ICES CM 2011/F:06

Autonomous underwater vehicle based camera and side–scan sonar assessments of scallop grounds in West Iceland

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Abstract

Autonomous Underwater Vehicles (AUVs) offer a new platform for fisheries studies. The use of an AUV survey technique for population density estimates of the Iceland scallop is briefly presented in this paper. The study analyzed part of the data set gathered during a pilot survey carried out in a defined site in Breidafjordur, West Iceland. For a chosen site, fundamental sampling theory and a statistical modeling approach was used to estimate abundance of scallops from the count data that were obtained from the digital photographs. This work was mainly an illustration of the analytical methods which can be applied to prospective data sets for larger areas from this region.

Keywords: AUV, abundance estimate, Iceland scallop

1 Introduction

Autonomous Underwater Vehicles (AUVs) offer a new platform for fisheries studies (Fernandes et al., 2003). The AUV approach to fisheries stock assessment is an emerging field of research.

Various benefits of AUVs over other survey techniques are known and use of AUVs has become popular for mapping and survey missions (Yoerger et al., 2007). One of the main advantages is the downward facing camera on an AUV. This feature is important to photograph an area of a known size, which plays an important role in the estimation of the area covered by the survey on the seafloor. The Doppler Velocity Log (DVL)-aided Inertial Navigation System (INS) on the AUV maintains the bottom-tracking and regulates the pitch and roll of the vehicle, which in turn helps the camera to photograph from the correct angle. It is also possible to take sufficient replicates in a defined area, which is important for reliable variance estimates. It should be noted that the common assessment methodology of counting organisms from a dredged sample will only give indices of abundance whereas images can in principle give absolute abundance under certain conditions. This survey technique is also not affected by the catchability, gear efficiency and by-catch issues inherent in the traditional survey methods.

AUVs have been applied for fisheries studies previously, although the number of studies are limited. Benthic evaluations have been carried out with the Seabed AUV to map the deep water coral reefs off of Puerto Rico and Bermuda (Singh et al., 2004a). This study, together with Singh et al. (2004b), was used to test the framework of the Seabed AUV designed for high resolution imaging, bathymetric, and side-scan sonar surveys. The abundance of a groundfish was estimated from AUV images by Tolimieri et al. (2008), in the West Coast of USA. The population distribution was also related to the different substrate types. Images were taken along a number of parallel transects from which a selection of random frames were used to identify and count organisms to estimate their biomass, and typify the substrate types. The unresolved issues in the study were avoidance by the fish and size estimation of individual fish. Other studies such as Armstrong et al. (2006, 2009) evaluated the percent of coral cover, and distribution of other benthic reef-dwelling organisms. Similarly, Rivero-Calle et al. (2009) also showed that the AUV images were adequate to identify the different genus of corals, sponges, and non-motile invertebrate species. All three studies used the Seabed AUV, and focused mainly on digital imagery. The most recent work by Williams et al. (2010) showed how AUV imagery can complement multibeam bathymetric surveys by superimposing the biological information onto the bathymetric map. The study was carried out in the deep rocky reef systems off Tasmania. Data were collated from multibeam sonars, ROVs, underwater towed cameras, and AUVs to study biological assemblages of reef systems.

The approach here was to investigate the AUV survey technique for macrobenthic organisms. These organisms have minimal movement hence are well suited for initial surveys, with primary focus on technical evaluations, thus the interference of the behavior of the organisms was avoided. The primary species of interest was the Iceland scallop *Chlamys islandica* (O.F. Müller), located in Breidafjordur, West Iceland.

In the past, assessment of scallop fisheries have been done with video surveys by e.g. Stokesbury et al. (2004) and Rosenkraz et al. (2004). One of the major studies of sea scallop abundance is the HabCam project which looks at the Atlantic sea scallop in the Northwest Atlantic and uses a towed camera system to take photographs of the seabed (Howland et al., 2006). Image processing techniques are used for automatic detection of scallops, size measurements, and benthic characterization (Gallager et al., 2005, 2009). A similar towed camera system has been developed, in collaboration with HabCam, to conduct the stock assessment of weathervane scallops in Gulf of Alaska (Rosenkraz et al., 2009). The Iceland scallop is generally smaller in size than the Atlantic sea scallop and the weathervane scallop and hence more challenging to detect on images. It is a long-lived species and the size at maturity is estimated at around $4-5$ cm shell height at the age of $5-7$ years (Galand and Fevolden, 2000).

The scallop fishery in Iceland commenced in 1969. As required, landings are monitored and catches recorded per hour of fishing in logbooks, and annual surveys have been conducted by the Marine Research Institute of Iceland from 1993-2003 in the inner part of Breidafjordur every March/April (Jonasson et al., 2007). From 1985 a steady decrease in catch was observed and by 2004 the population had been fished down to 35% when the fishery was stopped. This decline was attributed to a combined effect of a protozoan infestation, increased sea bottom temperature, and partly to scallop dredging (Jonasson et al., 2007; Garcia, 2006).

