3D-view Generation and Species Classification of Aquatic Plants Using Acoustic Images

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Abstract:

In this study, we used a new integrated measurement system that combines the acoustic imaging sonar of DIDSON (Dual-frequency IDentification SONar) with concentrator lenses, motion sensors, and GPS receivers to find and identify different species of aquatic plants. Two types of experiments were performed at two lakes in Japan: Lake Yamanaka and Lake Yunoko. In the first experiment at Lake Yamanaka, the image was captured with a one-degree concentrator lens. Multi-beam image processing was used to generate 3-D images of aquatic plants. The lens used in this experiment concentrated the vertical beam width within 1 degree. The second experiment at Lake Yunoko DIDSON with a 3-degree concentrator lens was applied, and histogram and spatial spectrum analyses were performed for plant species classification. Three species of aquatic plants, *Myriophyllum spicatum*, *Chara globularis*, and *Elodea nuttallii*, were classified by the parameters obtained from the current methods. The ability to visualize the features of each aquatic plant for species classification, e.g., leaf and branch dimensions, was attributed to spatial spectrum and scattering analyses of the acoustic images. The high spatial resolution of the integrated DIDSON measurement system will contribute protection of endangered species in rapidly changing underwater environment.

Classification: Fisheries Acoustics, Bioacoustics, Miscellaneous (Observations, Measurements etc.)
Keyword: acoustic images, aquatic plants, species classification, 3D-views generation

1. Introduction

Aquatic plants play an important role in the underwater ecosystems and have an impact on the biological diversity of the world. Many species, however, are decreasing in number and facing possible extinction due to eutrophication, grass carps,
introduced species, and anthropologic impacts intervention\textsuperscript{2,3}). Sustainable management of the underwater environment is required for the preservation, restoration, and establishment of aquatic plants\textsuperscript{4). A more accurate mapping and monitoring system to assess the well-being and distribution of aquatic plants is needed.

Conventional survey methods (e.g., surface survey with optical video cameras and divers) have been widely used to detect the aquatic plants and estimate their density\textsuperscript{5,6). However, these methods are affected by the transparency of the water and the observation abilities of the divers. All these cause the low accuracy in the survey outcomes. For plants mapping, acoustic systems, such as side-scan sonar\textsuperscript{7,8), echosounder\textsuperscript{9,11), and multi-beam sonar\textsuperscript{12,13), have been used to measure aquatic plants under turbid water condition. Side-scan and multi-beam sonars are especially suitable for wide-area mappings\textsuperscript{7,12). In shallow area, sonar systems using high frequency in the MHz order has been commonly used for the survey of the aquatic plant since the sonar enables to obtain the high resolution spatial data, which contribute to estimate the biomass of the aquatic plants\textsuperscript{9). However, few studies have reported the feasibility of high resolution acoustic image of the aquatic plants in shallow area. Application of the high resolution acoustic imaging is not fully exploited for aquatic plant survey, especially the individual species classification so far.

In recent years, the use of Dual-frequency IDentification SONar (DIDSON, Sound Metrics, Bellevue, WA, USA), which is one of the high resolution imaging sonars, has resulted in near-video-quality images created by simultaneously transmitting and receiving multiple acoustic beams\textsuperscript{14). DIDSON has been adopted by many fishery researchers and scientists for a wide range of purposes (e.g. observation of fish behavior\textsuperscript{15), size detection\textsuperscript{16), counting\textsuperscript{17), abundance estimation around the trawl\textsuperscript{18), and classification of fish shape\textsuperscript{19). However, the application of DIDSON to the survey of aquatic plants has not been reported, to the best of our knowledge, despite the strong advantage of using DIDSON in the near field, such as shallow areas in lakes.

Submerged aquatic plants, such as the endangered species \textit{Chara globularis} Thuillier var. \textit{globularis} [\textit{Chara globularis}] maintain the sustainability lake ecosystems\textsuperscript{20,21). The distribution of these plants in 26 Japanese lakes was recorded in 1964; however, it was observed in only eight of 18 lakes during the 1994-1997 survey\textsuperscript{22). Application of DIDSON for precise mapping of aquatic plant will be useful for accurate measurement of the plant species for protection of endangered species.

