Research paper

JMorph: Software for performing rapid morphometric measurements on digital images of fossil assemblages

Peter G. Lelièvre[a,*], Melissa Grey[b,*]

[a] Memorial University of Newfoundland, St. John's, NL, Canada
[b] Joggins Fossil Institute, Joggins, NS, Canada

ARTICLE INFO

ABSTRACT

Quantitative morphometric analyses of form are widely used in palaeontology, especially for taxonomic and evolutionary research. These analyses can involve several measurements performed on hundreds or even thousands of samples. Performing measurements of size and shape on large assemblages of macro- or microfossil samples is generally infeasible or impossible with traditional instruments such as vernier calipers. Instead, digital image processing software is required to perform measurements via suitable digital images of samples. Many software packages exist for morphometric analyses but there is not much available for the integral stage of data collection, particularly for the measurement of the outlines of samples. Some software exists to automatically detect the outline of a fossil sample from a digital image. However, automatic outline detection methods may perform inadequately when samples have incomplete outlines or images contain poor contrast between the sample and staging background. Hence, a manual digitization approach may be the only option. We are not aware of any software packages that are designed specifically for efficient digital measurement of fossil assemblages with numerous samples, especially for the purposes of manual outline analysis. Throughout several previous studies, we have developed a new software tool, JMorph, that is custom-built for that task. JMorph provides the means to perform many different types of measurements, which we describe in this manuscript. We focus on JMorph's ability to rapidly and accurately digitize the outlines of fossils. JMorph is freely available from the authors.

1. Introduction

Morphometrics is the quantitative analysis of form (size and shape). Morphometric analyses are widely used in palaeontology, especially for taxonomic and evolutionary research. Data analyses such as Fourier (e.g. Crampton, 1995; Haines and Crampton, 2000) and landmark (e.g. Stempien et al., 2001), and other traditional morphometric techniques (e.g. Strauss and Bookstein, 1982; Bookstein et al., 1985; Kowalewski et al., 1997; Marko and Jackson, 2001) are commonplace. Table 1 lists some types of measurements and associated data processing options. A thorough literature review on quantitative morphometric data analysis in palaeontology or other fields is outside the scope of our manuscript but interested readers will find an extensive volume of material by the authors referenced above and others that cite their work.

Statistically rigorous morphometric studies can involve hundreds or even thousands of samples and several measurements may be performed on each sample. For example, Grey et al. (2008a) measured six traits (linear and angular measurements) on more than 1500 shells of one bivalve genus. They used the data to determine size and shape

change over evolutionary time and across a variety of environments. Grey et al. (2008b, 2008c) used up to 10 morphological variables for species discrimination of buchiid bivalves. Grey et al. (2012) digitized the outlines (valve perimeter) of about 400 microfossil ostracod specimens and performed Fourier shape analyses.

Data collection is integral to morphometric studies to provide the form-related measurements on which to apply the data analyses. Performing measurements on macrofossil hand samples with traditional instruments such as vernier calipers is a relatively lengthy process and is infeasible for fossil assemblages with numerous samples, such as those used by Grey et al. (2008a, 2008b, 2008c). Furthermore, the types of measurements available are limited with traditional instruments: linear measurements are possible with vernier calipers, angular measurements are possible with vernier protractors, but calculating precise outline or landmark coordinates may be inconvenient or infeasible. Landmarks can be obtained directly on a specimen using a coordinate measuring machine (CMM), e.g. a microscribe. However, this may be infeasible for small specimens. It is also only possible when both a CMM and the original specimens are available in

---

Table 1

Some morphometric techniques and their measurement types that can be obtained using JMorph.

Measurement type	Possible data analyses
Linear and angular	Traditional morphometrics
Outlines	Fourier, curvature
Landmarks	Procrustes fitting, thin-plate spline

the same location. For microfossils, measurements must be made under microscope and are difficult or impossible to achieve by hand.

For those reasons, digital image processing software is finding more use in the field, to perform measurements via suitable digital images (e.g. photographs) of samples. For example, Webster and Sheets (2010) and Laflamme and Casey (2011) both mention ImageJ (Schneider et al., 2012; Schindelin et al., 2015) as one option for collecting landmark data. Webster and Sheets (2010) presented examples involving Cambrian olenelloid trilobites to demonstrate various landmark-based morphometric techniques; Laflamme and Casey (2011) discussed Ediacaran fossils. Hsiang et al. (2016) also used ImageJ, inside a workflow requiring several pieces of additional software, for semi-three-dimensional morphometrics using vertically stacked images; they presented a test case using planktonic foraminifera.

It is beyond the scope of this manuscript to mention all the numerous software tools available for morphometrics on fossils. We mention ImageJ because it is mentioned frequently in palaeontological morphometrics literature and it shares some similarities to the JMorph program which we present in this manuscript. ImageJ is not designed specifically for morphometric studies on fossils: it is primarily designed for biomedical image analysis. One package that is designed specifically for morphometric studies on fossils is Geomorph (Adams and Otárola-Castillo, 2013). Geomorph provides tools for landmark-based geometric morphometric analyses in two and three-dimensions.

Some software (e.g. see Knappertsbusch, 1998; Rohlf, 2017) is designed to automatically detect the outline of a fossil sample from a digital image. The tpsDig program (Rohlf, 2017) is a Windows program for digitizing landmarks and outlines for geometric morphometric analyses. The program can automatically determine the outline of an appropriately enhanced image. However, fossil samples often have incomplete outlines, either through damage or because the fossil is partly obscured by matrix material. Furthermore, outline detection algorithms can have difficulty when there is poor contrast between the sample and the staging background in the images. In such cases, automatic outline detection methods may perform inadequately and a manual digitization approach may be the only option.