A pilot AUV survey was conducted in a defined site in Breidafjordur in September, 2010. This study analyzed part of the data set gathered during the survey. The main focus was to illustrate the analytical methods used to obtain the scallop population abundance estimates from the digital photographs (images). This work was mainly an illustration of methods which can be applied to prospective data sets for larger areas from this region.

2 Materials and methods

Data

A Gavia AUV (Figure 1), jointly owned by the University of Iceland (UI) and the Vor Marine Research Center at Breidafjordur, equipped with a digital camera, and a Marine Sonic Technology, Ltd. dual frequency 600/1200 *kHz* side-scan sonar was used for this research. A black and white camera of resolution 1600×1200 was used. Images were stored in an 8-bit jpeg format.

A total of ten sites were surveyed. Sample locations were previously known scallop dredging sites to the West and South West of Stykkisholmur (Figure 2). Two to four parallel transects, $30 - 50$ m apart, were taken at each site, which covered between $400 - 800$ m in length. The AUV was navigated either at 2.0 m or 2.5 m from the bottom at 500 rpm, which roughly corresponds to 1.4 m/s. Both digital photographs and side-scan sonar data were collected from the survey.

For this study, the data set from site 7 was analyzed. At this site the AUV was programmed to navigate at 2 m from the bottom in a lawnmower pattern with 4 parallel lines of 800 m. From this four transects of approximately 640 m in length were extracted for analysis. The transects were 50 m apart (Figure 2). Due to undulations in the AUV navigation, the altitude ranged from 1 - 3 m. For consistency, a subset of images taken at 1.8 - 2.2 m from the bottom were extracted from the data set giving 2594 images, approximately 69% of the set. A random sample of 100 images were selected from this subset using a stratified sampling approach. Each transect was divided into 5 equal sections, referred to as strata. From each stratum 5 random samples (images) were selected, which gave 25 samples per transect and 100 samples in total. The area of each stratum was 640 m /5 * 50 m. The scallop abundance was extrapolated for a total survey area of 640 m * 200 m (Figure 2). The random sample was considered a true representative of the population within this defined area.

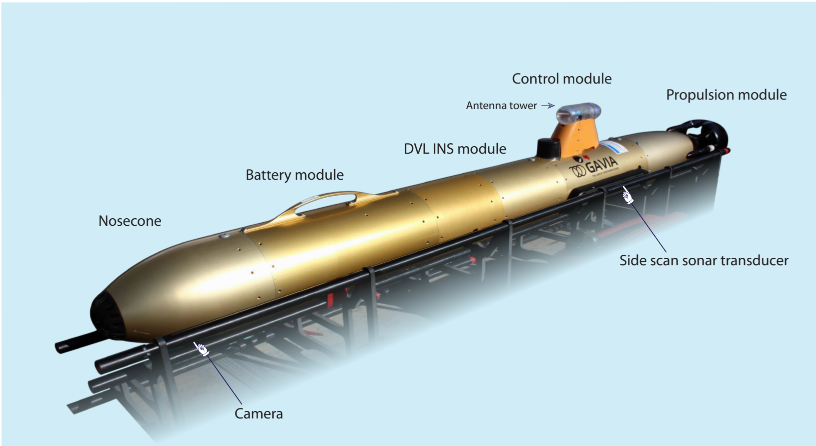


Figure 1: The Gavia AUV, approximately 2.2 m in length, modules from the right; Nose cone with camera, battery module, DVL-INS, control unit with tower and side-scan sonar, and propulsion module.

2.1 Image Enhancement

The original images from the AUV were considerably grainy with a vignetting effect i.e.bright in the center with darker edges. To improve image quality, blurring and spatial filtering were applied for noise reduction and image smoothing. A gamma correction was applied afterwards for contrast enhancement (Gonzales and Woods, 2002). These routines were carried out within the package *EBImage* in the R statistical software, with *blur* and *filter2* functions (Sklyar et al., 2011).

2.2 Abundance Estimation

Each image from the random sample was visually examined to obtain an absolute count of all the scallops from the image. It was also important to differentiate

