STATION KEEPING OF AN ROV USING VISION TECHNOLOGY

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ABSTRACT

This paper will present the results of a demonstration of two degree-of-freedom automatic station keeping of a remotely operated vehicle (ROV) in an ocean environment using vision feedback. This work was done as a collaborative effort in vehicle control between the Aerospace Robotics Laboratory (ARL) and the Monterey Bay Aquarium Institute (MBARI). The results show how the transfer of technology from a testbed autonomous underwater vehicle (AUV) to an ocean-going ROV can be applied to the creation of pilot aids that reduce ROV pilot workload during certain tasks.

I. INTRODUCTION

The joint program between the ARL and MBARI provides a research environment that takes advantage of MBARI's operational experience and ARL's background in autonomous technologies. This paper presents the transfer of vision technology used in vehicle control to MBARI's ocean-going ROV. Details involving the implementation issues and experiments designed to prove the feasibility of using vision as a sensor in an operational environment will be discussed.

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A. Motivation

To perform science missions underwater, an ROV often needs to hover over a fixed reference point on surfaces such as the ocean floor or a canyon wall, or over a specific object of interest. Currently, the pilot performs this task by viewing video from the vehicle's cameras and controlling vehicle position and orientation using a joystick to command its thrusters. This station keeping task can be difficult, particularly when tasks requiring manipulation or precise maneuvering are also involved. Pilots must be highly trained to be able to control a vehicle in three dimensions from two-dimensional video images, handle time delays of the system, and coordinate with other pilots' actions when the manipulators are operated as well. They also must continuously adapt to the changing effects of the ocean environment on the vehicle. Such operations require intense concentration in order to achieve adequate control over the ROV's maneuvers. These types of tasks can cause pilot fatigue, hindering performance after long periods of operation. It is desirable, then, to develop autonomous pilot aids that can reduce the pilot's workload. By controlling some degrees of freedom of the vehicle autonomously, the pilot is then free to concentrate on other tasks.

B. Background

The use of vision as a feedback sensor for closing loops on AUVs has been successfully developed and demonstrated in the past. Closing vehicle position control loops with vision has been applied on the *OTTER* (Ocean Technology Testbed for Engineering Research) autonomous vehicle in a test tank, allowing the vehicle to perform tasks in real-time such as station keeping (hovering over a fixed point), object tracking (following a moving reference point), and mosaicking (creating a map from successive images snapped by a moving vehicle) [3]. Passive mosaicking has also been performed on MBARI's ROV, with the pilot driving the vehicle and the vision system processing video in real-time, not as part of the feedback control loop [2]. Mosaicking from post-processed video data taken from an ROV has been performed as well [2].

For the station keeping task, a reference image over the desired hover point is snapped and stored. Each subsequent image that is taken is filtered and correlated to this original image to determine its relative offset, which can then be used to feedback into a control law that will regulate the error to zero. A more complete description of this task will be provided in later sections.

Operation of the vision system on the *OTTER* vehicle in the test tank always involved good video quality due to the clear water and bright ambient lighting. The surface over which the station keeping task was performed was well-textured and planar, providing an ideal operating environment for the vision system.

C. Technology Transfer

Recently, this real-time station keeping technology was used on MBARI's ROV, *Ventana*, on a mission in the Monterey Bay, showing how autonomous control from vision can be transferred from a testbed robot in a benign environment to an operational vehicle in the ocean. The focus of this work was to prove the feasibility of using vision as a sensor for control in the ocean environment. The vision system was used to hover the vehicle in two degrees of freedom in the horizontal plane over a reference point on the ocean floor. Several control laws were designed and applied to observe the system's response. The transfer of this technology from *OTTER* was not trivial, as challenging issues arose that necessitated the customizing of the system implementation. The dynamics of the *Ventana* vehicle differ greatly from those of the *OTTER* vehicle, and the ocean environment added factors such as current and tether forces that affected performance significantly. Decreased video quality from that seen in the test tank, due to the presence of marine snow (light reflected off suspended particles) and poor, non-uniform lighting, also affected performance.

This paper will present a description of the station keeping task performed on *Ventana*, including the system setup and design. We will also present results from the first experiments to demonstrate the capability of vision as an operational feedback sensor which can be used as a pilot aid to reduce pilot workload. This mission is the first step toward creating levels of autonomy for an ROV that can be used to improve the execution of science missions and provide a new, inexpensive way of carrying out tasks underwater.