These problems are illustrated well in Fig. 1(a) and (b). The ostracod specimen has some damage and the valve outline is incomplete. Hence, automatic outline analysis will never be able to provide a sensible estimate of the outline. Furthermore, the poor contrast between the sample and staging background in the photograph has made it impossible to use the image enhancements available in tpsDig to achieve an image upon which automatic outline analysis performs appropriately: the outline in red in Fig. 1(b) is clearly not an adequate representation of the ostracod specimen seen in Fig. 1(a), particularly at the part of the specimen closest to the bottom of the image. While this difficulty might have been avoided with more appropriate lighting, or a different coloured staging material, there are other complications that can not be avoided through photographic techniques. For example, consider Fig. 1(c). The sample is a single value of a *Buchia*. To the right of the umbo, the part of the sample at the top the image, there is a small "ear-like" feature labelled "E". The definition of what constitutes an "outline" measurement is up to the researcher; for a bivalve it is generally taken to be the valve perimeter but in this case one may not want to include the ear feature in their shape analyses. Ignoring the obvious difficulties introduced by having the sample too close to the

ruler and the adjacent samples, it may be impossible to exclude the ear feature in the automatic outline detection and a manual approach is then required. The tpsDig program does allow the user to manually alter the automatically detected outline of a sample, by selecting and dragging points around the outline as desired. However, if a fine discretization of the outline is required, and the procedure must be applied to many samples, then that manual approach may be infeasible.

While some software has been developed to aid data collection for fossil morphometrics, we are not aware of any packages that are designed specifically for efficient measurement of fossil assemblages with numerous samples, especially for the purposes of outline analysis. Throughout previous studies (Grey et al., 2008a, 2008b, 2008c, 2012), we have developed a new software tool, JMorph, that is custom-built for efficiently measuring micro- and macrofossils from digital images. JMorph provides the means to perform many different types of measurements, which we describe in the remainder of this manuscript. We focus on JMorph's major asset: the ability to rapidly and accurately digitize the outlines of fossils for use in outline analyses. The key aspect of our approach is to employ splines to dramatically reduce the number of points the user must manually select around the outline of a sample.

2. System requirements, installation and documentation

JMorph is written in Java and will therefore run on any operating system that can run Java, including Linux, Mac and Windows. JMorph is freely available as source code or a compiled JAR file packaged with required libraries. Running the compiled JAR file simply requires that Java is installed on a user's machine.

The documentation evolves along with the software. It currently provides a tutorial that introduces the basic working concepts of JMorph, explains some essential functionality, and demonstrates how to perform various common tasks. We have designed the application to be as intuitive as possible to reduce the learning curve.

3. Components of the JMorph graphical user interface

Fig. 2 shows the JMorph GUI. Because this is a Java program, the GUI may look different on different operating systems. The JMorph window is split into two main panels. On the left of the GUI is a sample viewing panel that displays the sample image that is currently being measured. The sample viewing panel is where the user performs the measurements via cursor interactions. Measurements are overlaid on top of the sample image as they are performed.

On the right of the GUI is a text panel that shows information about the measurements. The measurement panel can be removed to maximize the size of the sample viewing panel while measurements are being performed.

Above each of those two main panels lie two small status bars that display the (x,y) cursor location and sample name (image file name). At the bottom of the window is a tool bar with buttons for navigating between sample images and a button to begin measuring. All other tasks are available through the menu bar.

4. Measurements

JMorph currently provides the functionality to perform the following measurements. These measurements are illustrated in Fig. 3, which uses the same image as that in Fig. 1(c).

4.1. Counts

Counts are the number of times a particular feature is observed on a sample. To perform a count measurement, the user clicks on the image as many times as required. White dots are drawn wherever the user clicks. The user can click anywhere but of course it is most helpful to

(a)

(b)

(c)
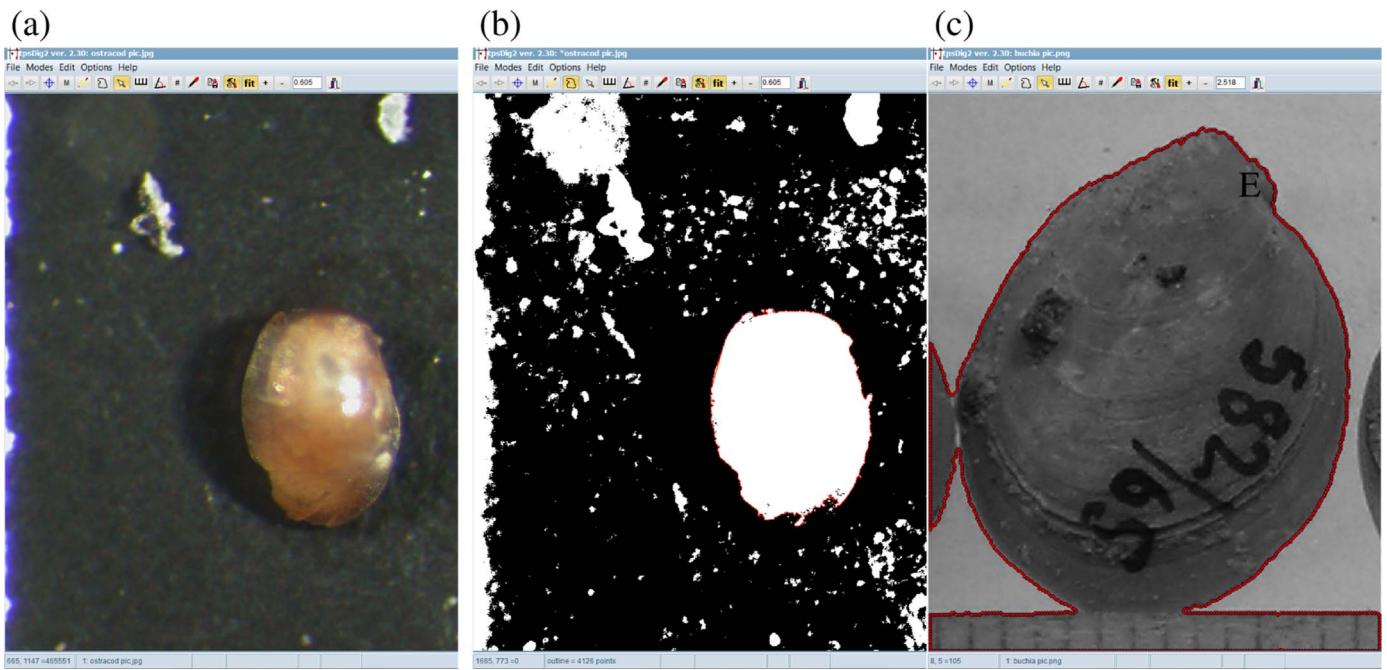
Fig. 1. Screenshots from the tpsDig program. Panels (a) and (b) show an ostracod specimen: the original image is in panel (a); the image after enhancement and conversion to binary (black-and-white) is in (b); the automatically recovered outline for the ostracod image is drawn red in (b). Panel (c) shows an image of a *Buchia* specimen loaded into the program: the image has been converted to greyscale, which is enough to obtain a reasonable result from automatic outline detection (the red outline), ignoring the obvious problems associated with having the sample too close to the ruler and the adjacent samples. A small "ear-like" feature is labelled "E" in panel (c) for reference in the text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