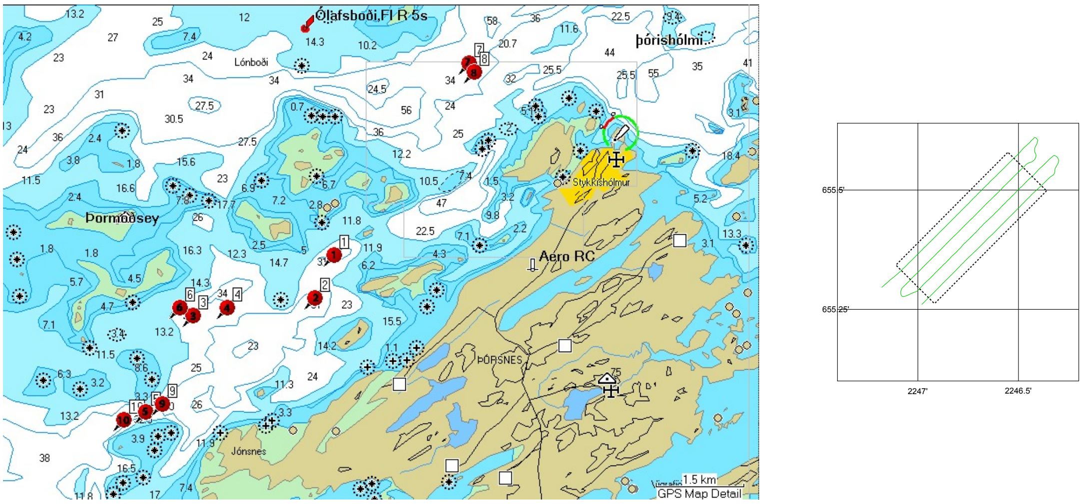


Figure 2: Survey locations in Breidafjordur, West and South West of Stykkisholmur. Areas covered were previously known scallop dredging sites. The plot on the right shows the survey pattern at site 7 (green). The area enclosed in black represents the total survey area (640 m * 200 m) for which the scallop abundance was estimated from the 4 transects.

between live and dead shells. Scallops shells that appeared decolorized were considered dead. The metadata from each image on time, latitude, longitude, altitude (the distance above the bottom), depth from the surface, pitch, roll and surge of the vehicle were also extracted.

The next essential step was to determine the area covered on the seabed by the images. This is dependent on the angle of view of the camera, and the altitude. The angle of view (α) is dependent on the dimension of the sensor chip (d), and the effective focal length (f);

$$\alpha = 2 \arctan \left(\frac{d}{2f} \right) \tag{1}$$

Given the altitude (H), and the appropriate sensor dimension, the horizontal and vertical distances covered on the seafloor (D) can be obtained by;

$$D = 2H \tan\left(\frac{\alpha}{2}\right) \tag{2}$$

The refraction of light at the air/water boundary has to be accounted for when the angle of view in water α_w is calculated;

$$\frac{\sin(\alpha/2)}{\sin(\alpha_w)} = \frac{nw}{na} \tag{3}$$

where $nw = 1$ and $na = 1.33$ are the refraction indices for water and air respectively. The area can be obtained from the horizontal and vertical distances. The Scorpian model SCOR-20CSO camera with Fujinon CCTV lens DF6HA-1B, used for this study, has a sensor chip size of 8.50×6.80 mm, and a focal length of 6 mm.

Furthermore the area calculations can in principle be corrected for pitch and roll of the AUV, with the use of basic trigonometry. The average pitch and roll were approximately 4° and 2° respectively (Figure 3). A pitch and roll of approximately 10°, the highest observed deviation, results in an uncertainty of ±4% in the area calculation thus the effect of pitch and roll was considered negligible.

To remove the variance caused due to differences in altitude, the area calculations were scaled to an altitude of 2 m from the bottom by

$$a_i = a_o \frac{H}{2} \tag{4}$$

where a_o is the original image area, a_i is the scaled image area and H is the distance from the bottom at which the image is taken.

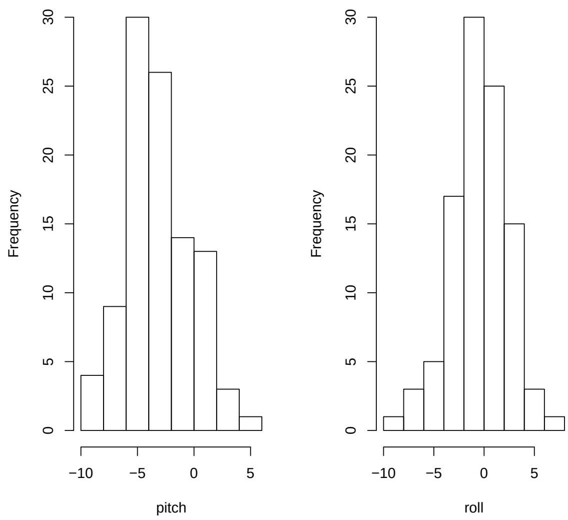


Figure 3: A histogram of the pitch and roll of the random sample of 100 images.

Fundamental sampling theory (Cochran, 1977) can be applied to estimate abundance from count data. Given the area covered by each sample, the scallop counts were converted to densities as follows:

$$x_{si} = \frac{y_{si}}{a_{si}} \tag{5}$$

where x_{si} is the i^{th} density in stratum s, y_{si} is the observed number of scallops in sample (image) i, a_{si} is the area of sample i. The mean scallop density within each stratum was then obtained by dividing the total density within stratum by the number of samples n_s in a stratum s:

$$\overline{x}_{s.} = \frac{1}{n_s}\sum_{i=1}^{n_s} x_{si} \tag{6}$$

The estimated total abundance Z was obtained by multiplying the mean density within stratum by the area of stratum A_s and summed up over all strata:

$$Z = \sum_{s=1}^{S} \overline{x}_{s.} A_s \tag{7}$$

The variance of the estimated total abundance is as follows:

$$\hat{\sigma^2} = \widehat{V[Z]} = \sum_{s=1}^{S} A_s^2 \frac{\hat{\sigma_s^2}}{n_s} \tag{8}$$

where $\hat{\sigma_s^2}$ is the sample variance given by

$$\hat{\sigma_s^2} = \widehat{V[x_{si}]} = \frac{\sum_{i=1}^{n} (x_{si} - \overline{x}_{s.})^2}{n_s - 1} \tag{9}$$