II. EXPERIMENTAL TASK

A. *Ventana* Vehicle Platform

The *Ventana* vehicle, built by International Submarine Engineering, has been operated by MBARI for its daily science missions in the Monterey Bay since 1988 (see Figure 1). Its dry weight without tools is 5150 lbs. Equipped with data collection sensors, specimen collection devices, and two manipulators, *Ventana* is capable of a variety of tasks in the mid-water range.

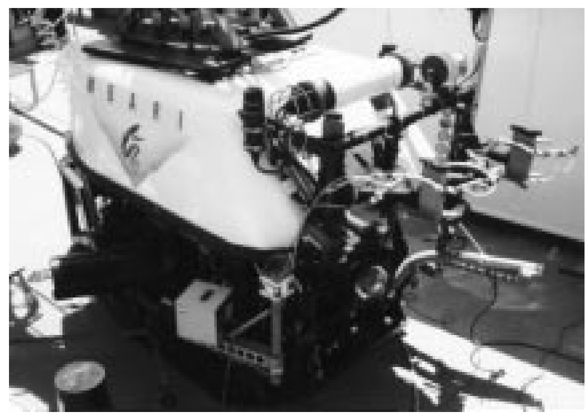

Figure 1: ***Ventana* vehicle built by International Submarine Engineering, owned and operated by MBARI for science missions.**

Its support ship, the Point Lobos, has a control room where the pilots and scientists can control and observe feedback from the vehicle. The vehicle is controlled remotely by a pilot through a 2100 m tether, which supports two-way communications. The vehicle is maneuvered by its six hydraulic thrusters, each with a servo valve manifold. The pilot controls the vehicle's position and orientation using these thrusters by operating a slide bar for depth and a joystick for all other degrees of freedom. The desired commands are sent to the vehicle's main control computer, which operates at 10 Hz. These commands are then sent as voltage commands to the thruster valves through the vehicle's tether. Telemetry indicating the vehicle's status from on-board sensors is sent back to the main computer through the tether and displayed for the pilots.

The pilot can also control the view from the main camera, a Sony DXC3000, which is on a three-axis pan-tilt mechanism. The video from this camera is displayed in the control room for the scientists to use in identifying specimens or locations of interest and for the pilot to use in determining the vehicle's position and orientation with respect to the environment. *Ventana* also has on-board lights to illuminate the underwater view.

B. Vision Processing and Interface to System

The real-time vision system uses the video stream from the *Ventana* vehicle that is sent into the control room of the ship as its input, and then processes the video for its autonomous control algorithms. With the assumptions that the surface viewed by the camera is planar and all rotation angles are small, motion in the $x-y$ plane of the camera view corresponds to lateral and forward motion of the camera base, depending on its distance from the surface and the camera's field of view (FOV). The video data is sent to the Advanced Vision Processor (AVP), a dual Pentium 133 MHz PC that runs vision processing software written by Teleos Research, now a division of Autodesk. The AVP snaps a digitized picture and stores it in a frame buffer. The buffered image is then filtered through a Sign of Laplacian of Gaussian (SLoG) filter and a window of pixels is aligned to a window in the reference image in a process known as correlation. The correlation techniques work well for images that are highly textured. Algorithms in the AVP determine the relative error vector in pixels, as well as the error velocity vectors, based on these correlations. The quantization of the vision system is four pixels for an image size of 512 x 480 pixels.

The AVP supports parameters such as filter width and correlation threshold that help adjust the SLoG for the environment's lighting or amount of marine snow present. The operator can tune these values on-line until the vision system can successfully correlate with and calculate relative errors to the reference point, or "lock on" to it, with the vehicle still under pilot control. Due to the sensitivity of the AVP system to image texture, the number of locations over which the station keeping task could be performed successfully was limited.

Once the system is operating correctly over the desired reference point, the pilot touches a button on his interface to begin automatic control of the appropriate degrees of freedom. During these tests, for which a bottom-looking vehicle would have its axial and lateral degrees of freedom under vision control, the pilot kept control of depth, and heading was controlled by an already-existing automatic loop that uses the vehicle's compass as the feedback sensor. Vision control commands are calculated using the error and error velocity vectors, then sent via serial link at 19.2 kBd to the main control computer, where they are summed with any pilot stick commands and written out to *Ventana*.

