD model representations of each target (see Figure 6). The pose estimation software uses the same CAD models as the laser scanner simulation uses to draw its images and thus benefits from perfect surface geometry models of the targets. These measurements are computed at rates which vary depending upon a number of factors: the complexity/symmetry of the object, the availability of predicted poses for the image time, the degree of occlusion by the EVAHR arm/hand, and of course the computing resources available. The output rate of the pose estimator may vary from .1 sec (laser scanner minimum image interval) to several seconds.

These measurements are provided to independent Kalman filters which estimate the target's translational and rotational states. These model-based state estimators are different from those in the orbital EVAHR software, due to the different environment dynamics, and are described more fully in [13]. The rotational filter required only minor modifications, namely redefinition of the inertial coordinate system (CS). While the orbital version used an Earth-centered CS, the KC-135 version uses the aircraft's orientation at the beginning of each parabola. Thus the target's attitude is EVAHR-relative from that point on, due to the arm being fixed to the aircraft. The KC-135 translational state estimator had to be made explicitly EVAHR-relative, due to the lack of the Earth-based position correction (e.g. Global Positioning System (GPS)) that was assumed in the orbital software. The target's state is thus estimated in the EVAHR's coordinate system, using inertial measurements from the IMU and initializations/corrections from vision. For the purposes of this round of simulation testing, both the measurements and corrections were taken, noiseless, directly from the dynamics simulation. Both the translational state (position, velocity, acceleration) and rotational state(attitude, rotational velocity and acceleration) states are computed at 100 Hz for the EVAHR Manipulator Trajectory Controller. They are also archived in the World Model database as predictive feedback to the Tracking/Pose Estimation modules for images to be processed shortly thereafter.

The Manipulator Grasp Planning and Trajectory Control module[14] receives an estimated target state at 100 Hz. At 10 Hz, the Grasp Planner decides which of the multiple grasp regions available for the target is optimal for grasping. (Prior to runtime, the graspable regions on the target's surface were computed and placed in a database. These regions were found automatically based on CAD models of the JH4 hand and the target.) The Manipulator Trajectory Controller (MTC) computes RR/JH4 joint accelerations to track the motion of the chosen grasp region on the target at 100 Hz. Each cycle the MTC also computes joint accelerations to avoid a) joint singularities, b) joint limits, c) RR link-link collisions, d) RR-EVAHR body collisions, and e) collisions between the RR/JH4 and regions on the target which are not to be grasped. The MTC uses a potential field-based algorithm to compute these avoidance accelerations.