In this study, we tried to create 3D-view image of the plants and classification of species with using the acoustic imaging sonar of DIDSON. Two types of the field experiments were performed at Lake Yamanaka and Lake Yunoko in Japan. In the first experiment at Lake Yamanaka, 3D-view of \textit{Myriophyllum spicatum} was generated. In the second experiment at Lake Yunoko, species classification of three aquatic plants, \textit{Myriophyllum spicatum}, \textit{Chara globularis}, and \textit{Elodea nuttallii}, was conducted.

2. Field experiments and setting

Acoustic imaging sonar DIDSON, concentrator lenses, a motion sensor, and a GPS receiver were integrated into the original measurement system for this study. The lens concentrated the vertical beam width from the default 14° to very narrow beam: that was suitable for the shallow water monitoring such as in the lake survey. Two types of the concentrator lenses (1° and 3°: Sound Metrics,
Bellevue, WA, USA) were prepared for the experiments, and the lens allowed beams to go farther with less interference from surface and bottom reverberation. Depending on the beam width of the concentrator lens, the acoustic image recorded by DIDSON was different. Therefore, the effective image processing methods need to be selected and applied to the images captured with each concentrator lens as described later sections. The 1° concentrator lens enabled us to capture the vertical “slice” image and detect the accurate arrival angle of backscatter echo from the aquatic plants. It was suitable for 3D image reconstruction of the aquatic plant with the conventional multi-beam image processing. The 1° concentrator lens was used in the first experiment at Lake Yamanaka during the period from July 27 to July 30, 2010. Because only one plant species was found in Lake Yamanaka, high spatial resolution was beneficial rather than plant shape detection using wide beam width. On the contrary, the 3° concentrator lens expanded the vertical beam width, and the image including the wide area information was able to be obtained. Therefore, the characteristics of the aquatic plant, such as shape of leaf and branch dimensions, were appeared in one image. Histogram and spatial spectrum analyses were performed to the acoustic image, which was captured with a 3° concentrator lens, in the second experiment at Lake Yunoko during the period from July 4 to July 6, 2011.

2.1 Lake Yamanaka: 3D-view generation of aquatic plants

The experimental setting is illustrated in Fig. 1. The survey boat was equipped with a standard DIDSON (to page 2.), DGPS (A30 and R100, Hemisphere, Alberta, Canada) and a motion sensor (C100, Applied Micro Systems, Tokyo, Japan). The DIDSON unit was mounted to a pole with a 1° concentrator lens that was tilted downward at 45° from the horizontal surface of the lake. The data were collected at 1.8 MHz (high-frequency mode) and at a maximum range of 5.5 m from the imaging sonar. The two-dimensional (2D) frame consisted of 96 horizontal beams×512 range samples. The frame rate was 10 fps. The boat was moved by an electric motor screw at a speed of ca. 0.5 m s⁻¹, as shown in Fig. 2. The continuous slice images were captured from the root to the tip of the aquatic plant with moving boat. In addition to the acoustic measurements, optical images were captured using the underwater optical video camera (Marine Eye,
KOWA, Osaka, Japan). This optical video camera was used to compare the visual shapes of aquatic plants with acoustic images. The main aquatic plant distributed in this survey area was *Myriophyllum spicatum*, and we were unable to find additional aquatic plant species, such as *Chara globularis*, in the data collected from Lake Yamanaka.

2.2 Lake Yunoko: species classification of aquatic plants

The setting was almost the same as the first experiment (shown in Fig. 1). The standard DIDSON with a 3° concentrator lens, built-in motion sensor (True Point, Honeywell, NJ, USA), and DGPS (GPS16X, GARMIN, Olathe, KS, USA) were used in this experiment. The 3° concentrator lens, which replaced the 1° lens used in the first experiment, enabled the expansion of the vertical view angle, and the obtained image included the information of wide area. The frame rate was 5 fps, and the maximum range varied from 2.5 to 5.5 m, depending on the lake bottom conditions at the measurement points. In this survey area, we often observed not only *Myriophyllum spicatum* but also other aquatic plants such as *Chara globularis* and *Elodea nuttallii* by on-board visual observation and optical video camera images. The optical images of three aquatic plants are shown in Fig. 3. The density of the aquatic plants in this area was much greater than that in Lake Yamanaka, and it was difficult to perform the 3D-view generation of the individual aquatic plant.