place the white dots on or near the objects being counted.

4.2. Landmarks

Landmark locations are the (*x,y*) coordinates of a point on the image. To perform a landmark measurement, the user clicks once at the location of the landmark. A pink dot is drawn at the clicked location.

4.3. Lengths

Linear measurements are straight-line distances between two selected points. The user must click on two points on the image. Between the first and second clicks, JMorph displays a blue line indicating the candidate measurement, which is drawn between the location of the first click and the current location of the cursor. Once the second click is performed, the finalized measurement is drawn as a
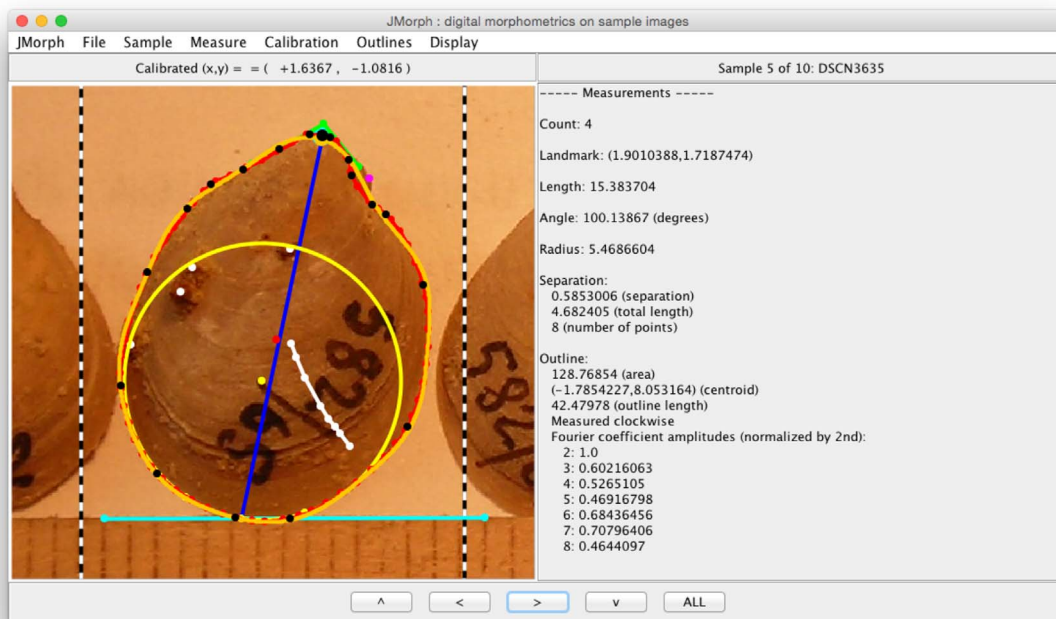
Fig. 2. The JMorph GUI. A sample image is displayed on which several measurements have been performed.
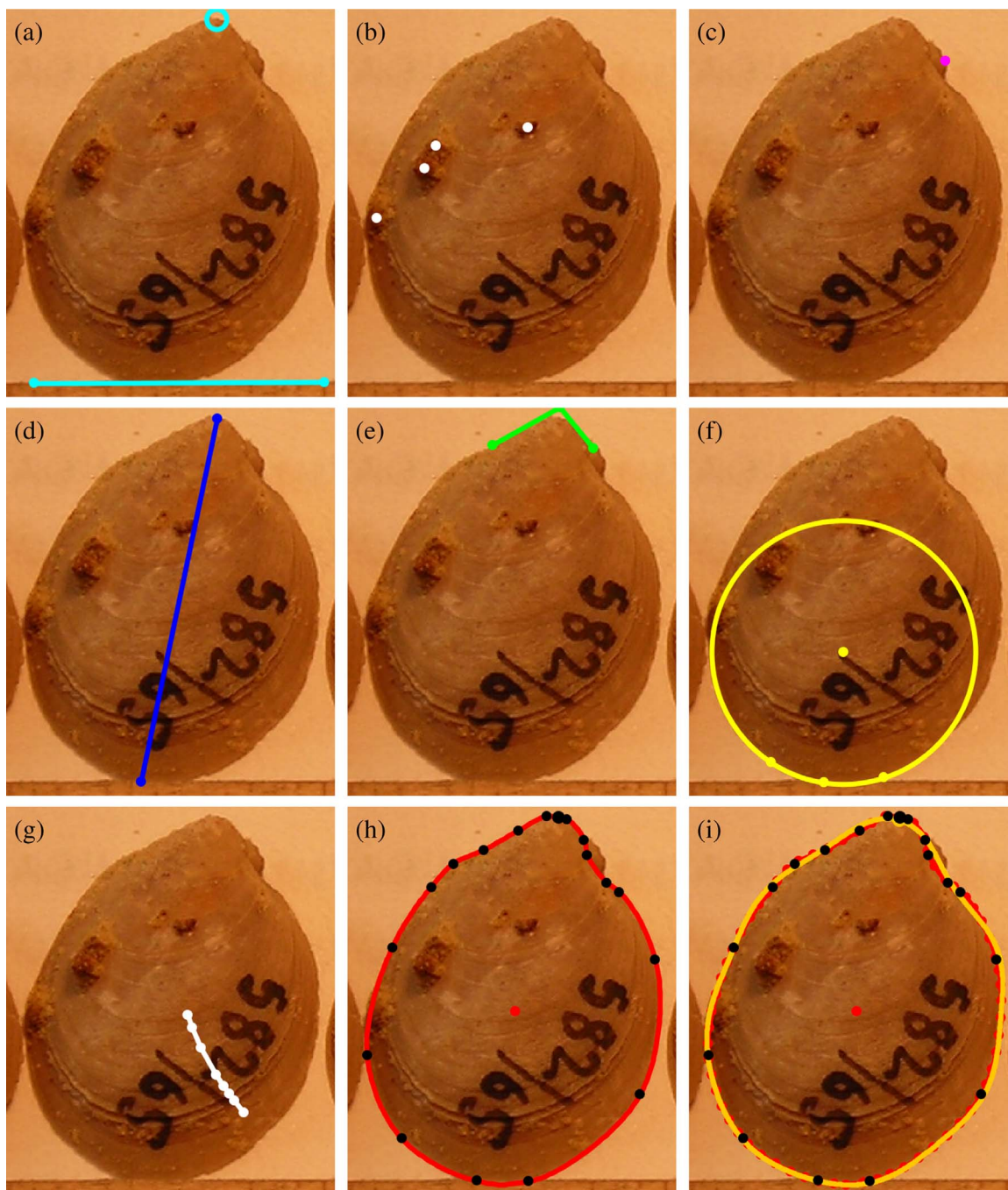
Fig. 3. Each panel shows a different type of measurement, or calibration information, available in JMorph: (a) calibration length and origin, (b) count measurement, (c) landmark measurement, (d) linear measurement, (e) angular measurement, (f) radial measurement, (g) separation measurement, (h) outline measurement, (i) outline measurement with a recovered outline from Fourier analysis. All the measurement colours shown here are the defaults used by JMorph: these drawing colours can be changed as the user desires, as can the point size and line width for overlays. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