Also on-board in the control room is a workstation which can record data from both the vehicle main computer and AVP systems so that data from both sources could be matched for a given test run. This was used for the preliminary experiments shown in this paper, but data recording is now done exclusively by the AVP machine.

C. System Model and Control Law Design

Before designing a control law, it was necessary to determine a model of the *Ventana* vehicle system. Extensive work has been done determining dynamic models of underwater vehicles, as in [4]. These models are nonlinear and can involve extensive parameter identification. Since the focus of this research was to prove the capability of using vision as an ocean-going sensor, we focused on achieving stability with a simple model instead of aiming for high performance. As a first order approximation, we modeled the vehicle as a simple mass with no drag or added mass terms, and no coupling between any degrees of freedom. We also considered only linear motion, since the vehicle is relatively stable in roll and pitch, and the automatic heading control would be turned on during tests. Although complex nonlinear models of underwater thruster behavior exist [1], we again chose to use a simple model to maintain focus on the sensor and not system modeling or closed loop performance. A linear relationship was assumed to exist between voltage commands sent to the valve and thrust output from the thrusters. Thus, the simple preliminary model we used for motion in each direction took the form of $u = M\frac{d^2x}{dt^2}$, where u is voltage input, x is vehicle position in meters, and M is an unknown constant related to the mass.

In order to find the value of M, we mounted a Motion Pak sensor package, normally used on *OTTER*, onto the *Ventana* vehicle. This package, manufactured by the Systron Donner Inertial Division of BEI Electronics, Inc., contains three accelerometers and three gyros, so the sensor provides linear acceleration and angular rate measurements. This was used to provide a rough estimate of the linear acceleration of *Ventana* when given a unidirectional pilot stick input. A rough estimate of drag was also determined for use in some of the control designs.

A loop closure could then be modeled by including the vision system as a feedback sensor (see Figure 2). The vision system can determine position error in pixels, which can then be converted into meters using the approximation:

$$e_m = a(e_p \tan \frac{FOV}{w}) \quad (1)$$

based on the assumptions that rotation angles are small and the surface viewed is planar, where e_m is the position error in meters, a is the height of the camera base from the surface, FOV is the field of view in radians of the camera in water in one dimension, e_p is the error in pixels, and w is the length of the image in that dimension in pixels. Here, the image is 512 x 480 pixels. Velocities are then determined discretely. A voltage output can then be calculated based on the control algorithm being used. For this application, it is assumed that the camera is looking straight down so that the $x - y$ axes in the video image correspond to the vehicle's lateral and axial directions. This caused some problems when trying to station keep on sloped surfaces, though the pilot tried to compensate by adjusting the vertical control to keep the vehicle at a constant altitude during test runs.

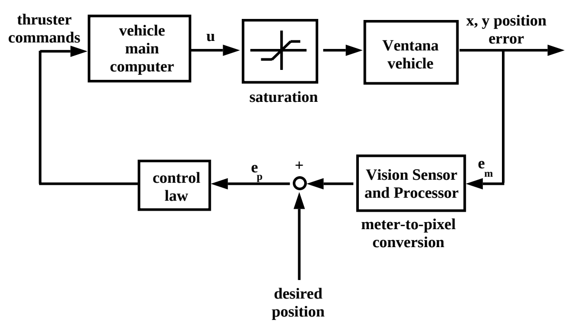

Figure 2: **System model of *Ventana* integrated with AVP sensor**

Although this system identification is simple, it allowed us to model and simulate the system sufficiently for our purpose. A discrete system model was used in conjunction with the nonlinear pixel-to-meter vehicle position error conversion, given a camera FOV of 72° and assuming an altitude of 1 m. The input voltages have saturation limits of ± 10 V. External disturbances such as current and tether pull could be included in the system model as well, although exact measurements weren't available when experiments were being carried out. Through this simulation method, preliminary estimates of parameters for various candidate controllers could be determined.

Since it was not possible to determine beforehand what type of controller would be the easiest to adjust on-line for the system, four different types of controllers were designed for the first set of experiments: PD, PID, sliding mode, and simple lead. There was no closed loop performance comparison done between the different controllers, so their design will not be discussed in detail here. The control loops run between 5 and 15 Hz, depending on whether or not a live video image was displayed on the monitor, as this slowed the processing down. The control efforts were slew-rate limited to prevent damage to the propellers.