3. Image processing and data analysis

Acoustic imaging reveals feature information about objects such as their shape, size, and texture. After the acoustic images were acquired, various data-processing methods were used to extract the information about the plant species for classification. The block diagrams of each data-processing method are shown in Figs. 4(a)-(c). As mentioned above, the feature of the acoustic image was different depending on the type of the concentrator lens and the effective image processing methods were respectively performed to the images captured with each concentrator lens.

3.1 Steps in the generation of 3D view of aquatic plants

3.1.1 Pixel selection

The image-processing procedure is shown in Fig. 4(a). If the pixel’s intensity was under the threshold...
level, then it was treated as noise and set to zero (black level). When the sonar received the backscatter echoes larger than the threshold level, pixels within the tilt angles of $45-0.5^\circ$ to $45+0.5^\circ$ were selected as the backscatter echoes from the aquatic plants, which appeared in each vertical range of image. Then, the pixels of the strongest intensity in each vertical range were selected as the pixels which were reflected from the arrival angle of $45^\circ$.

### 3.1.2 Coordinate transformation from DIDSON frame to 3D space

The DIDSON frame always represents the backscatter echo information from aquatic plants in 2D space. Coordinate transformation from 2D to 3D space was required for each frame before the 3D view of the aquatic plants could be generated. The information from the motion sensor and GPS was used to correct the effect of the boat’s motion and generate the 3D coordinates in the global coordinate system. The schematic coordinate of the 2D acoustic image is illustrated in Fig. 5, and the equations for coordinate transformation are given below:

$$ L_j = L_0 + j / 512 \times w \quad (j = 0 \text{ to } 511), \quad (1) $$

$$ \theta_i = (-14.25 + 0.3i) \times \pi / 180 \quad (i = 0 \text{ to } 95), \quad (2) $$

$$ x_{ij} = L_j \cos(\theta_i), \quad (3) $$

$$ y_{ij} = L_j \sin(\theta_i), \quad (4) $$

$$ z_{ij} = 0, \quad (5) $$

where $L_j$ is the distance from the imaging sonar to the aquatic plants at the sample number $j$, $w$ is the window length, $\theta_i$ is the horizontal beam angle at the beam number $i$, and $(x_{ij}, y_{ij}, z_{ij})$ are the initial coordinates of the 2D acoustic image, as shown in Fig. 5. The coordinate transformation from 2D to 3D space was performed with the correction to the boat’s motion as follows:

$$ \begin{bmatrix} X_{ij} \\ Y_{ij} \\ Z_{ij} \end{bmatrix} = \begin{bmatrix} x_{ij} \\ y_{ij} \\ z_{ij} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta\text{roll}) & -\sin(\theta\text{roll}) \\ 0 & \sin(\theta\text{roll}) & \cos(\theta\text{roll}) \end{bmatrix} \begin{bmatrix} \cos(\theta\text{pitch} + \pi/4) & 0 & \sin(\theta\text{pitch} + \pi/4) \\ 0 & 1 & 0 \\ -\sin(\theta\text{pitch} + \pi/4) & 0 & \cos(\theta\text{pitch} + \pi/4) \end{bmatrix} \begin{bmatrix} \cos(\theta\text{head}) & -\sin(\theta\text{head}) & 0 \\ \sin(\theta\text{head}) & \cos(\theta\text{head}) & 0 \\ 0 & 0 & 1 \end{bmatrix} $$

where $(X_{ij}, Y_{ij}, Z_{ij})$ are the transformed 3D coordinates, and $(\theta\text{roll}, \theta\text{pitch}, \theta\text{head})$ correspond to the values measured by the motion sensor. Finally, the GPS information was added to $(X_{ij}, Y_{ij}, Z_{ij})$ as offset values to obtain the 3D coordinates in the global coordinate system.

### 3.1.3 Generation of 3D view of aquatic plants

As mentioned above, the continuous frames were captured by moving the boat at a frame rate of 10 fps in this experiment. However, there were some intervals between frames and it was necessary to cover them. The frame intervals were interpolated using the transformed 3D data which were calculated in the previous section, 3.1.2. The
selected pixels in each frame were expanded into a block containing eight points in the 3D coordinates, as represented in the following equations:

\[
(x, y, z), \\
(x, y, z + dz), \\
(x, y + dy, z), \\
(x, y + dy, z + dz), \\
(x - dx, y + dy, z), \\
(x - dx, y + dy, z + dz), \\
(x - dx, y, z + dz), \\
(x - dx, y, z), \\
\]

where \(dx\) and \(dy\) are the intervals between adjacent pixels in a frame, and \(dz\) is the first of two continuous frames. Finally, a 3D view of the aquatic plants was generated with 100 sequential frames, and the color was printed in brown (the bottom of the lake) or green (body of the aquatic plants) and compared with the image captured by the optical video camera.