blue line, and blue dots are drawn at the two locations where the user clicked.

4.4. Angles

Angular measurements are defined as the angle between three selected points. The user must click on three points on the image. The first and second points clicked are connected by a line, as are the second and third points, and the angle is that between the two lines. Once the measurement is finished, it is drawn as green lines, and green dots are drawn at the three locations where the user clicked. As with linear measurements, JMorph displays temporary green lines as the

measurement is being performed, with the lines following the cursor as it is moved by the user.

4.5. Arc radii

Radial measurements are defined as the radius of a circle that fits through three selected points. This provides a measurement of curvature. The user must click on three points that are not co-linear. The measurement is drawn as a yellow circle with yellow dots drawn at the three clicked locations and at the centre of the circle. Between the second and third click, the candidate circle is drawn, which changes as the user moves their cursor.

4.6. Separations

Separation measurements are calculated as the average straight-line distance between pairs of several clicked points. The user must click on several points, which are drawn as white dots. White lines are drawn between the points, in the order in which they are clicked, to generate a polyline. Other measurements of the resulting polyline could also be calculated but have not currently been implemented.

4.7. Outlines

Outline digitizing can provide several measurements and is the most complex of the available measurements. The user must click on several points around the outline of the sample. In the most basic mode of operation, the points (drawn black) can be connected by straight lines, creating a polygon. However, this approach will not provide an accurate representation of curved features unless many points are clicked, which takes considerable time. Hence, JMorph will interpolate a smooth curve through the clicked points (drawn red) using a Catmull-Rom spline (Catmull and Rom, 1974). This dramatically reduces the number of points the user must click on the sample image to enable an accurate outline digitization, as illustrated in Fig. 3(h). This feature is also helpful when fossil samples have incompletely preserved or obscured outlines: such a situation is illustrated in Figs. 4 through 6.

The calculated measurements for a digitized outline include the area of the outline and the coordinates of the centroid of the outline. The centroid is drawn as a red dot.

5. Data analysis

While JMorph is first and foremost designed as a rapid data collection tool, there is one built-in data analysis tool: Fourier outline shape analysis. Grey et al. (2008b, 2012) used the methods of Haines and Crampton (2000) to analyze the outlines of *Buchia* and ostracod fossils. We have integrated the same outline representation used by Haines and Crampton (2000) (tangential angle versus arc-length) such that Fourier shape coefficients can be calculated directly in JMorph.