While operating the vehicle under autonomous vision control, it is possible to alter several parameters on-line. AVP displays make it possible to change the vehicle mode (i.e., station keeping, mosaicking), the control mode (i.e., PD, PID), and the gains or controller parameters for each control law. Since the gains selected *a priori* were determined by an estimated plant and an assumed altitude, either of which could be different than predicted, this allowed the operator to fine-tune the gains while observing the vehicle's behavior.

Under certain circumstances, the vision system is unable to correlate successive images above a certain confidence level and loses its lock on the reference point. This can be caused by a decrease in the quality of the video, such as changing lighting or poor texture. For multi-image station keeping, if the vehicle lost lock on its target hover point, it would snap a new image and resume station keeping around that point. Ideally, this would result in only a steady state error from the desired target. However, the vehicle may drift if large external forces are present. To prevent the vehicle from drifting if it is frequently difficult to maintain lock, it was accounted for in the control output by including a bias determined by the average of the last known errors when a new reference image was snapped. This attempts to obtain zero offset from the original hover point and prevents drifting by applying a control against the direction the unmodeled disturbance had pushed it in before it lost lock.

III. EXPERIMENTAL RESULTS

Tests were conducted on several different dives, offering a variety of environmental conditions for the system. During each dive mission, we applied the different controllers one at a time and attempted to keep the vehicle stationary using the methods described above. For each control law applied, the same parameters were used for both the axial and lateral controllers. Results are shown here for a dive over clam fields using two different controllers, each over a unique hover point at a depth of about 900 m and an altitude of about 1 m. No truth measurement of the deviation of the vehicle from its desired position was available, so these errors simply indicate the output of the vision system. Video taken during the dives was also used as an indication as to whether or not the vehicle was holding station to within reasonable accuracy. Although it was often difficult to find textured surfaces over which the vision system could maintain lock, the sensor and control system was shown to be robust enough to perform adequately in the ocean environment over those locations with enough texture.

Figure 3 shows the pixel errors calculated by the vision system using a PD controller applied at a sample rate of about 15 Hz. These data indicates that *Ventana* was able to achieve marginally stable hover over a reference point using this control law. The position error for both degrees of freedom is bounded by approximately ± 50 pixels, or ± 0.15 m at the approximate altitude of 1 m. The mean of the lateral error was -2.4 pixels with a standard deviation of 18.1, while the mean of the axial error was 12.1 pixels with a standard deviation of 19.7. Figure 4 shows the control efforts applied for this test. Since the resolution of the pixel error determined by the vision system is 4 pixels and the data is not filtered before velocity is determined discretely, this led to spikes in the velocity calculation. This, in turn, appears as small spikes of about 0.25 to 0.75 V in the control commands.

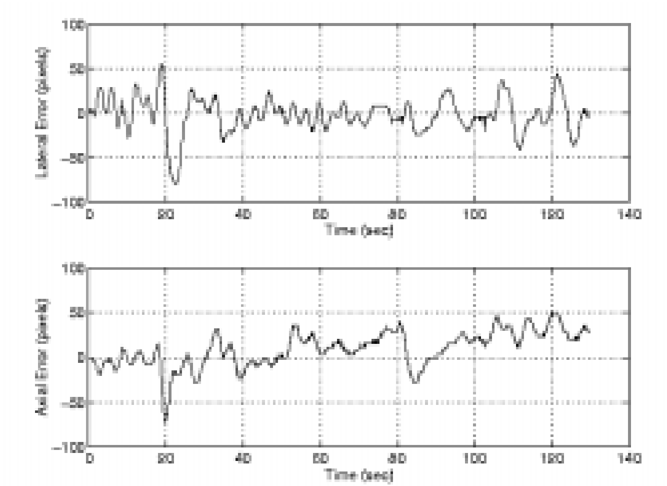

Figure 3: **Error time history for station keeping task: PD controller**

Error is shown in pixels for a 130 second test run; for the approximate altitude of 1 m above the ocean floor, 1 pixel is about 3 mm, so position error for this case remains within ± 0.15 *m.*

Results from the application of sliding mode control are shown in Figure 5. The error in the lateral direction was kept to within ± 12 pixels, or about ± 0.04 m, of the reference point, with a mean of 1.7 pixels and a standard deviation of 5.2. The axial error was within a +5/-30 pixel boundary, or approximately +0.015/-0.09 m, with a mean of -13.4 pixels and a standard