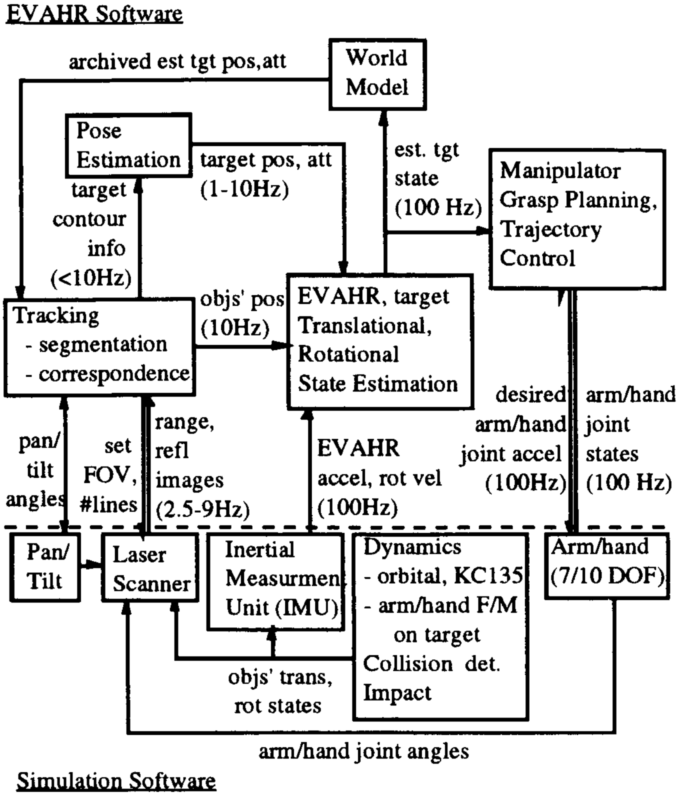


Figure 4. EVAHR/Simulation Software Architecture

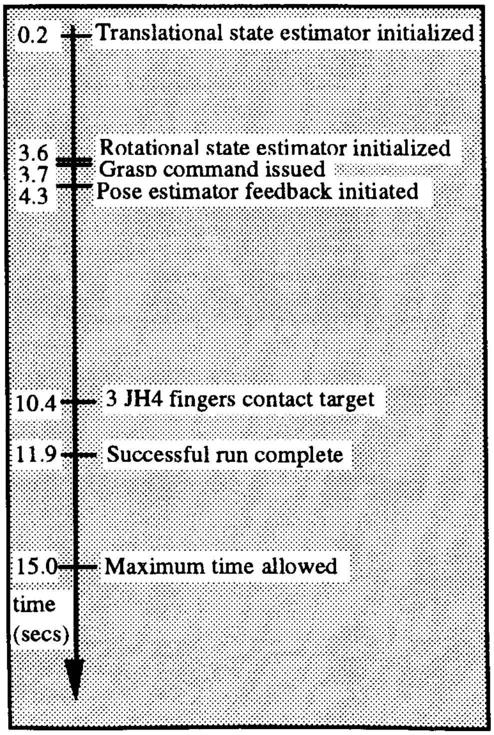


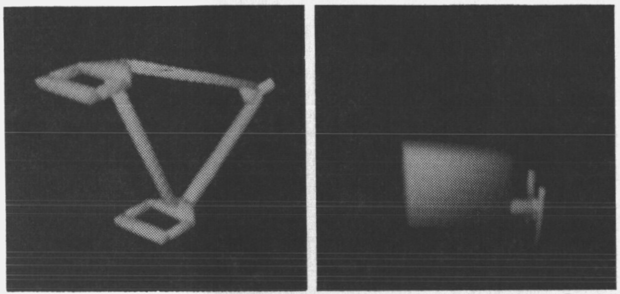
Figure 5. Avg event timeline for NBox.

The MTC takes advantage of the extra DOF in the manipulator to minimize the effects on the end-effector trajectory.

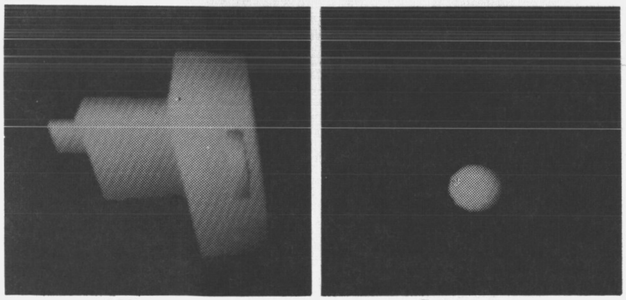
The cycle rate of 100 Hz was determined primarily by the need to control RR joint accelerations at that rate. It was also determined previously that propagation of the target's rotational state would diverge if the integration timestep were less than approximately 50 Hz.

The software was run on 2 Sparcstations and 1 Silicon Graphics 70GT for the experimental testing. Figure 5 shows a representative sample event timeline for an attempted grasp of the NBox.

Two different types of target shapes were used in testing: spherical and polyhedral. In the case of the sphere, the pose and rotational state estimation modules are unnecessary and grasping is greatly simplified as well. Therefore, polyhedral objects were used almost exclusively for testing. Three different polyhedral shapes were used (Figure 6).



Jettison handle (JettH) Orbital replacement unit (ORU)



NBox Sphere

Figure 6. Polyhedral and spherical target shapes

An additional major difference between the orbital and KC-135 software lies in the area of image segmentation. While the background of space provides an extremely convenient basis for segmenting the target in each image, the inside of the KC-135 aircraft is very difficult and compute-intensive. To minimize the computational load, a black curtain will cover the inside of the aircraft to simulate space.

7. CONCLUSION

The EVAHR software for grasping a target floating free on-orbit has been described, as well as the KC-135 simulation for testing the software as an integrated whole. The software was integrated and successful grasps were achieved, similar to those obtained in thorough, integrated testing with the orbital simulation. This result suggests that the software is ready for flight testing on-board the KC-135.

8. FUTURE WORK

A preliminary KC-135 flight test using spherical targets exclusively will be conducted in the near future. The advantage of spherical targets is that they have no rotational state and, hence, neither the pose estimation software nor the rotational Kalman filter are required. A Teleos PRISM3 stereo-vision system, instead of the Perceptron laser scanner, will be used to provide target position inputs (at > 20 Hz). The translational state estimation and grasping software modules have been reimplemented on parallel Intel i860 and Siemens Transputer architectures to achieve real-time speeds. Calibration of the arm and PRISM3 systems has been completed and pre-flight integrated systems testing is to begin shortly.

Meanwhile, modifications are being made by Perceptron to the laser scanner to improve its noise characteristics. Of primary concern is range drift, which is serious enough to prevent the sensor from being calibrated. Assuming that the problems with the laser scanner are corrected, a flight with the polyhedral targets is scheduled for sometime in the summer of 1994.

10. ACKNOWLEDGMENTS

This work was performed under contract NAS 9-17900 with the Automation & Robotics Division of Johnson Space Center. Also, the Lockheed (LESC) developers of the software modules - G. Anderson, C. H. Chien, L. Hewgill, and M. Littlefield - are as responsible for this paper as the author. Without them, these results could not have been produced. Comments and suggestions regarding the testing made by Dale Phinney (LESC) and Jon Erickson (NASA) were also greatly appreciated.

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