Many other outline analysis methods exist beyond tangent-angle Fourier, for example radial Fourier and analysis of curvature. Again, a thorough literature review on morphometric outline analysis in palaeontology or other fields is outside the scope of our manuscript. We are in no way arguing for the general use of one outline analysis method over others; we are simply mentioning the existing functionality of the JMorph program.

To perform the Fourier analysis, the smooth spline is first resampled with some point density specified by the user, the tangential angle versus arc-length data is then calculated and a 1D Fourier transform is performed to calculate the Fourier coefficients for each frequency. The "measurements" are the coefficients returned by a Fourier transform. Alternatively, the resampled (x,y) coordinates around the outline can be exported to individual files for use with external processing software.

If a subsequent 1D inverse Fourier transform is performed then the original outline is recovered. If, however, only the coefficients for lower frequencies are kept, and the higher coefficients are set to zero, then the inverse transform yields a recovered outline with fewer high frequency (short wavelength) features. As fewer high frequencies are kept, the recovered outline approaches a circle. The user can have JMorph draw the recovered outline with some specified number of non-zero coefficients, as illustrated by the orange line drawn in Fig. 3(i). It may be important to carefully select the number of harmonics to use in subsequent multivariate analysis: using too many may give overfitting and loss of degrees of freedom. JMorph's functionality of allowing the user to compare the original digitized outline and the Fourier reconstruction can help ameliorate that issue.

A complication of the approach of (Crampton and Haines, 1996; Haines and Crampton, 2000) is the starting point normalization. The user can avoid this issue in JMorph by simply specifying a homologous starting point for each specimen and digitizing the outline in the same direction for all specimens, clockwise or counter-clockwise.

6. Numerical characteristics of Catmull-Rom splines

A Catmull-Rom spline is type of cubic Hermite spline. A cubic Hermite spline is defined in a piecewise manner between a set of points. For a particular segment, for example two points $\mathbf{p}_1$ and $\mathbf{p}_2$ selected along a specimen outline, the polynomial spline function is

$$\mathbf{p}(t) = (2t^3 - 3t^2 + 1)\mathbf{p}_1 + (t^3 - 2t^2 + t)\mathbf{m}_1 + (-2t^3 + 3t^2)\mathbf{p}_2 + (t^3 - t^2)\mathbf{m}_2 \tag{1}$$

where t runs from 0 at $\mathbf{p}_1$ to 1 at $\mathbf{p}_2$, and $\mathbf{m}_1$ and $\mathbf{m}_2$ are the tangents specified at those end points. For a collection of N points $\mathbf{p}_k$, $k = 1...N$, our implementation chooses tangents

$$\mathbf{m}_k = (\mathbf{p}_{k+1} - \mathbf{p}_{k-1})/2. \tag{2}$$

When the N points sit around a closed outline, one sets

$$\mathbf{m}_1 = (\mathbf{p}_2 - \mathbf{p}_N)/2 \tag{3a}$$

$$\mathbf{m}_N = (\mathbf{p}_1 - \mathbf{p}_{N-1})/2. \tag{3b}$$

JMorph draws a spline curve through the selected points as the user is adding the points around the outline. To do so, the tangents at the first and last points on the open curve are set as follows:

$$\mathbf{m}_1 = (\mathbf{p}_2 - \mathbf{p}_1)/2 \tag{4a}$$

$$\mathbf{m}_N = (\mathbf{p}_N - \mathbf{p}_{N-1})/2. \tag{4b}$$

There are other possible splines that could be used, and several possible choices for how to specify the tangents. Other options could easily be incorporated into JMorph but we find our implementation provides an appropriate balance between performance and user-friendly functionality. Two important advantages of a Catmull-Rom spline are that the curve generated is guaranteed to pass through the control points, and the tangent direction and magnitude are continuous along the curve. The former characteristic is important to help the JMorph user to digitize the outline. The second characteristic has relevance to Fourier shape analysis. If a spline outline is resampled densely before converting to tangential angle versus arc-length, or radius versus polar angle, the converted function will have continuous first derivatives. Therefore, fewer high Fourier coefficients will be required to accurately recover the function and the related outline after inverse Fourier transform.

7. Example

We now provide a brief demonstration of the intended use of JMorph. We use an image of an ostracod (a bivalved crustacean) from the Joggins Fossil Cliffs UNESCO World Heritage Site (Nova Scotia, Canada). The image is the same as that used in Fig. 1(a) and (b). This specimen is from a study of morphological changes within the species over a period of one million years (Grey et al., 2012).

7.1. Loading sample images

The first step is to load the digital images for the samples. There may be one image per sample or multiple samples per image. All common image formats are supported (e.g. JPEG, PNG, TIFF). Once the sample images are loaded, the first sample is displayed in the viewing panel on the left of the GUI: see Fig. 4.

