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Methods in Ecology and Evolution

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ABSTRACT

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- Accepted Article
1. Close range photogrammetry (CRP) is a well-established technique to retrieve quantitative information from objects using photography. CRP is often used in morphology studies when the direct handling of individuals is unpractical or unethical, or to reduce processing costs and time. Although multiple software to extract quantitative information from 3D reconstructions of objects exist, tools for 2D CRP are scarce and often tailored for specific applications.
 2. We present AragoJ, a cross-platform, open-source, Java based software designed to integrate and streamline all 2D CRP workflow steps in a single program.
 3. AragoJ allows the user to perform all the main tasks involved in obtaining measurements from digital pictures, namely: 1) performing camera calibration and correcting radial picture distortions; 2) calculating a scaling factor either by: a) utilizing a scale in the picture, or b) based on camera specifications (focal distance and digital sensor size) and distance to object; 3) measuring and scaling the relevant traits in the photographs; 4) obtaining information from pictures' digital metadata files; and 5) exporting measurements and metadata to a comma separated values (CSV) file.
 4. AragoJ was designed to be versatile and unconstrained, in order to be useful for 2D CRP studies across multiple disciplines. The software, source code and detailed documentation are available from <https://github.com/AzWhaleLab/AragoJ>.

KEY-WORDS: Close-range photogrammetry, image processing, morphometrics, Java, OpenCV.

1. INTRODUCTION

Quantitative analysis of size and shape (morphometrics) is fundamental for the study of organisms' ecology and evolution (Rohlf 1990; Reyment 1996; Elewa 2010).

Close-range photogrammetry (CRP) is a technique widely used to remotely obtain measurements of objects and organisms, by scaling measurements taken on their 2D photographic reproductions (planimetric measurements), or from photography-based 3D reconstructions (Luhmann *et al.* 2006; Kraus 2011). The technique has been long used in morphometric studies to expedite acquiring and processing data (Zou *et al.* 2014; Ivosevic, Han & Kwon 2017; Hsiang *et al.* 2018), for conservation and ethical concerns (Whitehead &

Payne 1981; Whitehead & Gordon 1986), or to obtain data on organisms that are difficult to locate, manipulate, or are inaccessible in other ways (e.g. Breuer, Robbins & Boesch 2007; Deakos 2010; Willisich, Marreros & Neuhaus 2013; Letessier *et al.* 2015; Durban *et al.* 2016; Muneza *et al.* 2019). Another incentive for using 2D photogrammetry is its relative low cost when compared to direct measurement, which is often made clear in publication titles, by the use of terms such as 'inexpensive', 'low-cost', or 'cost-efficient' (e.g. Dawson *et al.* 1995; Langlois *et al.* 2010; Letessier *et al.* 2015; Dawson *et al.* 2017). Despite its widespread use, 2D CRP is not without caveats, and can be affected by several error sources (Scherz 1974; Wenhao 2001; Dai, Feng & Hough 2014). Nonetheless, the method has been shown to be both accurate and to produce suitable levels of precision, when properly implemented (e.g. Grochowsky *et al.* 2006; Deakos 2010; Jeffreys *et al.* 2013; Jadejaroen *et al.* 2015; Weisgerber, Medill & McLoughlin 2015; Galbany *et al.* 2016; Dawson *et al.* 2017; Monkman *et al.* 2019).

The surge in computing power in the last decades, combined with development of consumer-grade high-definition digital photography and democratization of low-cost Unmanned Aerial Vehicles (UAV) led to a rapid increase in the utilization of CRP for 3D scene reconstruction, using either stereogrammetric or 'structure from motion' methods (Remondino *et al.* 2014; Micheletti, Chandler & Lane 2015). Accordingly, an ever-increasing number of software for 3D scene reconstruction and measurement are available (Rupnik, Daakir & Pierrot Deseilligny 2017). Notwithstanding, 3D CRP is not suited for all applications. Methods for 3D scene reconstruction are not well suited for moving subjects, and usually rely in the acquisition of a large number of images taken from different angles, which is not always feasible. Additionally, in many applications, 2D and 3D metrics are comparable, making the use of 2D CRP more desirable due to its simplicity and lower associated costs (Birgfeld *et al.* 2013; Cardini 2014).