3.2 Methods of the species classification of aquatic plants

3.2.1 Histogram analysis

Figure 4(b) represents the steps in the histogram analysis. First, the region of interest (ROI) was set to 128×128 pixels for each acoustic image. This region included the nearly whole shape of each aquatic plant. There was a slight variation in the size of the pixels covers whole plant depending on the size of the plant species. In this study, Myriophyllum spicatum was much taller than the other species and the maximum range of beam was set to 5 m, and those of the other ones were set to 2.5 m. Therefore, the pixel sizes used in this analysis were about 10×10 mm\(^2\) for Myriophyllum spicatum and about 5×5 mm\(^2\) for Chara globularis and Elodea nuttallii. The ROI was 128×128 cm\(^2\) for Myriophyllum spicatum and 64×64 cm\(^2\) for the other species. After the area setting was fixed, the pixels intensities below the threshold were eliminated as noise and set received level as zero to blackout the image.

Next, the intensity of the pixels in both the horizontal and vertical directions was normalized. In the horizontal direction, the intensity of each of the 96 beams (at the same distance) was set to the same level in the default setting of DIDSON before the measurements. In the vertical direction, because transmission loss occurred in each beam depending on the distance, time-varying gain (TVG) was applied to compensate for the transmission loss. The transmission loss is given in the following equation:

\[
TL = 20 \log r + ar,
\]

where \(TL\) is the transmission loss; \(r\) is the distance from the transducer to the object; and \(a\) is the absorption coefficient. In this study, \(a\) was set to 0.97 [dB m\(^{-1}\)], which was calculated according to the equation of Thorp\(^{23}\) at 1.8 MHz.

After normalization, the aquatic plants (valid pixels) were extracted from the ROI. The intensity of focal pixel was compared with the intensities of eight neighboring pixels. The pixel having difference of the intensity exceeded the threshold was regarded as the reflection from the contours of each aquatic plant. The threshold value was determined by comparing background noise level with the intensity level of the targets. The echoes lower than the intensity of the targets was not used to generate intensity histogram. Valid pixels inside the contours were extracted, as shown in Fig. 6. The histograms of intensity of each aquatic plant were calculated, and the shape of histograms was used for the species classification.
3.2.2 Spatial spectrum analysis

As the second tool for the classification of the species, spatial spectrum analysis was performed on the acoustic images, as shown in the steps listed in Fig. 4(c). For the calculation of spatial spectrum, periodical spatial data is needed. In between qualified pixels, we need null pixels (zero intensity data) every 5 mm, which corresponds to the length of ROI (128 cm). Then, the new pixels were interpolated at 5 mm intervals in the horizontal direction, as shown in Fig. 7. To get fine resolution of image, the observation range of beam was set to 2.5 m. Then, intensities of 256 pixels were collected along an arc. The center pixel was always set to the centerline of the DIDSON frame (between beam No. 48 and beam No. 49). After collecting the 256 pixels, conventional fast Fourier transform (FFT) was applied on each data along the arc. This spectrum analysis of the image enables us to quantify the feature of the aquatic plants (e.g. shape and size). The high/low spatial frequency mainly reflects the fine/rough part of image. From these results, three parameters were obtained: (1) the average center frequency of the spatial spectrum; (2) the amplitude ratio of the high/low components of spatial spectrum; and (3) the standard deviation of the center frequency of the spectrum. Here, the average center frequency of the spectrum shows the width (half wavelength) which reflects the feature of size and shape of the aquatic plants well. The amplitude ratio of high/low components of spatial spectrum reflects whether the image is composed of fine or rough parts. The threshold value between high/low components was determined considering the shape and size of the aquatic plants. The standard deviation of the center frequency of the spectrum shows the degree of the shape distribution (leaf and body) in each plant.