Alternatively a modeling approach can be taken to estimate the abundance and study the variability in the data. The random variable Y_{tsi} denotes the i^{th} scallop count in stratum s within transect t, where t and s are considered factor levels with replications. A poisson model was fitted to the count data with t and s as random factor variables with s nested within t. This nested design model can be represented as follows:

$$\begin{aligned} Y_{tsi} &\sim P(\lambda_{ts}) \\ ln(\lambda_{ts}) &= \phi + \tau_t + \zeta_{s(t)} \end{aligned} \tag{10}$$

where ϕ is a constant; τ_t is the random transect effect, $\zeta_{s(t)}$ is the random stratum effect nested within the transect, with expectations 0 and variances σ_τ^2, and σ_ζ^2 respectively (Kutner et al., 2005).

The estimated mean abundance in numbers μ_{si} with a confidence bound can be obtained from the expectation of Y_{tsi} and the standard error from the output:

$$
\begin{aligned}
E[Y_{tsi}] &= e^{\phi+\tau_t+\zeta_{s(t)}} \\
\hat{\mu}_{si} &= e^{\hat{\phi}} \\
C.I &= (e^{\hat{\phi}-z^{*}\hat{\sigma}_{\hat{\phi}}}, e^{\hat{\phi}+z^{*}\hat{\sigma}_{\hat{\phi}}})
\end{aligned} \tag{11}
$$

All the analyses were carried out in the R statistical software (R Development Core Team, 2011).

The side-scan sonar images were also visually examined to get an indication of the substrate type.

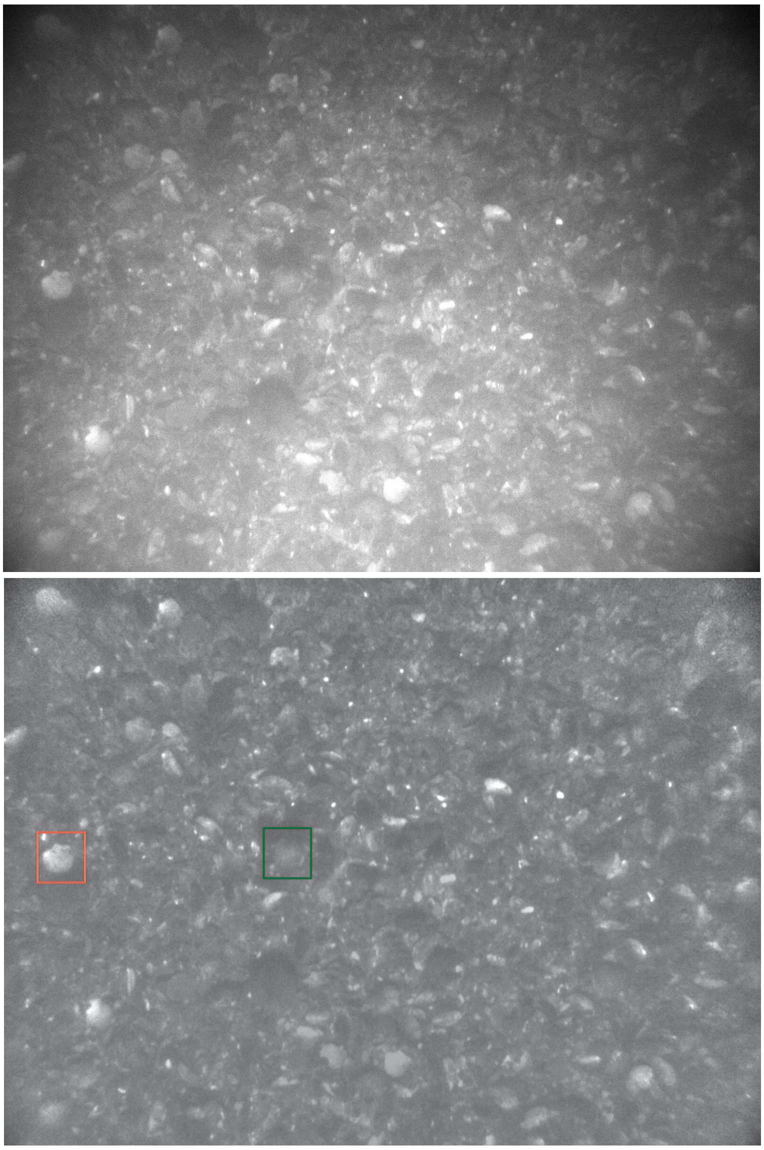
3 Results

3.1 Image Enhancement

The enhanced images were less grainy with sharper edges for easier object identification. The brightness of the images were also normalized with reduced vignetting effect and this is reflected in the histogram of the images (Figure 4 & 5).