Yet, and paradoxically, software specifically designed to aid in obtaining simple planimetric measurements in 2D CRP are scarce and often tailored to specific problems, narrowing their applicability (e.g. Burnett *et al.* 2018; Hsiang *et al.* 2018). Instead, 2D CRP studies often make use of image editing software to obtain measurements from digital photographic reproductions (e.g. Franke-Gromberg *et al.* 2010; Leurs *et al.* 2015; Galbany *et al.* 2016; Rhee 2018; Gašparič *et al.* 2019). Measurements are subsequently transcribed to a digital database and scaled, adding to the lengthy process of data acquisition and preparation prior to analysis, and also increasing the chances of transcription errors compromising data quality (Kim *et al.* 2003). Any other operations, such as calibrating the camera, undistorting images, or retrieving image metadata, usually require separate processing on other software (Balletti *et al.* 2014; Wehkamp & Fischer 2014).

The scientific image-analysis software ImageJ (Abramoff, Magalhães & Ram 2004) stands out as an exception and powerful tool for 2D CRP. With over 30 years of continuous development, ImageJ has become one of the most widely used scientific imaging software (Schneider, Rasband & Eliceiri 2012). Among its strengths are the cross-platform nature, modular architecture with numerous extensions (macros and plugins), and the free and open-source nature of the software (Abramoff, Magalhães & Ram 2004; Schneider, Rasband & Eliceiri 2012). However, one of the qualities of ImageJ is also a challenge for new users, as the sheer number of extensions makes selecting, maintaining, and learning to work with the appropriate add-ons a complex and time-consuming task (Collins 2007). Moreover, most of these extensions are tailored for medical imaging, microscopy and material sciences (Collins 2007; Schneider, Rasband & Eliceiri 2012), not being well suited for other 2D CRP applications.

Here, we introduce AragoJ, an open-source Java application designed specifically with the purpose of streamlining 2D CRP tasks. Apart from small variations, most 2D CRP studies follow a similar workflow (e.g. Gale, Renouf & Worthy 1994; Shrader, Ferreira & Aarde 2006; Rothman *et al.* 2008; Deakos 2010; Meise *et al.* 2014; Jadejaroen *et al.* 2015; Dawson *et al.* 2017) consisting of the following steps: 1) camera calibration and picture distortion correction; 2) calculating a scaling factor either by: a) utilizing fiducial markers, or b) based on camera specifications (focal distance and digital sensor size) and distance to object; 3) measuring and scaling the relevant traits in the photographs; 4) extracting information embedded in the picture's metadata; and 5) transcribing measurements and metadata to a digital database.

AragoJ includes tools that address all of those steps, through a user-friendly Graphical User Interface (GUI). This way, processing time can be greatly reduced and transcription errors are avoided, as all measurements, calculation results, and metadata selections made using AragoJ are automatically exported as a tabulated comma separated values (CSV) file, accepted by most analysis and editing software.

Unlike other software, such as Automorph (Hsiang *et al.* 2018), AragoJ does not implement automatic object recognition and measurement intentionally, because that usually requires high image quality and strict orientation, and constrain the measurements to a set of pre-defined metrics. The automation offered by software such as Automorph is invaluable to reduce processing time under controlled conditions (Hsiang *et al.* 2018), but also limits applicability when that is not the case. AragoJ was designed to be flexible enough to handle situations that are not addressed by existing software, being useful for a wide range of users, while not competing with other applications optimized for more specific tasks.

AragoJ software releases and source code are openly available on GitHub (<https://github.com/AzWhaleLab/AragoJ>), and an illustrated user manual is also available with detailed information on tools and functionalities.

2. SOFTWARE DESCRIPTION

AragoJ has a multi-modular architecture implemented in Java for its cross-platform capabilities. The GUI is implemented through JavaFX framework comprising three main panels (*Navigation*, *Work*, and *Info*), along with *Menu* and *Tool* bars (**Figure 1**). *Navigation* is where thumbnails and names of imported images are presented; the *Work* panel is the main working area, where image manipulation and measuring is performed; the *Info* panel is sub-divided in two tabs: 1) *Metadata tab*, where the metadata embedded in the images are displayed, and 2) *Layer tab*, where information about measurements and results from calculations are displayed.

