A Remote Monitoring System for Open Ocean Aquaculture

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***Abstract*- The purpose of this project was to determine the practicality and characteristics of a remote monitoring system for an open ocean aquaculture fish cage. The Open Ocean Aquaculture program at the University of New Hampshire currently uses two fish cages to develop the technology and methodology to raise finned fish in the open ocean. The cages are located about six miles offshore in the Gulf of Maine, making daily monitoring both expensive and time consuming. Scientists and aquaculture farmers, therefore, need a way to remotely observe fish feeding habits and growth on a regular basis without having to visit the cages themselves and eventually control the feeding and offshore operations monitoring remotely.**

This project was a first-order feasibility study on the utility of using optical and acoustic sensors to monitor the submerged North Atlantic Halibut (*Hippoglossus hippoglossus)* fish cage, and remotely telemeter data back to shore. There, scientists will be able to monitor the status of the fish and feeding operation. Video and sonar systems were selected to image fish in the cage, and a radio telemetry system was tested on the cage's feed buoy. Imaging capabilities of the optical and acoustic systems, and the data transfer capabilities of the telemetry system were tested.

Preliminary results for this feasibility test are encouraging. Adequate imaging cannot be accomplished by camera or sonar alone. Further testing and development is required, but after a first-order analysis of results, a dual system is recommended for fish cage monitoring. In addition, the telemetry system seems feasible.

I. INTRODUCTION

This project examined the feasibility of developing a remote monitoring system for an open ocean aquaculture fish cage. The University of New Hampshire (UNH) Open Ocean Aquaculture program currently uses two fish cages to raise finned fish in an experimental program (Fig. 1) [1]. The cages are located in the Gulf of Maine approximately six miles offshore of Portsmouth, New Hampshire near the Isles of Shoals, making daily monitoring both expensive and time consuming (Fig. 2). The scientists, therefore, need a way to remotely observe fish feeding habits and growth on a regular basis without having to visit the cages themselves.

The overall goal of the UNH Aquaculture effort is to stimulate the further development of commercial aquaculture in New England, thereby increasing seafood production, creating new employment opportunities and contributing to economic and community development. To accomplish this, UNH is working at a demonstration site to (1) develop the technology and engineering tools to deploy open ocean fish containment structures, (2) develop the methodology of feeding and maintaining an open ocean aquaculture operation, (3) study various finfish as candidates for aquaculture in the Gulf of Maine, and (4) transition these findings to the commercial sector.

This project was a first-order feasibility study on the utility of using optical and acoustic sensors to monitor North Atlantic Halibut (*Hippoglossus hippoglossus)* (Fig. 3) in a submerged fish cage and to remotely telemeter data back to shore. There, scientists will be able to monitor the status of the fish, particularly during the feeding operation. Video and sonar systems were selected to image the fish cage, and tests were carried out from aboard the R/V Gulf Challenger. A radio telemetry system was installed on the cage's feed buoy and its data transfer capabilities were set up to be tested for one week. In addition to the selection and testing of hardware, the second goal of the project was to carry out a cost comparison for the two monitoring systems and to provide recommendations based on capabilities and cost.

Fig. 1. Photograph of the Ocean Spar fish cage at the surface during deployment. These cages have been used to raise summer flounder, haddock and cod. The cage that was imaged during this study was submerged and was being used to raise halibut. The commercial fishing boat in the background was deploying the mooring system for the fish cage system [2, 3, 4].

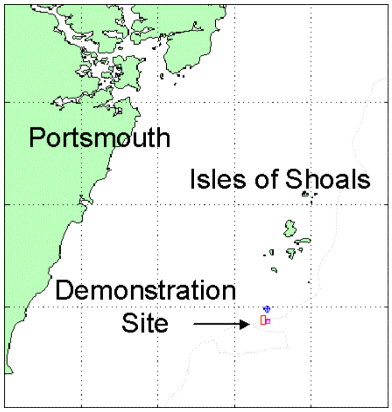

Fig. 2. A map of the coastal waters of the Gulf of Maine off New Hampshire showing Portsmouth, NH, the Isles of Shoals, and the fish cage site. The site is six miles off the NH coast in 52 meters of water [2].

Fig. 3. Close-up of a 30g halibut (*Hippoglossus sp.*) at the R&R Finfish Development Ltd. Facility in Digby, Nova Scotia [1].

II. OBJECTIVES

As stated above, the goals of this project were to determine the feasibility and cost of a remote monitoring system for the submerged UNH fish cage. The cage itself is octagonal, with a 15-meter main axis, and ten meters tall (Fig. 4) [5].