3.2 Abundance Estimation

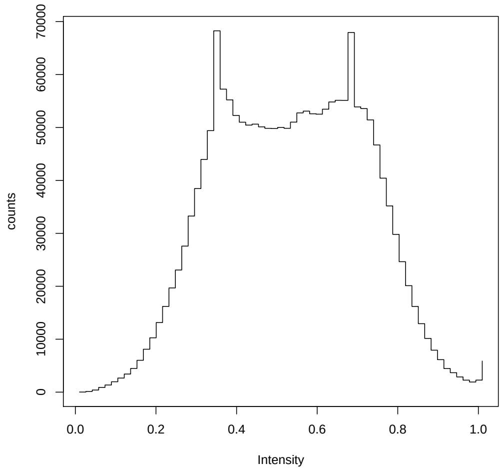
The site chosen for analysis is a previously known scallop ground. The number of live scallops observed per image ranged from 0-4 (Figure 6). From the analysis, the estimated total abundance of scallops in numbers within a total area of 12.8 sq km at site 7 (Figure 2) was 27,812 with a standard deviation of 4,633. For each stratum, the total scallop count, estimated mean density with standard deviation, and estimated total abundance with standard deviation is outlined in Table 1.



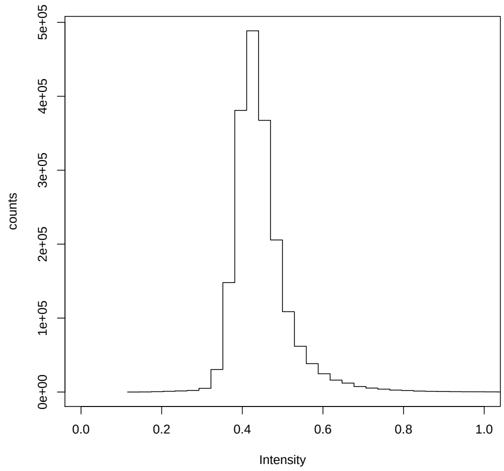
(a)

(b)

Figure 4: (a) An original grayscale image of a scallop bed in Breidafjordur, Iceland, collected from the Gavia AUV (b) an enhanced version of the original image after applying spatial filtering for noise reduction and smoothing. The image was taken at 2.04 m above the bottom and 38.44 m depth with a pitch and roll of $-5.6°$ and $2.4°$ respectively, and shows a scallop and mussel dominated bed. A live and a dead scallop are marked in green and red respectively.



(a)



(b)

Figure 5: (a) A histogram of Figure 4a and (b) Figure 4b showing the normalization of image brightness to reduce the vignetting effect in the original image.

The results from the poisson random model are presented below:

```
Generalized linear mixed model fit by the Laplace approximation
Formula: y ~ (1 | t) + (1 | t:loc)
   AIC   BIC logLik deviance
 135.1 142.9 -64.56    129.1
Random effects:
 Groups Name        Variance Std.Dev.
 t:loc  (Intercept) 0.57519  0.75841
 t      (Intercept) 0.11548  0.33982
Number of obs: 100, groups: t:loc, 20; t, 4

Fixed effects:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)  -0.7421     0.2797  -2.653  0.00797 **
```

Table 1: The observed number of scallops y_{si}, estimated mean density $\overline{x}_{s.}$ with standard deviation $sd(\overline{x}_{s.})$, and estimated total abundance Z with standard deviation $sd(Z)$ of the Iceland scallop at site 7 (Figure 2) in Breidafjordur, Iceland. The results are presented for each stratum as per the stratified sampling approach taken.

Stratum	y_{si}	$\overline{x}_{s.}$	$sd(\overline{x}_{s.})$	Z	$sd(Z)$
1	9	0.45	0.34	2880	1669
2	10	0.60	0.31	3840	1594
3	1	0.05	0.01	320	286
4	2	0.17	0.12	1088	991
5	7	0.55	0.44	3520	1899
6	1	0.09	0.03	576	496
7	0	0.00	0.00	0	0
8	3	0.17	0.07	1088	757
9	4	0.30	0.18	1920	1214
10	7	0.57	0.44	3648	1899
11	0	0.00	0.00	0	0
12	6	0.44	0.24	2816	1402
13	7	0.41	0.29	2624	1541
14	3	0.15	0.05	960	640
15	1	0.06	0.01	384	286
16	0	0.00	0.00	0	0
17	2	0.11	0.03	704	496
18	1	0.07	0.02	448	405
19	1	0.09	0.03	576	496
20	1	0.07	0.02	448	405

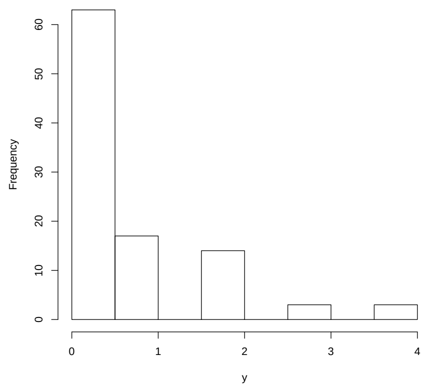


Figure 6: A histogram of scallops counts plotted for the random sample of 100 images.