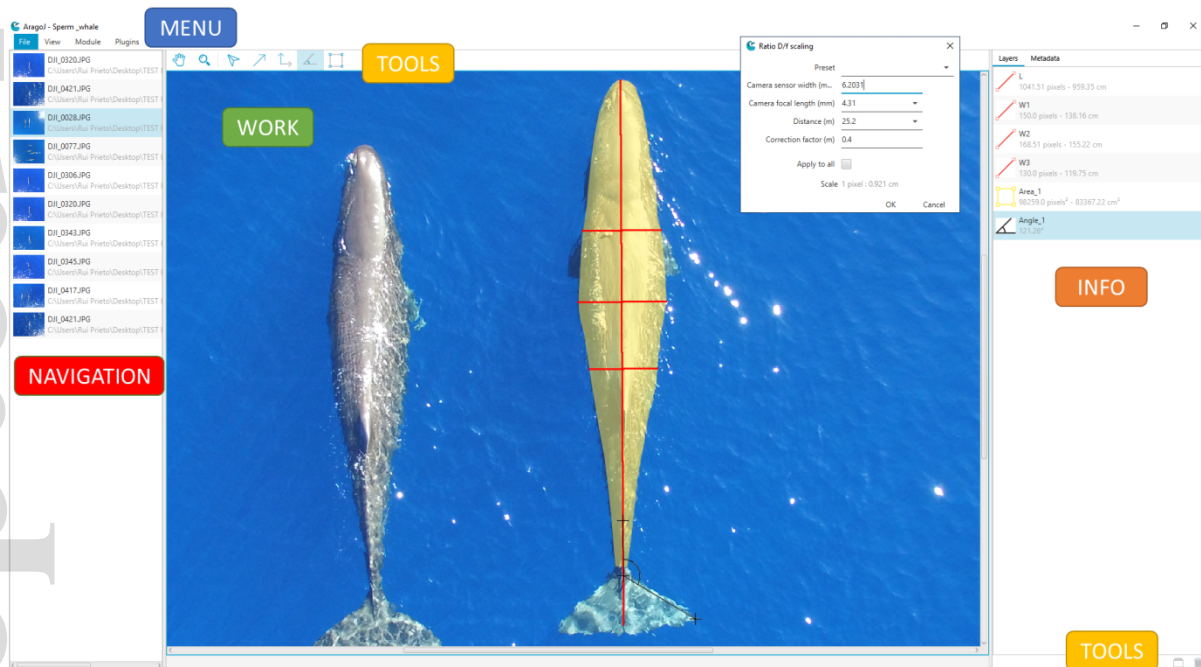


Figure 1: Graphical User Interface of AragoJ, showing the different components of the main screen. The pop-up window to configure distance-based scaling is also shown (to the left of the *Info* panel). Measurements (body length and widths, area, and angle of fluke with body axis) of a sperm whale (*Physeter macrocephalus*) from an aerial picture are visible in the *Work* panel. Scaled measurements using distance from camera to object are visible in the *Info* panel.

The software consists of seven modules: *Camera Calibration*; *Lens Distortion Correction*; *Image I/O (Input-Output and Metadata Reader)*; *Measuring*; *Scaling and Units Conversion*; *Mathematical Expressions*; and *Session Handling*. In conjunction, these modules comprise a complete pipeline for data extraction and exporting (Figure 2). Functions of each module are described in detail in the following sections.