The cage is completely submerged and is attached via a compliant feed hose to a surface feed buoy (Fig. 5). Approximately 1,700 halibut, each about 30 centimeters long, live in the cage. This project was broken down into three tasks:

1. Image fish in cage using both optical and acoustic sensors.
2. Characterize a spread spectrum radio telemetry link from the food buoy to shore.
3. Compare the monitoring sensors for their potential benefits to the system as a whole and the ability to provide the required information for control and monitoring of an offshore aquaculture effort.

The experimental system consists of three parts: an underwater still camera for optical imaging of the fish in the fish cage, an Imagenex scanning SONAR for acoustic imaging of the fish, and a radio telemetry system for sending the imaging data back to shore. The testing was designed to determine the following characteristics.

Optical System

1. The usable range of the Deepsea Power and Light SeaCam camera, with consideration for the camera characteristics and physical factors.
2. The number of cameras needed to image the entire cage.
3. Type of light, ambient or artificial, required for good imaging.
4. Required power and amount of data collected.

Acoustic System

1. Ability of acoustics to image the fish
2. Length of time needed to scan the entire cage.
3. Optimum acoustic frequency.
4. Required power and amount of data collected.
5. Ability to calculate fish biomass.

Telemetry System

1. Amount of data that imaging systems will produce.
2. Robustness of telemetry link.
3. Maximum data transfer rate.
4. Constraints on data being transmitted given telemetry link characteristics.
5. Required power.

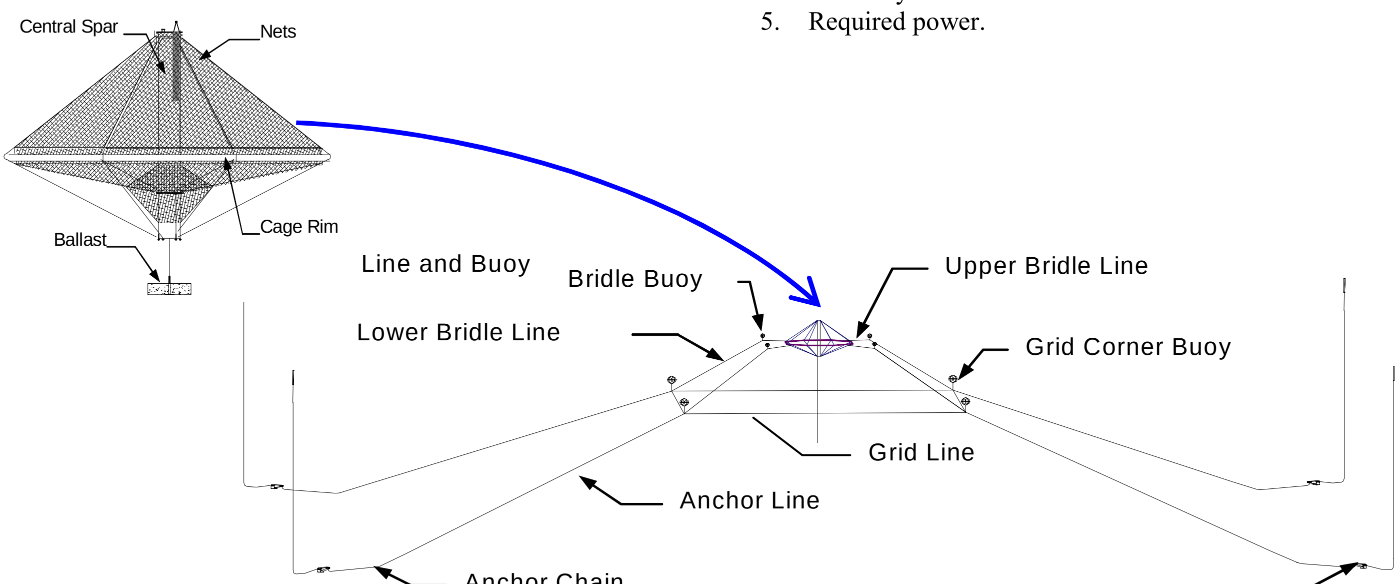

Fig. 4. Open ocean aquaculture fish cage [2].

Fig. 5. Surface feed buoy platform for controlling the feeding operation, observing the fish in the cage below and telemetering the images to shore [2].

III. SYSTEMS OVERVIEW

A. Optical System

The optical system consisted of a Deepsea Power and Light Multi-SeaCam, underwater cabling, a power supply, a standard video monitor, and a video recorder. The housing of the camera was titanium, making it corrosion resistant and giving it a depth rating of up to 6,000 m. The camera was rated to a much higher depth than is necessary for this application. Therefore, in an actual set-up, a less expensive camera, with a lower depth rating could be used. The camera is equipped with fixed focus optics. The camera lens used in this test is a 2.9 mm, f1.8 wide-angle lens. The camera is capable of focusing as close as 10 cm. In water, the field of view is 75° (H) x 92° (V) x 81° (D). The camera uses a 1/3" CCD image sensor, and works between -10°C and +40°C. A cable connected to the camera provided power (11-30 volts DC) and allowed the images to be sent to the video system inside the R/V Gulf Challenger (Fig. 6) [6].