Fig. 4. The JMorph GUI with a sample image loaded and calibrated, and a single measurement defined. The calibration length is drawn as a cyan line. The calibration origin is drawn as a cyan circle.
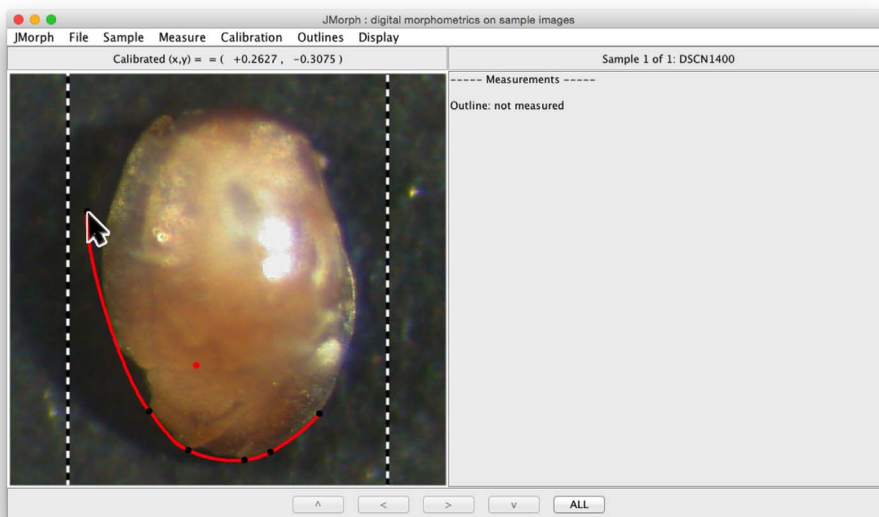
Fig. 5. An outline measurement in the middle of being performed. The clicked points around the outline are drawn black. The smooth interpolated spline curve fit through those points and the current cursor position is drawn red. The zoom-box defined by the user is drawn as a black-and-white dashed line: JMorph zooms to either the height or width of that box. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

7.2. Defining measurements

The next step is to specify the measurements that you wish to measure on each sample. The type of measurement (linear, angular, etc.) is chosen from a pull-down list and a unique user-defined name can be applied to the measurement, for example to distinguish between two linear measurements named "length" and "width". If the user wishes to perform many different measurements, e.g. in cases where there are many different landmarks to mark, it is possible to load the measurement definitions from an ASCII file.

For this demonstration we will only use an outline measurement, which we will name "Outline". All defined measurements are displayed in the right panel of the GUI: see Figs. 2 and 4.

7.3. Calibration

All measurements rely on an initial calibration that allows the program to calculate transformations from image pixel coordinates to spatial coordinates so that measurements taken on an image can be transformed to true spatial units. The calibration involves two pieces of information: an origin point and a length. The origin is important for landmark locations and would typically be defined at the location of some identifiable physical feature common to all samples. The length calibration requires that some length scale is present in the sample image, e.g. a ruler or grid of known spacing.

For this sample, the calibration length is defined by the width of the image. The sample was glued to a standard gridded micro-palaeontological cardboard slide comprising 1 mm wide grid squares. The photograph was taken such that a single grid square took up the entire width of view. We have placed the calibration origin in some out-of-
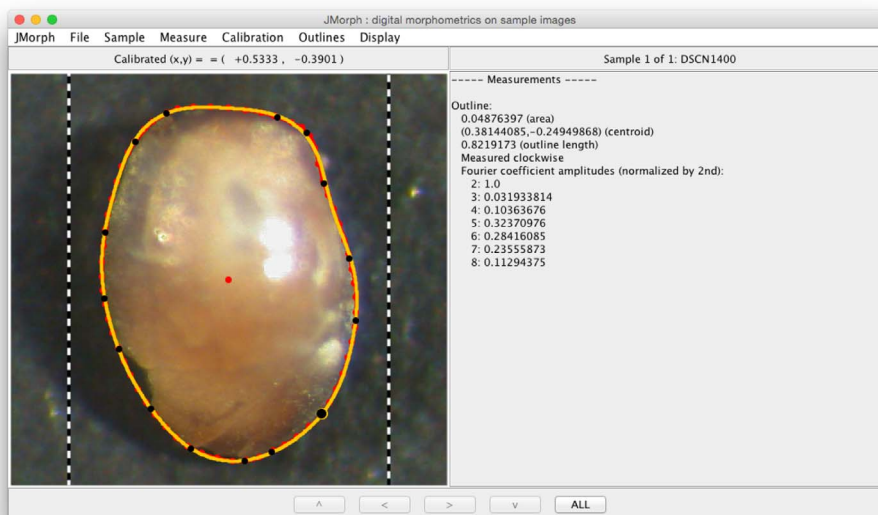
Fig. 6. As in Fig. 5 but with an approximate Fourier outline reconstruction (using only the first eight coefficients) drawn orange.

the-way location because its placement is irrelevant for this demonstration. By default, the calibration origin is drawn as a small cyan circle and the length as a cyan line: see Fig. 4.

7.4. Performing measurements

Once sample images are loaded and measurements defined, JMorph can automatically cycle through each required zooming, calibration and measurement task on each sample, thus allowing the user to rapidly gather their required data. Before each measurement, an instruction dialog is provided that clearly directs the user. For example, the user is instructed to "Click on two points to define the calibration length", after which they are instructed to "Enter the calibration distance" (in spatial units) into the text field of a dialog box.

Fig. 5 shows the outline measurement being performed. The user has selected several points around the outline, drawn as black dots. The interpolated spline curve is drawn red and changes as the user moves their cursor around the outline. This is a very helpful feature of JMorph: being able to see the interpolated curve during the outline digitizing process makes the process faster and more accurate. Fig. 6 shows the competed outline digitization along with a Fourier outline recovery.

Once all defined measurements are completed for a sample, JMorph automatically moves to the next sample and repeats the measurements.

7.5. Saving and exporting

The current session can be saved to continue work later. The user-defined measurements (names and types) can be saved to an ASCII file. The numerical values of the measurements performed on each sample can be exported to a comma-separated-variable (CSV) file for use with other software packages dedicated to morphometric analyses. Each line of the CSV file lists information about a single sample.