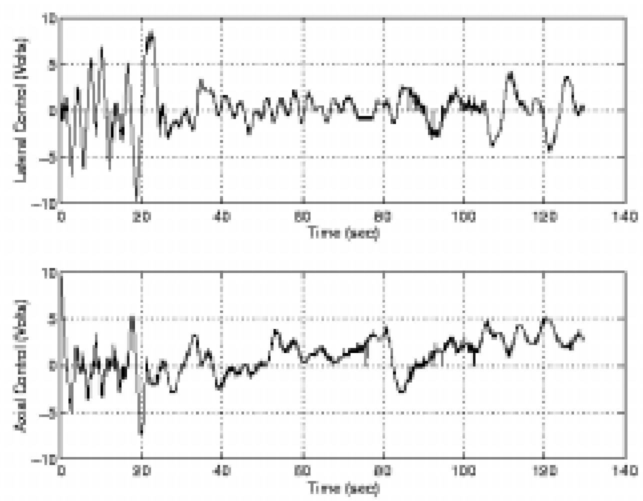

Figure 4: **Control time history for station keeping task: PD controller**

Control effort is shown in Volts, the units used to command the hydraulic thruster valves.

deviation of 7.8. Oscillation periods were between 2 and 3 Hz. In Figure 6, the spikes due to the vision system quantization of error can be seen more easily for this controller due to its lower range.

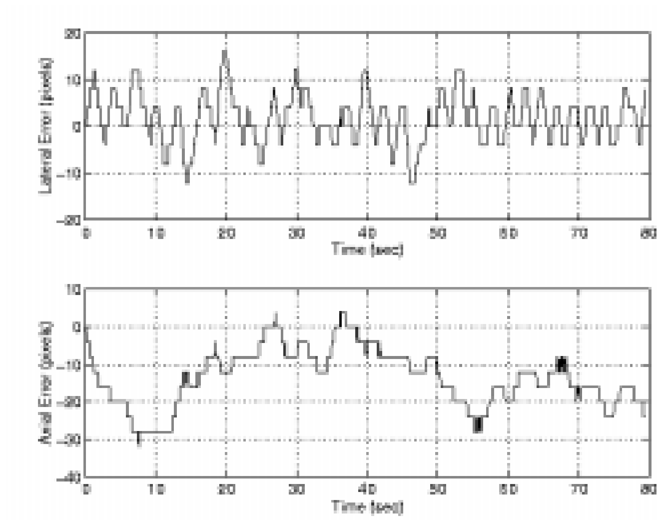

Figure 5: **Error time history for station keeping task: sliding mode controller**

Vehicle position error for this case remains within approximately ± 0.04 *m.*

The control parameters for both the PD and sliding mode designs shown here were tuned as well as possible in the alloted time for the tests in order to demonstrate the achievement of stability. Performance

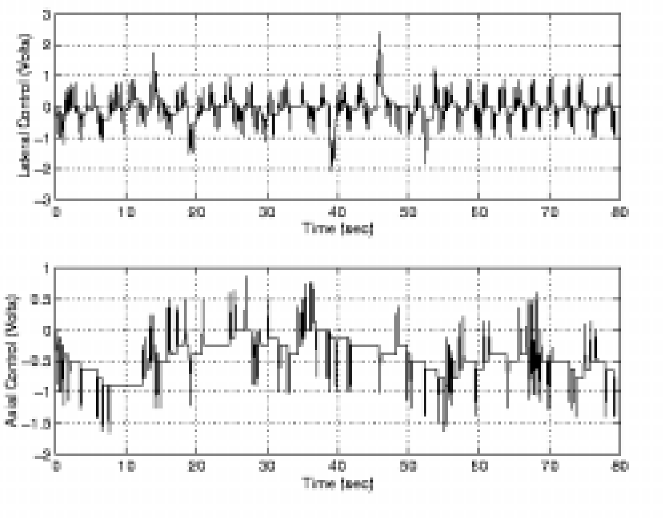

Figure 6: **Control time history for station keeping task: sliding mode controller**