4. Results and Discussion

4.1 The 3D view of aquatic plants

As shown in Fig. 8, an example of 3D view of an aquatic plant is displayed from two different view angles. 3D images enabled to estimate their heights. Images from both acoustic and optical measurements of the same measurement point are shown in Fig. 9. The shape of the aquatic plant in the acoustic 3D view was broadly similar to the one in the optical image. However, the optical...
image was often difficult to capture due to the turbidity of the water in this study; under low visibility conditions, the acoustic method provides a more accurate image of the object. A comparison of the acoustic and optical images identified the species of this aquatic plant as *Myriophyllum spicatum*, with a height of ca.1.2 m and width of ca.0.06 m. The 3D views help us to visually classify the shape and size of the objects. Although we have succeeded in generating the 3D view of the aquatic plants, some limitations of the measurement condition are remained. As mentioned above, the density of the aquatic plants distribution was comparatively low and it was easy to construct the individual 3D view of them. However, it is considered that this method is difficult to be performed in the survey area in which the aquatic plants are distributed with high density because the complex scattering and acoustic shadow will be occurred. In addition, the frame interpolation is affected by the strong boat’s moving and it causes the difficulty of the reconstruction of 3D view of the aquatic plant.

### 4.2 Species classification of aquatic plants

#### 4.2.1 Histogram analysis

The histograms were obtained from the three species of aquatic plants, which were *Myriophyllum spicatum*, *Chara globularis*, and *Elodea nuttallii*, are shown in Fig. 10. The intensities of all images were compressed to one-fifth, and the number of pixels at the same intensity value was normalized by the total number of valid pixels at each data point. The results show that the locations of peaks of the histogram of echo intensity for each species were different. The echo intensities in the acoustic image of *Chara globularis* showed the smallest

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**Fig. 8.** Transformed 3D views of the aquatic plant *Myriophyllum spicatum*. Left: front view; right: side view.

**Fig. 9.** Comparison of the images obtained by acoustic and optical methods at the same measurement point.

**Fig. 10.** Histograms of each species. Black bar shows the result of *Myriophyllum spicatum*, oblique line bar is *Chara globularis*, and gray bar is *Elodea nuttallii*. 
and reflected a characteristic shape for the specie. As shown in Fig. 3 and Fig. 6, the parts of *Chara globularis* were fine and almost uniform, then, it is considered the distribution of the acoustic echoes reflected from the plant was small. The echo intensity of the *Myriophyllum spicatum* peak was larger than those of the other aquatic plants in this figure. In our data, the images in Fig. 6 show typical acoustic images of the three species; however, the echo intensity of the echo from the aquatic plants appeared to be particularly sensitive to a variety of factors, such as the condition of water. This suggested that we should collect a larger number of samples and develop more robust processing algorithm for the histogram analysis to classify aquatic plants in future work.

4.2.2 Spatial spectrum analysis

Typical results from spectrum analysis representing 25 slices obtained by integrating frames from the *Myriophyllum spicatum* image are shown in Fig. 11. The x-axis represents the spatial frequency of the slices. The amplitude of spectrum is shown by thin lines, and the averages of the amplitudes at each position obtained from all of the data are represented as bold line. The results of the three parameters calculated using spatial spectrum analysis are given in Table 1. A brief commentary on each parameter is given below:

1. **Average center frequency of spatial spectrum**

   The center frequency of spectrum reflects the width (half wavelength) of the aquatic plants in the slice. In the case of *Myriophyllum spicatum*, the mean value of the spatial frequency was 29.6 [1/m], which means that the half wavelength at that frequency was 1.7 cm; in general, wavelength was obtained as the inverse of the spatial frequency. It is assumed the value reflected a *Myriophyllum spicatum* leaf width of 0.3-2.0 cm[^24]. The average center frequency of spectrum of *Chara globularis* was 23.1 [1/m], and that of *Elodea nuttallii* was 17.6 [1/m]. Then, the half wavelength of *Chara globularis* was 2.2 cm, and that of *Elodea nuttallii* was 2.8 cm. From these results in *Chara globularis* and *Elodea nuttallii*, it was assumed that the mean value of the center frequency indicated the width of the whole body because we collected the slice data with 5-mm intervals between two points, which is more than the leaf width of them.