The estimated mean abundance $\hat{\mu}_{si}$ was $e^{-0.7421} = 0.48$ with a confidence interval of $e^{\phi \pm 1.96 * 0.2797} = 0.28, 0.82$. The estimated total abundance can be obtained by multiplying these estimates with a raising factor of $A/\overline{a}$ where A is the total survey area and $\overline{a}$ is the mean area per sample. This gave an estimated total abundance of 18,678 with an lower bound of 10,795 and an upper bound of 32,316.

Furthermore, it can be seen that the variability within transects was higher than between transects ($\hat{\sigma}_{\zeta} = 0.76$, $\hat{\sigma}_{\tau} = 0.34$).

It was generally observed that images taken at 1-2 m from the bottom were of higher clarity (Figure 7). In turbid waters the clarity of the images were low at $>$ 2.5 m from the bottom. Overall the images from Breidafjordur gave a rough indication of the scallop distribution and habitat type. Relatively more scallops were seen at sites 7 and 8, together with mussels, sea urchins, common whelk and starfish.

A visual examination of the side-scan sonar images showed that the scallop habitat was mainly smooth with occasional rough bottom, and some rocks present

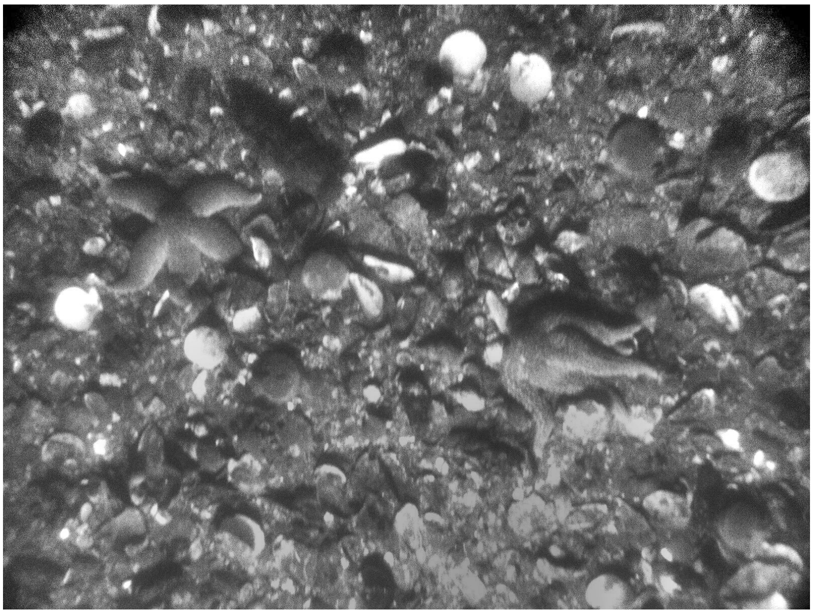


Figure 7: Image from Breidafjordur (site 5 in Figure 2) obtained with a black and white gavia camera, showing some live and dead scallop shells, and two starfish. The image was taken at 1.34 m above the bottom and 31.55 m depth, with a pitch and roll of $-7.01°$ and $-1.18°$ respectively.

(Figure 8).

4 Discussion

In a pilot AUV survey conducted in Breidafjordur, 10 selected sites were surveyed. They were chosen according to known information on previous dredging sites and scallop habitats. This pilot survey is not large enough to make inferences about the overall population in the entire survey area but the techniques required to achieve such an abundance estimate for an area can be developed with the data obtained. In this paper, a portion of the pilot data set i.e. from one site, were analyzed as a case in point. The analytical methods outlined in this study for abundance estimation of scallops can be applied to future survey data from this area, subsequent to proper survey design and data collection.