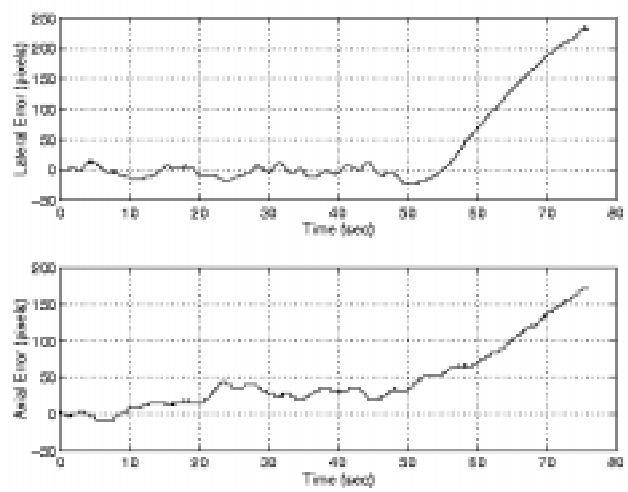

Figure 7: **Error time history for station keeping task: sliding mode controller turned off at $t = 54$ seconds**

This plot shows the position error in pixels for the vehicle when the sliding mode controller was applied for the first 54 seconds, then turned off to let the vehicle drift. This shows the affect of the external forces on the vehicle that the controller must work against to remain over the reference point.

could probably be improved by additional fine-tuning of the gains or using an adaptive design that would use estimates of the system model parameters to achieve better behavior.

Since there was no available way to measure the external disturbance forces acting on the vehicle at any given time, it was useful to observe the behavior of *Ventana* if the control was turned off. Figure 7 shows the vehicle error calculated when *Ventana* was under sliding mode control for the first 54 seconds, then afterwards when the pilot turned off the automatic vision controller inputs to the vehicle. The vehicle's drift indicates that there were in fact significant external forces such as tether pull and current acting on the vehicle that the controller was able to overcome in order to keep station.

IV. CONCLUSIONS AND FUTURE WORK

A. Conclusions

This work showed the successful achievement of two degree-of-freedom station keeping on an ROV using vision technology developed on the *OTTER* vehicle, showing that vision is a viable sensor which can be used for automatic control in the ocean environment. We were capable of interfacing with *Ventana's* current setup in the control room with relative ease. We were able to handle new issues that were presented, such as different vehicle dynamics and unmodeled external forces, as well as varying video quality that affected the performance of the vision processing system. Specifically, hover over a fixed reference point was achieved to within ± 0.04 m laterally and $+0.015/-0.09$ m axially using a sliding mode control law and within ± 0.15 m with a PD controller, even under the effect of large disturbance forces on the vehicle. These results demonstrate the feasibility of the vision system for this application with only a simple model; if better performance is desired, an improved system model could be developed and suitable control algorithms designed.

B. Future Work

There are several areas in which changes are being made since the execution of the tests presented here to improve both vehicle performance and ease of operation. In particular, the control law designs has been improved in various ways. The previous designs assumed a certain altitude and sample rate, but in reality both were changing during testing. The AVP system now reads data in from the vehicle's main control computer, which provides it with vehicle status parameters, the most important of which is altitude since it affects the vision pixel-to-meter calibration. Thus, control gains and parameters are now functions of altitude instead of being fixed. Also, the gains now take into account the variable sample rate of the control loop so that they are robust to possible fluctuations, and the time delay of the system has now been modeled and can be incorporated into the control law as well. To eliminate the spikes in the control calculations due to quantization, the position error is now filtered before calculating velocity. In addition, the bounds on the sliding mode controller are also better designed to take the system behavior into account.

In the previous setup, relative error data was printed out numerically to give the operator a rough idea of system behavior, in addition to the video display. Software to provide a graphical display of signals has now been incorporated and is used to plot the error and control values in real-time. This offers a better view of the vehicle's maneuverings and an improved sense of time response parameters such as damping ratio and speed of response.

Another significant advancement is the on-going work to control the vehicle in three degrees of freedom, achieved with the use of an altimeter placed on *Ventana's* camera boom. Successful station keeping missions were conducted in the Monterey Bay in the spring of 1997 using the altimeter for control of a third degree-of-freedom. This will allow the vehicle to station keep relative to not only a flat part of the ocean floor, but also sloped surfaces and walls, which are common areas of science applications.

These improvements mark the beginning of an effort to make this pilot aid more robust to the ocean environment. Including more of the available information into the design and analysis procedures will facilitate the iterations of tuning the controllers for each dive. The techniques involved in creating an automatic station keeping system can also be used in future autonomous modes for an ROV, such as mosaicking or navigation.

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