B. Acoustic System

The primary component of the acoustic system was an Imagenex Model 881-000-420 Digital Imaging/Profiling Sonar Head (Fig. 7). This particular unit is multi-frequency, capable of operating at 1MHz, 675 kHz, and 310 kHz, with 1.4 deg., 2.4 deg., and 4.8 deg. beamwidths, respectively. The unit can image objects at a range of 10-50 meters, depending on operating frequency. Power required is 22 - 48 VDC at a maximum of 1A. Maximum operating depth is 1,000m. This unit has an azimuth control to the standard 881A sonar head that allows two axes of motion to enable the entire fish cage to be imaged [7, 8].

The sonar unit was controlled by a Toshiba Satellite personal notebook computer, running WIN881A, a Windows program that controls, displays, and records data from the sonar head. WIN881A uses a 2-wire RS-485 COM port to communicate with the sonar head.

Divers attached the sonar head to the middle of one of the sides of the fish cage near the rim, as shown in Fig. 8. The transducer was not exactly in the same plane as the cage rim, as will be shown in the results. The sonar was attached to the fish cage netting, and therefore moved slightly with the waves and currents, between and during images. This provides some unnecessary distortion to some images that would not be present with a permanent installation to the cage rim.

Power and communications cables ran up from the sonar unit to the ship and into the lab. From the ship's lab, a number of tests were run to characterize the capabilities of the sonar system, in relation to the movement and characteristics of the fish in the cage (Fig. 8).

Fig. 6. Video equipment setup on boat.

Fig. 7. Imagenex two axes SONAR system. The red section houses the pencil beam transducer, the grey section houses the electronics and motor for the 881A and the black case houses the azimuth rotation motor, control and overall electronics for the system.

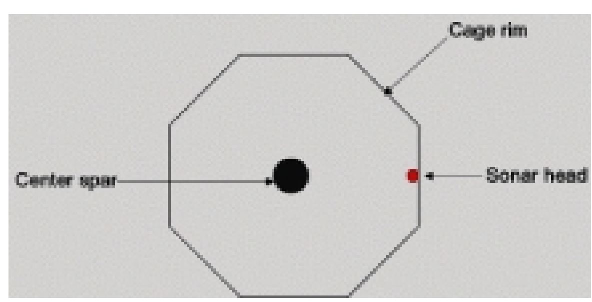

Fig. 8. Top view of the fish cage, with the sonar head mounted to the center of one of the sides.

C. Telemetry System

The telemetry system consisted of a Persistor CF1 microprocessor and a Data-Linc SRM6000 spread spectrum radio modem (Fig. 9) [9]. Both were enclosed inside of a waterproof PVC housing along with a battery pack of three parallel 12V batteries (made of 8 D-Cells each). In a final, working system, the Persistor would:

1. Turn on at user specified interval such as two times a day to allow for power saving.
2. Power-up acoustic and/or optical system and gather data for a set length of time.
3. Power up the RF modem and send data files to shore.
4. Receive user input while the RF modem is powered up to change sampling or fish feeding parameters.
5. Enter low-power mode.
6. Return to step one at correct time.

In our test system, the Persistor was set up to send a fixed test data file, a temperature reading from a thermistor outside the pressure case, and a battery voltage reading to shore for a period of one week. It operated as follows:

1. Turn on at user specified rate of once/hour or twice/hour.
2. Warm up the radio for one minute, during which the user can telemeter into system to change parameters.
3. Sample the system battery voltage and the air temperature (thermistor voltage divider).
4. Transmit the temperature, battery and fixed data file.
5. Leave the radio on for one minute during which time the user can telemeter into system to change parameters and the remote radio can continue sending the data if the transmission link is poor and it has had to retransmit many packets.
6. Enter low power mode.
7. Return to step 1.

The temperature was sampled with a thermistor, placed outside of the housing. The thermistor's voltage divider circuit was wired directly onto the Persistor board. The battery voltage was also measured directly from the Persistor board (with a 6:1 voltage divider), and the analog battery and temperature signals were digitized by the Persistor's 12 bit A/D converter [10].

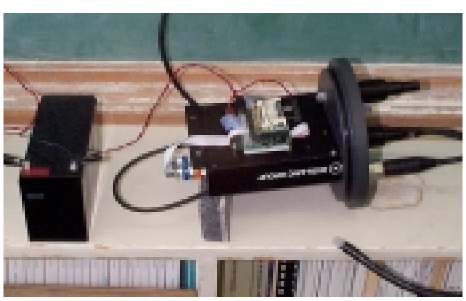

Fig. 9. Radio system being tested in lab prior to sea trials.