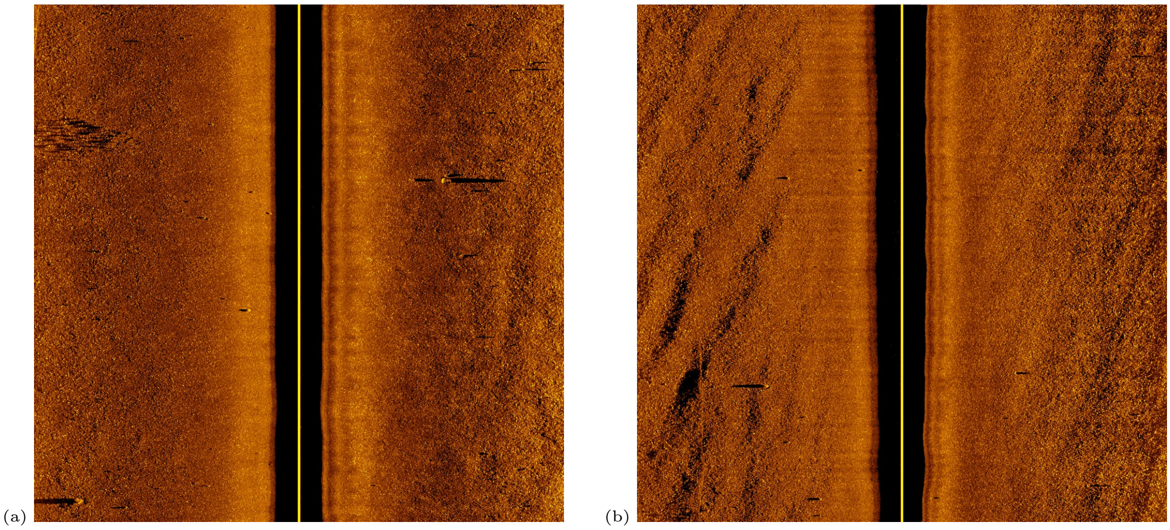


Figure 8: Low frequency (30 m range) side-scan sonar images from Breidafjordur (site 5 in Figure 2); (a) shows a smooth habitat with some rocks, a shoal of fish can also be seen in the upper left corner; (b) shows rough and wavy bottom.

The Iceland scallop most commonly dwells in waters between $10 - 100$ m with a preferred physical environment characterized by strong currents and temperatures between -1.5 to $8\,^{\circ}$C (Galand and Fevolden, 2000). Survey sites 7 and 8 show a higher number of live scallops, and other invertebrates. These areas, which are exposed to more wave action, are known to be preferred scallop habitats, and have been sampled by the Marine Research Institute of Iceland previously, for scallop fishery management. These sites will be revisited in future surveys.

Commonly, the scallops tend to have a patchy distribution. This is reflected in the data also where some areas (strata) have no observed scallops. This could also explain the high variability observed within strata in the model. Given the patchy distribution of scallops a stratified sampling approach was used. Since the data were counts, and the survey sites were chosen at random, a poisson random effects model was applied to the data. It is acknowledged however that a poisson assumption may not hold for such count data with a lot of zeros and further development may be needed.

For this study the enumeration of live scallops from the images were carried out visually. Dead scallop shells tend to break off at the hinges and decolorize. These shells have a brighter appearance on the images and hence can potentially be differentiated from the live ones. Automatic detection of the scallop shells from the images form part of the future objectives. For size estimation of the scallop shells the images have to be corrected for lens distortion and pitch, roll and yaw.

Images taken at $1-2$ m from the bottom showed increased clarity. Obtaining a count of the organisms from such detailed images would also be more feasible, although safety measures have to be taken into account when navigating an AUV too close to the bottom. Images taken at greater distances from the bottom ($>$ 2.5 m) cover more area on the seabed, and tend to lack details. A number of other macrobenthic invertebrates and flatfish were also identified from the images, which indicates that this technique can be applicable to other macrobenthic species. Starfish, which are the chief predators of scallops were also observed in a number of images where scallops were found.

Basic image enhancement techniques were used here to improve the image quality. However, investigations into better camera options will also be carried out in the future for improved raw image quality.

For macrobenthic organisms, habitat mapping is also an elementary step in the assessment surveys because they highly depend on the substrate type. Important links exist between scallop abundance, sediment type and habitat structure (Kostylev et al., 2003). Therefore, investigations into the sea floor structure (seabed classification) of the study site is of considerable interest to better understand the distribution of the species. From the current survey, a visual examination of the side-scan sonar images show that the scallop habitat was mainly smooth with occasional rough bottom, and some rocks present. Mosaicking side-scan sonar images and application of classification algorithms, to identify habitat types, are part of the future objectives.

In essence, AUVs offer improved logistics, are time and cost effective and present better platforms for "superior mapping capabilities" and are suitable for smaller area sonar surveys (Yoerger et al., 2007). The less destructive nature of this survey method is certainly appropriate for fragile habitats. This method is also potentially more precise. The time and cost effectiveness can be utilized to repeat entire surveys for better variance estimates, which is not feasible with traditional sampling methods.

5 Acknowledgements

To Simon Mar Sturluson, Richard Yeo and Heimir Kristinsson for most valuable support in data collection. This research work was funded by the Icelandic Research Fund, Rannis and the United Nations University - Fisheries Training Programme.

References

Armstrong, R., Singh, H., Rivero, S., and Gilbes, F. 2009. Monitoring coral reefs in optically-deep waters. In Proc. 11th Int. Coral Reef Symp. 593–597.

Armstrong, R., Singh, H., Torres, J., Nemeth, R., Can, A., Roman, C., Eustice, R., Riggs, L., and Garcia-Moliner, G. 2006. Characterizing the deep insular shelf coral reef habitat of the Hind Bank marine conservation district (US Virgin Islands) using the Seabed autonomous underwater vehicle. Cont. Shelf Res. 26(2):194–205.

Clarke, M., Singh, H., C., Goldfinger, A., Fleischer, G., Hufnagle, L., Pierce, S., Roman, C., Romsos, C., Tolimieri, N., and Wakefield, Y. 2006. Integrated mapping of West Coast groundfish and their habitat using the Seabed AUV and the ROPOS ROV. Eos. Trans. AGU: Ocean Sci. Meet. Suppl., Abstract 87(36), OS46G-12.