2. **Amplitude ratio of high/low components of spatial spectrum**

   In the spatial spectrum results, the high-component parts represent the fine features of the aquatic plants, whereas the low-component parts reflect the rough features. In this experiment, the threshold value between the high- and low-component parts was set to 19.5 [1/m] whose half wavelength at the
frequency was about 2.6 cm (the dashed line in Fig. 11); this threshold showed the best species classification results in our collected data. Here, the high (low) component was summed up the amplitudes at each frequency which were higher (lower) than the value of 19.5 [1/m]. As mentioned above, the average half wavelength of three species were distributed between 1.7-2.8 cm, and the actual size of the leaf and branch of three species was usually varied in this range by our visual observation and optical image data at the survey point. From these reasons, we determined the threshold value. However, this value will change due to the kind of species and survey areas. Therefore, we should care this point and further data collection will be required before the practical use of this parameter.

(3) Standard deviation of center frequency of spectrum

This parameter indicates the distribution of the shape (leaf width and body) in each species. As shown in Fig. 3 and Fig. 6, the shape of *Elodea nuttallii* was almost constant from the root to the tip, and, as a result, its value was the smallest. On the other hand, the shape of *Myriophyllum spicatum* was dramatically changed from the root to the tip because it had large leaf and the value was highest in three species.

Finally, the relationships among the three parameters of each species are shown in Fig. 12, where the x-axis represents the amplitude ratio of the high/low components of spatial spectrum; the y-axis corresponds to the average center frequency of the spectrum; and the z-axis is the standard deviation of the center frequency of the spectrum. As shown in this figure, the three aquatic plants were clearly classified by the three parameters used in the spatial spectrum analysis. Actually, these parameters will be affected by the density of aquatic plants distribution in a narrow sense, and the application to the other aquatic plants has not been carried out. Then the calibration of the parameters at each survey area will be needed at each measurement point in the first time. However, the continuous collection of data and trial for the classification of the aquatic plants with quantified value will bring the good result us. These parameters will

| Object           | Total frame number | Total slice number | Average center frequency of spectrum [1/m] | Amplitude ratio of High component/Low component | Standard deviation of center frequency of spectrum [1/m] |
|------------------|--------------------|--------------------|-------------------------------------------|-----------------------------------------------|--------------------------------------------------------|
| *Myriophyllum spicatum* | 6                  | 150                | 29.6±6.5                                  | 4.91±0.43                                     | 16.5±2.6                                                |
| *Chara globularis*    | 10                 | 275                | 23.1±4.1                                  | 3.70±0.24                                     | 11.7±2.3                                                |
| *Elodea nuttallii*    | 13                 | 309                | 17.6±2.9                                  | 2.48±0.41                                     | 7.2±2.8                                                 |
be applied for the monitoring system to assess the well-being and distribution of aquatic plants as one of the helps.

5. Conclusion

In this study, we used a new integrated measurement system that combines the acoustic imaging sonar of DIDSON with concentrator lenses, motion sensors, and GPS receivers to find and identify different species of aquatic plants. The field experiments were performed at two lakes in Japan: Lake Yamanaka and Lake Yunoko. Using this measurement system, we were able to monitor one of Japan’s endangered aquatic plants species, *Chara globularis*, at Lake Yunoko.

In the first experiment at Lake Yamanaka, 3D-figure generation of aquatic plants was achieved using multi-beam image processing. The 3D view helped us to visualize the features of the aquatic plants, such as shape and size, and enabled the measurement of the height and width of the plants in 3D space. Additionally, the 3D view of the acoustic image was similar to the optical image captured by a video camera at the same measurement point. The optical imaging method, however, was often inapplicable because of the turbidity of the water. Hence, the combination of acoustic and optical imaging techniques provided a useful approach for identifying aquatic plants under low-visibility underwater conditions.

The experiments at Lake Yunoko used two types of classification method. In the histogram analysis of echo intensity, the peak location and width of the histogram for each species was different. Echoes from *Chara globularis* showed the smallest intensity compared with other two species. Additionally, the most frequent echo intensity of the *Myriophyllum spicatum* was higher than those of other aquatic plants. Spatial spectrum analysis was also used to classify the three aquatic plants using the following three parameters: the average center spatial frequency of the spectrum, the amplitude ratio of high/low components, and the standard deviation of the center spatial frequency. These parameters could be used for identification of the plant species and reflected key features, such as the leaf and body characteristics, of each plant species in this study.

In conclusion, the spatial spectrum and echo intensity analyses of acoustic imaging successfully identified aquatic plant species and was particularly sensitive to leaf and branch dimensions. This highly accurate measurement system will be useful for aquatic plant species classification. The collection of additional data, in addition to continued development and improvements in the new imaging system and processing methods, are the focus of ongoing studies on this system.

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