The user could telemeter into the system for two minutes per transmission cycle by typing a Ctrl-C command. The user was then prompted to change the sample rate between once/hour and twice/hour. The fixed file sent was a 56.8 kB binary data file converted into a 113.6 kB hex file upon sending. Although the hex file was larger, it was more useful as sample data, because it could be easily seen on the monitor as it was received. The test data is similar to the acoustic or optical data that would be sent once the final system is complete.

To test the system, it was mounted on top of the feed buoy (Fig. 10) and set up to communicate with the shore station, an RF modem at the UNH Seacoast Science Center. The on-buoy radio was set to talk to the Persistor at 9,600 baud, while the on-shore radio was set to talk to its control computer at 19,200 baud. The two radios communicated at 114 kbaud.

IV. RESULTS

A. Optical System

The first objective of the optical system test was to determine if optical imaging would give a good picture of what was going on inside the cage. The camera was first placed in the cage, and the video screen remained black. The divers discovered that the cage was covered with a thick mat of algae. Ambient light was not able to penetrate the algal mat therefore making the inside of the cage very dark. A diver then took a dive light into the cage and the illuminated diver could be seen in the video all the way from where the camera was mounted at the rim of the cage to the central spar, a distance of approximately seven meters. Fig. 11 shows that it was possible to see a fish when a light source was used. This was using a narrow beam of light. The camera was able to capture the entire diver, which demonstrated that a large field of view is possible with even a limited light source.

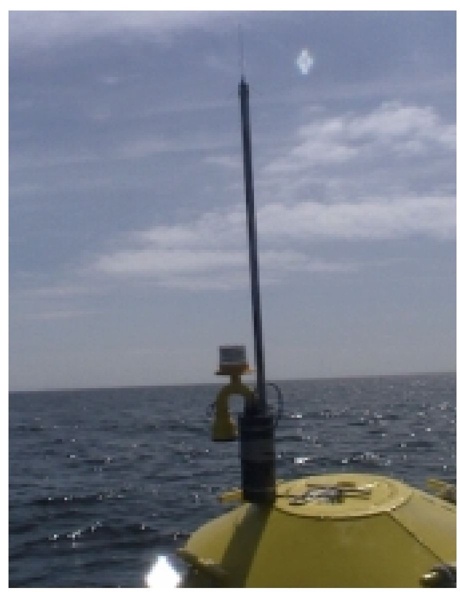

Fig. 10. Radio antenna on feed buoy.

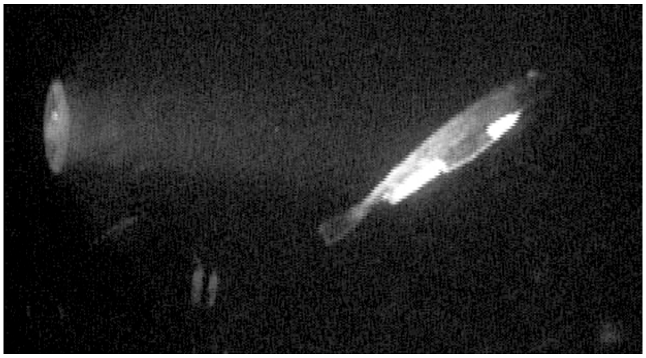

Fig. 11. Image of a fish as seen in the cage with a dive light as illumination.

1) Optical Solution

If the cage was not covered in an algal mat, ambient light may be sufficient. If additional light is needed, it could be added with strobe lights or continuous lights. The divers reported that the water in the cage was very clean as a result of the filtering of particles by the algal mat, therefore, eliminating backscatter. A light source could then be used without worrying about backscatter. However, when additional light is added, the effect on the fish must be considered. Biologists urge against the use of strobe light as the sudden flash startles the fish and instead they suggest the use of a steady light. As part of biological studies it has become apparent that continuous light delays the sexual maturity of some fish and allows for more meat growth before energy is spent on gonad development. This is a definite plus for aquaculture. A continuous light is therefore recommended to be used if ambient light were not sufficient. It must be noted however that one drawback with the use of continuous light is that it has a significantly higher power requirement than strobe lights.

The placement of the cameras must be considered to allow for the best imaging. The present day aquaculture use of video images places the camera at the bottom of the cage looking upward. This allows silhouettes of the fish to be seen against the sky since fish tend to swim horizontal. These images are therefore less subject to light variations than normal images, but details on the fish cannot be seen. Also, a camera directly under the feeding tube can image the feed falling through the cage and detect when the fish are finished eating and the feed is falling out of the cage. Since feed is a significant cost in aquaculture, optimizing its use is paramount.