Cochran, W.G. 1977. Sampling Techniques. John Wiley & sons, New York.

Fernandes, P., Stevenson, P., Brierley, A., Armstrong, F., and Simmonds, E. 2003. Autonomous underwater vehicles: future platforms for fisheries acoustics. ICES J. Mar. Sci. 60(3):684–691.

Galand, P., and Fevolden, S. 2000. Population structure of Chlamys islandica in the Northeast Atlantic-northern stocks compared with a southern relict population. Sarsia 85:183–188.

Gallager, S.M, Singh, H., Tiwari, S., Howland, J., Rago, P., Overholtz, W., Taylor, R., and Vine, N., 2005. High resolution underwater imaging and image processing for identifying essential fish habitat.. In: Somerton, D.A., Glendill, C.T. (Eds.), Report of the National Marine Fisheries Service Workshop on

Underwater Video analysis. NOAA Technical Memorandum NMFS–FSPO–68: 44–54.

Gallager, S.M, York, A.D., Taylor, R., Vine, N., Howland, J., Lerner, S., and Bolles, K. 2009. Summary of HabCam activities related to the NMFS/NEFSC sea scallop survey of the Nantucket Lightship closed area and yellowtail flounder observations in 2009. Unpublished, The HabCam group report.

Garcia, E. 2006. The Fishery for Iceland Scallop (Chlamys islandica) in the Northeast Atlantic. Adv. Mar. Biol. 51:2–58.

Gonzales R. C., and Woods, R. E. 2002. Digital Image Processing, Second edition. Prentice-Hall, Inc. pp 82, 119.

Howland, J., Gallager, S., Singh, H., Girard, A., Abrams, L., Griner, C., Taylor, R., and Vine, N. 2006. Development of a Towed Survey System for Deployment by the Fishing Industry. IEEE doi:10.1109/OCEANS.2006.307098.

Jonasson, J., Thorarinsdottir, G., Eiriksson, H., Solmundsson, J., and Marteinsdottir, G. 2007. Collapse of the fishery for Iceland scallop (Chlamys islandica) in Breidafjordur, West Iceland. ICES J. Mar. Sci. 64(2):298–308.

Kostylev, V., Courtney, R., Robert, G., and Todd, B. 2003. Stock evaluation of giant scallop (Placopecten magellanicus) using high-resolution acoustics for seabed mapping. Fish. Res. 60(2-3):479–492.

Kutner, M., Nachtsheim, C., Neter, J., Li, W., 2005. Applied linear statistical models. McGraw-Hill, Irwin, Boston, pp. 1091.

R Development Core Team, 2011. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Rivero-Calle, S., Armstrong, R., and Soto-Santiago, F. 2009. Biological and physical characteristics of a mesophotic coral reef: Black Jack reef, Vieques, Puerto Rico. In Proc. 11th Int. Coral Reef Symp. 567–571.

Rosenkranz, G.E., and Byersdorfer, S.C., 2004. Video scallop survey in the eastern Gulf of Alaska, USA. Fish. Res. 69: 131–140.

Rosenkranz, G.E., Gallager, S.M., Shepard, R.W. and Blakeslee, M.. 2008. Development of a high-speed, megapixel benthic imaging system for coastal fisheries research in Alaska. Fish. Res. 92(2-3): 340–344.

Singh, H., Armstrong, R., Gilbes, F., Eustice, R., Roman, C., Pizarro, O., and Torres, J. 2004a. Imaging coral I: Imaging coral habitats with the SeaBED AUV. P. Soc. Photo-opt. Ins. 5(1):25–42.

Singh, H., Can, A., Eustice, R., Lerner, S., McPhee, N., Pizarro, O., and Roman, C. 2004b. Seabed AUV offers new platform for high-resolution imaging. Eos. Trans. AGU. 85(31):289–294.

Stokesbury, K.D.E., Harris, B.P., Marino II, and M.C., Nogueira, J.I. 2004. Estimation of sea scallop abundance using a video survey in off-shore U.S. waters. J. Shellfish Res. 23: 33–40.

Sklyar O., Pau, G., Smith, M., and Huber, W. 2011. EBImage: Image processing toolbox for R. R package version 3.6.0.

Tolimieri, N., Clarke, M., Singh, H., and Goldfinger, C. 2008. Evaluating the SeaBED AUV for monitoring groundfish in untrawlable habitat. Marine habitat mapping technology for Alaska. Alaska Sea Grant College Program, University of Alaska Fairbanks.

Williams, S., Pizarro, O., Jakuba, M., and Barrett, N. 2010. AUV benthic habitat mapping in south eastern Tasmania. Spr. Tra. Adv. Robot. 275–284.

Yoerger, D., Jakuba, M., Bradley, A., and Bingham, B. 2007. Techniques for deep sea near bottom survey using an autonomous underwater vehicle. Int. J. Robot. Res. 26(1):41–54.