8. Measurement precision

For typical hand measurement tools, measurement precision is generally some absolute quantity. For example, measurement precision for vernier or digital calipers is typically 0.01−0.03 mm. In contrast, measurement precision for JMorph is based on the resolution of the digital images. It is not uncommon for current digital photography to

provide images on the order of 10 Megapixels, which provides images on the order of 3000 pixels wide. As an illustrative example, consider a 50 mm long fossil sample. If that image takes up half the width of a 3000 pixel wide photograph, it spans 1500 pixels. This means 30 pixels per mm, providing a precision of about 1mm/30 = 0.033mm. Hence, for such a fossil the measurement precision using JMorph is comparable to using vernier calipers. To improve precision when using JMorph, photographs of fossils should be taken with the specimens taking up as much of the image as possible.

One must also consider the accuracy, repeatability and quality control of measurements taken using hand instruments versus a digital tool like JMorph. For calipers, accuracy is related to how well a user can adequately position the jaws at the required locations, and this is likely to provide a far larger degree of error than the precision of the measurement device. For JMorph, accuracy is related to how well a user can position the cursor at the required location. Given that one can easily zoom into an image in JMorph, accuracy could potentially be on a similar order of magnitude to precision.

Repeatability of any scientific work is important and the measurements taken by any method should be repeatable. This comes down to accuracy, and again, measurements are expected to be more accurate for digital methods using sample images, like JMorph. We suggest that in any study involving JMorph, multiple samples should be measured multiple times. Assessment of the variation in those repeated measurements would aid in the estimation of measurement errors.

Quality control relates to being able to assess the rigour with which measurements were performed. With traditional hand instruments there is little one can do to control the quality of their data, beyond simply taking more care to avoid human error. However, a major advantage of using JMorph is that the measurements performed can be visualized long after having been performed. For example, consider a situation where an outlier is found in the data after all measurements have been performed on all samples. With traditional measurement instruments, there is no way to assess whether the outlier is an accurate measurement or if there was some user error. In JMorph, a user can simply load a saved session and investigate the specific specimen and measurement related to the outlier: if there has been a user error in taking the measurement then this will be immediately obvious from visualizing the measurement.

Two final sources of error that we mention are those associated with lens and perspective distortion. Ideally, a photograph of parallel lines should produce an image with parallel lines. Lens distortion can
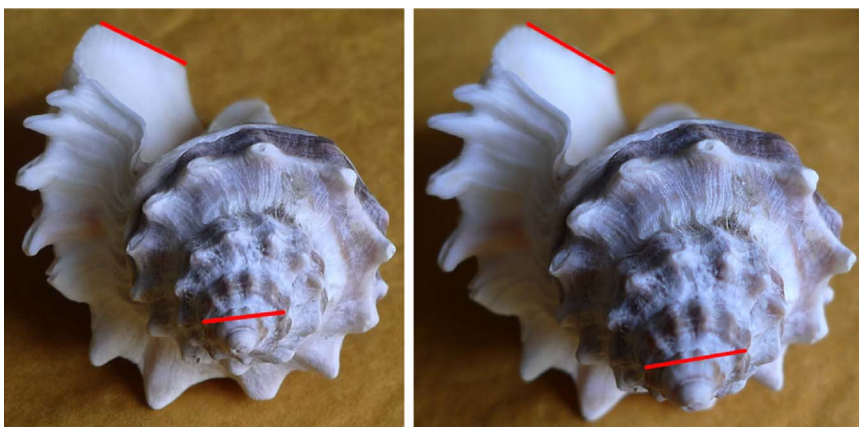
Fig. 7. Two photographs of the same sample with different focal lengths used. The image on the left was taken with a longer focal length than the image on the right. Red lines are drawn in consistent locations to illustrate the perspective distortion. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

produce curved lines instead. For example, with barrel lens distortion, image magnification decreases with distance from the image centre and the effect is that of projecting the image onto the surface of a sphere (or barrel). Lens distortion may give displacements of 2–3% before being noticeable by the viewer, which may be a significant source of error, but the distortion can often be corrected with appropriate software.

To understand perspective distortion, consider an object with a large dimension along the axis of view, such as that in Fig. 7. If a small focal length is used to take a photograph of the object then any lengths measured on parts of the object that were closer to the lens will not agree with equal lengths measured on parts of the object that were further from the lens. Angular measurements can also be affected. To reduce this error, photographs taken of such fossils should be taken with as long a focal length as possible. This means having the camera lens set at the highest possible optical zoom level, which may require the camera be moved further from the fossil.

9. Extensibility

Users interested in developing their own measurements can do so using the Java Measurement interface. This interface defines all the methods that must be present in a new measurement class. These methods perform all the required tasks such as providing the user with instructions on how to perform the measurement, defining how many user-defined points are required, calculating the measurement based on those supplied points and drawing an overlay of the measurement on top of the sample image.

10. Extension to 3D

Several researchers have indicated to us through personal communication that a 3D version of JMorph would be helpful for their studies. "3D images" may correspond to point clouds from laser scanning or stacked section images from computerized tomography (CT) scanning. We have developed another software package called FacetModeller which is designed for building 3D geological models. That software has the functionality to allow 3D morphometric measurements on fossil samples. A future publication is planned for that software.

11. Conclusion

We have developed a new software tool, JMorph, that is custom-built for efficiently measuring micro- and macrofossils from digital images. JMorph provides the means to perform many different types of measurements, including counts, landmarks, lengths, angles, curvatures, separations and outline digitization. JMorph's two major assets are 1) the speed in which measurements can be made, and 2) the ability

to efficiently and accurately digitize the outlines of fossils for use in shape analyses. These are important when a manual digitization approach is the only viable option, for example when many fossil samples have incomplete outlines because of preservation issues.

JMorph is primarily designed as a tool to rapidly collect data destined for further analyses with the many packages available (e.g. PAST Hammer et al., 2001). However, JMorph does contain one built-in data analysis tool: Fourier outline shape analysis.