Since the results of the halibut imagining in the offshore cage were poor, the SeaCam with an Axis 2400 Video Server [11] digitizer was used in a shallow cage under the dock at the UNH Coastal Laboratory which contained small cod fish. The camera was placed at the bottom of a cage located two meters underwater (Fig. 12). The shadow in the upper right was caused by a cover to prevent birds from “lunching” on the fish and to prevent sunburn on the juvenile fish. These additional tests on the small cod with a camera looking upward resulted in quality images. Feed was tossed

Fig. 12. Small (about 6-8") cod fish from the SeaCam in an upward looking configuration imaging the fish near and far from the camera in a coastal fish cage. The black dots between the fish are feed pellets that were thrown into the cage to simulate the release of feed by the feed buoy.

into the cage to see if it could be imaged, and was seen falling past the fish, indicating that they were through eating and it was time to stop supplying feed. This image (Fig. 12) easily allows the food and the fish to be distinguished and the feeding operation monitored. However, the range of fish imaged is much smaller as the coastal cage does not have the depth or volume of the offshore cage.

Using two cameras is also beneficial since their images can be used to determine the size of the fish. By taking stereo pairs of images, standard software can be used to determine fish distance and size. Therefore, several pairs of images could be taken, then telemetered over the radio link to shore. Then using the software, in 15-20 minutes the size of a dozen fish could be compared.

2) Optical Advantages and Disadvantages

The advantages of an optical system are that it is easy for people to use and it will monitor the feeding very well. People are used to looking at video images and know how to interpret the images. However, several disadvantages exist with this system.

A camera system may not provide an accurate view of the fish if a significant number of the fish are in the bottom of the cage. If lights are used, they would require a lot of power, which is not practical for a battery run system. Since strobes are not feasible, continuous illumination would require significant power.

Another consideration is that for accurate imaging, a good lens is required which adds cost. With two cameras, stereo images can be made allowing fish size to be obtained with standard software. However, distortion free lenses would be required. Aquaculture has traditionally used wide angle lenses to see more of the fish cage, which is quite expensive to do with high quality lenses, and can also produce inaccurate results.

B. Acoustic System

1) Optimum frequency

Frequency tests were inconclusive. The sonar was able to scan the entire cage using the frequency range available (310kHz-1MHz). Fig. 13 shows an image of the cage, using a 1MHz frequency and 20-meter range. This configuration gives good resolution all the way to the opposite side of the cage. The upper right portion of the fish cage shown in Fig. 14 has clearly distinguishable lines outlining the net and cage rim. The two cannot be distinguished in the bottom of this image because the transducer is slightly tilted. The central spar is in the middle of the cage, and it blocks a portion of the cage rim opposite the sonar head.

Individual fish were not identified at any frequency, however a group of fish may be seen in Fig. 15 as the green mass directly in front of the sonar. Fig. 16 shows that a diver can be identified in the sonar image.

2) Scan duration

The amount of time required to scan the cage depends on the geometry of the cage and the parameters of the sonar (frequency, beamwidth, etc.). When the sonar head is mounted at the middle of one of the rim cage sides, it must rotate a maximum of 210 degrees, and the azimuth angle is a maximum of 110 degrees. For 1MHz imaging, it takes approximately six seconds per horizontal scan (210 degree). Twenty-five scans are required to image 110 degrees in azimuth, so the maximum scanning duration is 150 seconds – about three minutes. This time could be reduced if the horizontal sector length were reduced as the sonar head images the top and bottom of the cage. Fig. 17 and Fig. 18 show that the sector angle can be reduced when moving away from the horizontal.

In addition, the azimuth increments can be optimized according to beamwidth, which depends on the selected frequency. However, the time to take an acoustic imaging by scanning the cage is still more than one minute long, and more accurate imaging requires more time as the sonar head moves slower to allow time for digitizing the additional data.

The cage needs to be imaged quickly as the fish are active swimmers. For example, having an image of 3,400 fish, when there are 1,700 in the cage, is undesirable. How fast the fish actually move could be quantified over a long period of time using sonar and cameras. The volume seen by the acoustic system half way across the cage is ½ m by ½ m by 10 cm, so can not resolve individual fish, but returns the scattering strength which can be related to the size and number of scatters.

3) Fish biomass and scattering

After conducting the acoustic tests, it was discovered that the haddock in the cage had not yet fully developed their swim bladders. The swim bladders are the most acoustically reflective organ because of the air-water interface. Therefore, the type of fish and age is critical when using this type of acoustical imaging. Additional

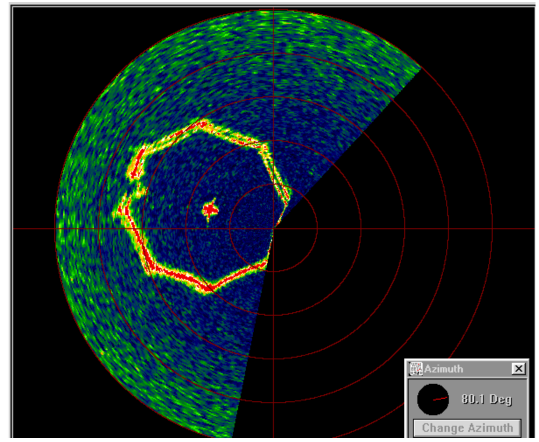

Fig. 13. Scan of fish cage.
1MHz, 20m range.

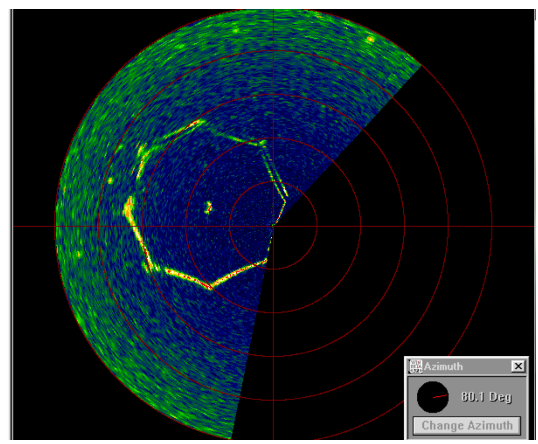

Fig. 14. Change in gain (23dB).
1MHz, 20m range.

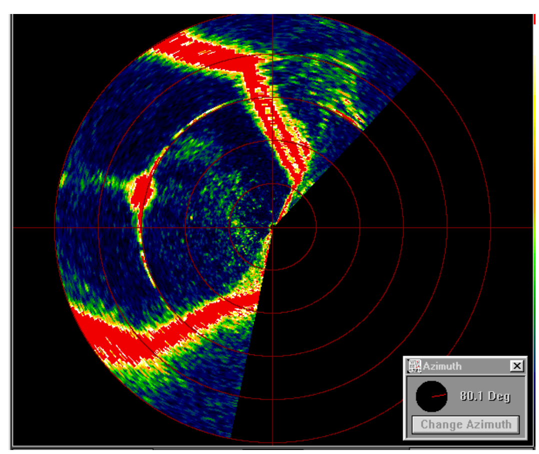

Fig. 15. Possible school of fish in cage.
675kHz, 10m range.

tests on some small cod being grown in a cage before transfer to the offshore cages were more successful (Fig. 19). The individual and groups of fish were easily imaged, and so the acoustic backscattering could be integrated to get total biomass estimates. However, again the imaging volume of the sonar is generally much larger than one small fish. The geometry can be determined from the transducer beam pattern. Once the swim bladders can be distinguished by the sonar, the biomass in the cage can be calculated from the size and number of bladders in the cage. The biggest drawback it that it takes minutes to get a detailed image which may not be an effective solution for swimming fish.

4) Interference

One unexpected roadblock encountered was external interference. Fig. 20 shows the Gulf Challenger's echosounder interfering with the received acoustic signal. Echosounders typically operate at low frequencies (up to 200-300 kHz). If a permanent sonar system is to be installed on the cage, it should not use a low frequency if images are required when a service vessel with operating sonar is nearby. However, this is unlikely most of the time.

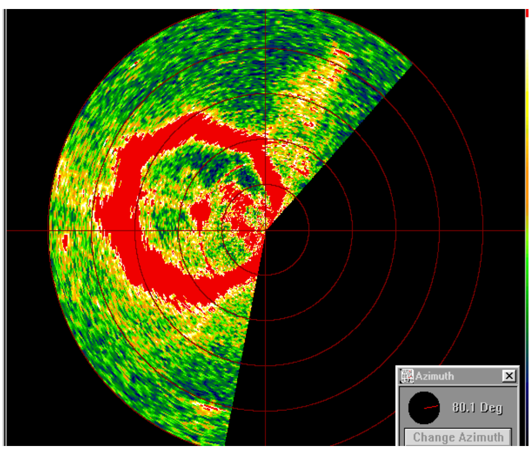

Fig. 16. Fish cage with diver in front of spar.
675Hz, 20m range.

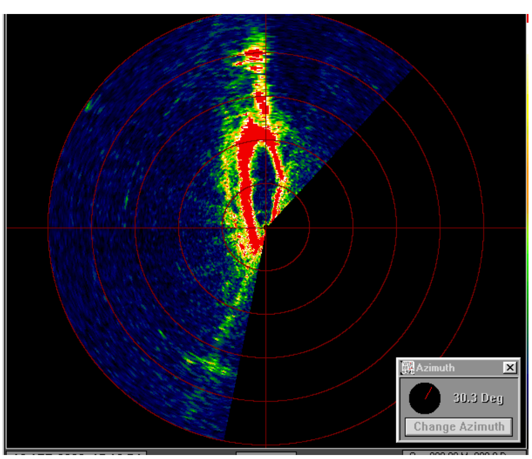

Fig. 17. Image of the top of the cage.