JMorph is written in Java and will therefore run on any operating system that can run Java. JMorph is freely available as source code or a compiled package. JMorph has been developed with extensibility in mind: developers can define new measurements using the Measurement interface. Other data processing tools could also be added to JMorph through its modular design.

JMorph, or its now obsolete Matlab predecessor MorphLab, has been used in several studies in which many measurements were taken on very numerous fossil assemblages (Grey et al., 2008a, 2008b, 2008c, 2012; Haggart and Smith, 2010). Without JMorph, collection of data for those studies would not have been possible. We hope that JMorph will be of use to other researchers undertaking morphometric studies, in palaeontology or other fields.

References

Adams, D.C., Otárola-Castillo, E., 2013. geomorph: an R package for the collection and analysis of geometric morphometric shape data. Methods Ecol. Evol. 4, 393–399.

Bookstein, F.L., Chernoff , B., Elder, R.L., Humphries, J.M., Smith, G.R., Strauss, R.E., 1985. Morphometrics in Evolutionary Biology. Ch. The geometry of size and shape change, with examples from fishes. Academy of Natural Sciences of Philadelphia.

Catmull, E., Rom, R., 1974. Computer Aided Geometric Design. Ch. A class of local interpolating splines. Academic Press, New York. pp. 317–326.

Crampton, J.S., 1995. Elliptic fourier shape analysis of fossil bivalves: some practical considerations. Lethaia 28, 179–186.

Crampton, J.S., Haines, A.J., 1996. Users' manual for programs HANGLE, HMATCH, and HCURVE for the fourier shape analysis of two-dimensional outlines. Technical Report. Institute of Geological and Nuclear Sciences Science Report.

Grey, M., Finkel, Z.V., Pufahl, P.K., Reid, L., 2012. Evolutionary mode of the ostracod, Velatomorpha altilus, at the Joggins Fossil Cliffs UNESCO World Heritage Site. Lethaia 45, 615–623.

Grey, M., Haggart, J.W., Smith, P.L., 2008a. A new species of Buchia (Bivalvia: Buchiidae) from British Columbia, Canada, with an analysis of buchiid bipolarity. J. Paleontol. 82 (2), 422–428.

Grey, M., Haggart, J.W., Smith, P.L., 2008b. Species discrimination and evolutionary mode of Buchia (Bivalvia: Buchiidae) from Upper Jurassic to Lower Cretaceous strata of Grassy Island, British Columbia, Canada. Palaeontology 51 (3), 583–595.

Grey, M., Haggart, J.W., Smith, P.L., 2008c. Variation in evolutionary patterns across the

geographic range of a fossil bivalve. Science 322 (5905), 1238–1241.

Haggart, M.G.J.W., Smith, P.L., 2010. Morphological variability in time and space: an example of patterns within buchiid bivalves (Bivalvia Buchiidae). Palaeontology 53 (1), 1269–1280.

Haines, A.J., Crampton, J.S., 2000. Improvements to the method of Fourier shape analysis as applied in morphometric studies. Palaeontology 43 (4), 765–783.

Hammer, O., Harper, D.A.T., Ryan, P.D., 2001. PAST: paleontological statistics software package for education and data analysis. Palaeontol. Electron. 4 (1), 9.

Hsiang, A.Y., Elder, L.E., Hull, P.M., 2016. Towards a morphological metric of assemblage dynamics in the fossil record: a test case using planktonic foraminifera. Philos. Trans. R. Soc. B 371, 20150227.

Knappertsbusch, M.W., 1998. A simple FORTRAN 77 program for outline detection. Comput. Geosci. 24 (9), 897–900.

Kowalewski, M., Dyreson, M.E., Marcot, J.D., Vargas, J.A., Flessa, K.W., Hallman, D.P., 1997. Phenetic discrimination of biometric simpletons: paleobiological implications of morphospecies in the lingulide brachiopod Glottidia. Paleobiology 23 (4), 444–469.

Laflamme, M., Casey, M.M., 2011. Quantifying the Evolution of Early Life. Vol. 36 of Topics in Geobiology. Ch. Morphometrics in the study of Ediacaran fossil forms.

Springer Netherlands, Dordrecht. pp. 49–71.

Marko, P.B., Jackson, J.B.C., 2001. Patterns of morphological diversity among and within Arcid bivalve species pairs separated by the Isthmus of Panama. J. Paleontol. 75 (3), 590–606.

Rohlf, F.J., 2017. Software by F. James Rohlf. ⟨http://www.life.bio.sunysb.edu/ee/rohlf/software.html⟩, (Accessed 22 March 2017).

Schindelin, J., Rueden, C.T., Hiner, M.C., Eliceiri, K.W., 2015. The ImageJ ecosystem: an open platform for biomedical image analysis. Mol. Reprod. Dev. 82, 518–529.

Schneider, C.A., Rasband, W.S., Eliceiri, K.W., 2012. NIH Image to ImageJ: 25 years of image analysis. Nat. methods 9 (7), 671–675.

Stempien, J.A., Daley, G.M., Kowalewski, M., 2001. Testing for ecophenotypic variation across a paleoenvironmental gradient in a small mactrid bivalve (Yorktown Formation, Pliocene, Virginia). In: Proceeding of Geological Society of America Annual Meeting. Boston, Massachusetts.

Strauss, R.E., Bookstein, F.L., 1982. The truss: body form reconstruction in morphometrics. Syst. Zool. 31, 113–135.

Webster, M., Sheets, H.D., 2010. Quantitative Methods in Paleobiology. Vol. 16 of The Paleontological Society Papers. Ch. A practical introduction to landmark-based geometric morphometrics. The Paleontological Society. pp. 163–188.