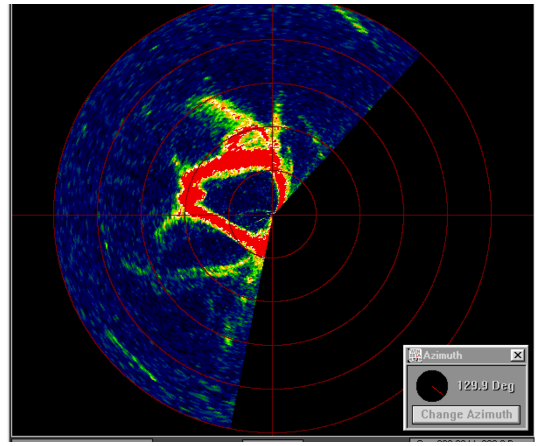

Fig. 18. Image of the bottom of the cage.

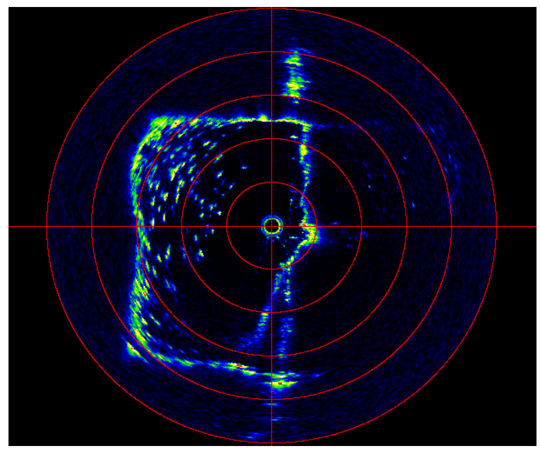

Fig. 19. Acoustic image of cod in a near-shore cage. The bottom of the cage is the left most part of the image.

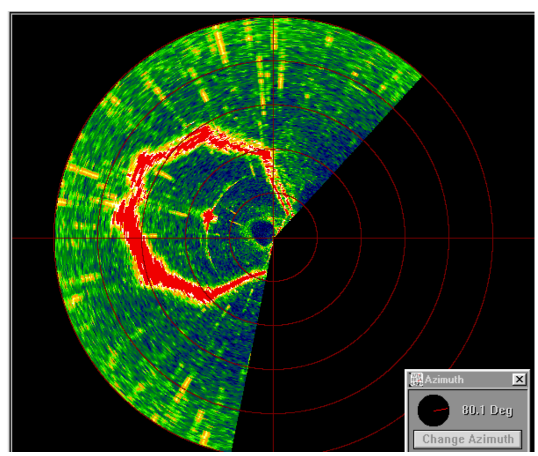

Fig. 20. Echosounder interference.
370kHz, 20 m.

C. Telemetry System

The telemetry system worked well during bench tests, and uncorrupted data was received at the correct times by an RF modem in the lab. However, when the system was placed on the feed buoy for a week, the shore station received no signals from it. The shore station did not receive the data because the RF transmission power was nearly zero. This problem was discovered once the system was taken back to the lab after the failed telemetry attempt. It still worked in the lab, because the low power required to produce enough signal strength to communicate over short distances – several feet. The radio system failed because the coaxial connector in the radio had a broken center connector that did not make contact with the antenna.

The system was repaired, and tested on land sending the file and diagnostic data to the radio at both 9,600 and 115,200 baud over the same distances as at sea – about five miles. The files were sent during two overnight tests without difficulty or errors. Plans are underway to continue tests of the radio link on cruises the offshore site and from a wave rider buoy during summer 2002 to determine the optimum configuration and capability to connect a computer on a moving platform with the shore based support team.

V. CONCLUSIONS and RECOMMENDATIONS

The preliminary studies show promising results but raises a number of issues that must be addressed in order for the imaging to be effective. Optical tests involved the characterization of a Deep Sea Power and Light Multi-SeaCam, and the determination of the physical properties in and around the cage. It was found that an algal mat of at least six inch thickness had grown over the cage. This mat blocked all ambient light from entering the cage, but it also cleaned the water inside the cage. This resulted in an extremely low light environment, with very little particulate matter that would backscatter artificial light introduced into the environment. The camera used requires a high light level to get an image and therefore the images obtained were poor. A low light level camera may have worked in this environment. Light level and variations in light need to be further studied to optimize camera and power requirements.

An acoustic system has the potential to provide fish biomass information. An Imagenex scanning sonar was tested as a possible alternative to optical methods. The sonar was able to scan the entire cage using the frequency range available – 310 to 1,100 kHz. The fish, however, had not yet developed their swim bladders, so no conclusive data could be gathered on the effectiveness of acoustic methods.

To send the data back to shore, a radio telemetry system is recommended. Although electrical problems prevented the experimental telemetry system from working, identical systems have been used for similar long distance two-way communication, and have functioned properly. The spread spectrum technology appears to work well, but severely limits the amount of data (number of images) that can be telemetered. Another possible solution to this bandwidth problem may be to use the new Ethernet modems, although their power and range are marginal for this application. Their large advantage is speed, e.g. 11 Mbps data rate.

After examining the results of these preliminary tests it is recommended that several different solutions be tried to minimize the power consumption and cost. The solutions are described here in the order in which they should be tried. The cost increases with each subsequent solution.

1) A pair of cameras should be placed in a looking upwards configuration with a known separation. The cameras would image an overlapping area to allow for redundancy of imaging and to allow for stereo imaging. The sole light source would be ambient light and the fish would be fed twice per day. A basic waterproof camera, with a plastic casing, can be purchased for ~$300. [12] This type of camera uses only 130mA of power and can be used with about 100 times less light than the camera used in this experiment. An underwater camera can range up to a cost of about $1200 and up to about 300mA. This solution will determine if the imaging can be done with a low light camera and only ambient light. This solution is the least expensive and uses the least amount of power.

2) A faster telemetry system would be tested which would allow the images to be taken at a speed that would allow them to create almost a real-time video of the fish feeding. A standard spread spectrum radio has a baud rate of 120kbps and costs $1,000 for each one, with two being required for this application. Each one uses one watt of power and can accept Ethernet or RS232 serial input. A high end telemetry system could use a wireless Ethernet modem (e.g. Esteem Model 192E) with a high telemetry rate of 11Mbps. Again two are needed and they each have a cost of $2,000. Each wireless modem uses 800mA for transmitting data and 300mA for receiving data. One issue that would need to be explored is how reliable the wireless modems are when used on a moving platform. The high speed modems are rated for traveling up to five miles and all of these radios are "line-of-site" transmissions.

3) Additional cameras could be used for imaging. This would enable more area of the cage to be imagined. A total of six cameras would be required to image the full cage. The Axis 2400 Video has inputs for four cameras, so two could be used for the stereo pair, and two more easily added elsewhere.

4) Acoustics has the potential to allow estimation of the biomass in the cage. Emerging technologies in acoustics should be explored. A higher resolution, but more costly acoustic solution, would be to install a system such as the Dual Frequency Identification Sonar (DIDSON), which has been designed and built at the University of Washington Applied Physics Laboratory. DIDSON operates at two frequencies and can image objects from 1 to 30 meters in range. It results in near-video quality images that can be used to identify objects under water (Fig. 21) [13].

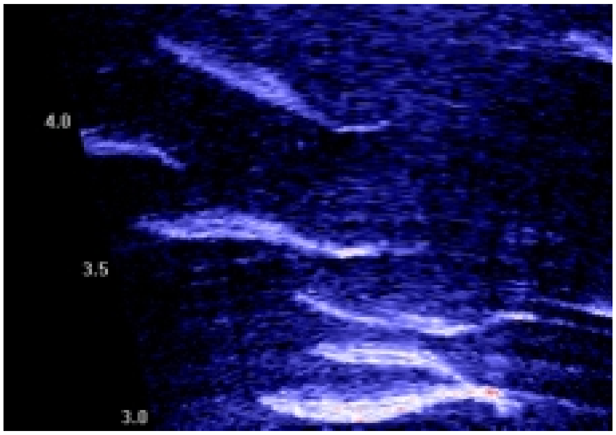

Fig. 21. Image taken with a DIDSON of adult salmon swimming at a range between two and four meters. [10]

The 2-axis Imagenex system used in the tests costs approximately $18,000, while a DIDSON system (still under development) would be about $80,000. The difference is a rather large price jump, but may be a worthwhile investment, as the DIDSON image quality is significantly better than the Imagenex. An additional cost of ~$2,000 would be necessary for a microcontroller that would be used between the sonar and telemetry link.

For all solutions a $1,300 video server, for example the Axis 2400 server, is necessary to digitize the images and to put them out on a serial port with a radio modem or by Ethernet. A microcontroller would be needed to turn on the video. This microcontroller could also be used to control any necessary lights and feeding operation. Therefore, this microcontroller is probably necessary for all of the above solutions. The microcontroller uses negligible power.

Preliminary results for this feasibility test are encouraging. Further testing is required to determine the best solution for the fish monitoring and to determine an effective telemetry system.

Acknowledgments

We would like to thank Dr. A.J. "Sandy" Williams, Dr. Hanu Singh, and Robin Singer of the Woods Hole Oceanographic Institution for sharing their engineering expertise with us. In addition, many thanks to Michael Chambers, Glen Rice, and Randy Cutter of the University of New Hampshire, and the Captain and crew of the R/V Gulf Challenger for the field work assistance.

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