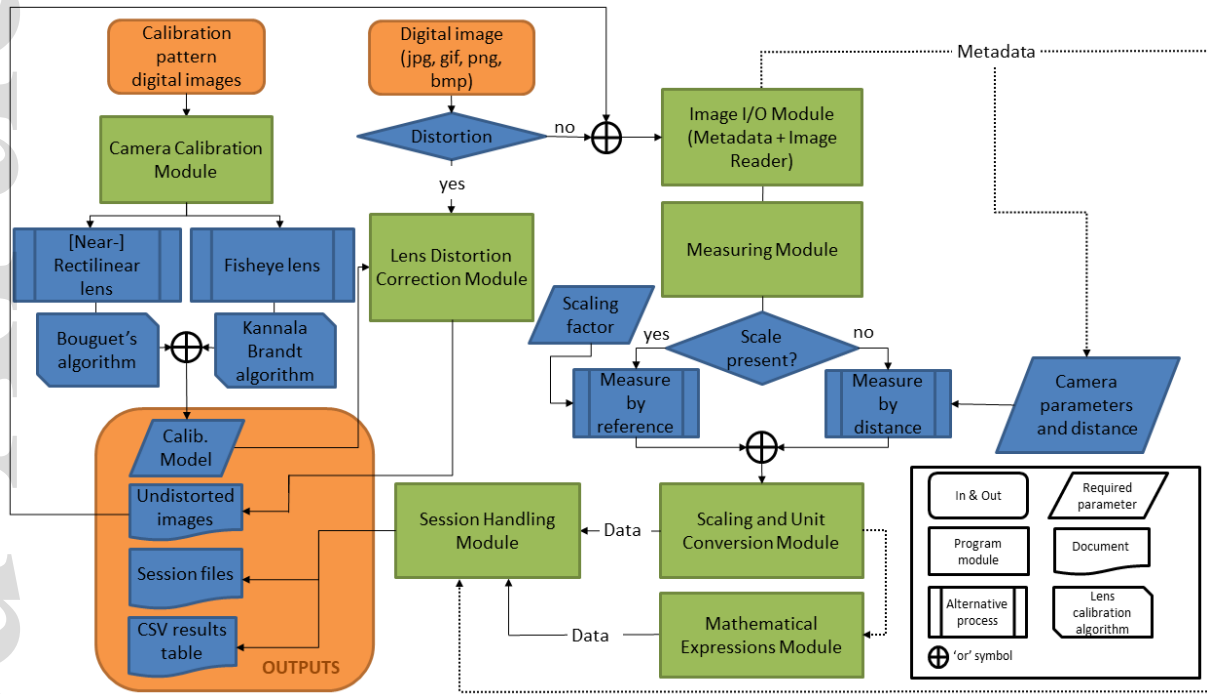


Figure 2: Scheme of module-interactions and high-throughput of close-range 2D photogrammetry workflow using AragoJ. Dotted lines denote optional information traffic.

2.1 Camera Calibration

Camera calibration is essential to scale measurements made on the photographic projections (Kraus 2011). Lenses used in true metric cameras produce images with negligible distortion, preserving straight lines and right angles (Kraus 2011). However, lenses used in most consumer-grade cameras warp the image projection, resulting in negative (barrel) or positive (pin-cushion) radial distortion patterns, eliciting the need to undistort images using an appropriate calibration model (Carbonneau & Dietrich 2017). AragoJ includes a module for camera self-calibration using the OpenCV library (Bradski 2000). Space constraints preclude a detailed description of the self-calibration method, but comprehensive information can be found in Hartley and Zisserman (2004) and Bradski and Kaehler (2008). Very briefly, camera intrinsic parameters for calibration

are calculated by analyzing multiple photographs of a planar calibration pattern, taken at different random angles (Zhang 2000). The resulting calibration matrix is written to a file that can subsequently be used for distortion correction. Since self-calibration models do not generalize well for all camera lens types, AragoJ offers two calibration algorithms (Figure 2). Distortion models for cameras using near-rectilinear lenses can be computed using the Bouguet's algorithm implemented in OpenCV (Bradski & Kaehler 2008; Bouguet 2015), based on the method presented by Tsai (1987) and Zhang (2000). Additionally, AragoJ also implements the generic model proposed by Kannala and Brandt (2006), specifically designed to handle large radial distortions caused by fish-eye lenses.

2.2 Lens Distortion Correction

The *Lens Distortion Correction* module uses OpenCV functions to correct radial distortion in images, based on a calibration model produced by the *Camera Calibration* module. Images can be batch processed and undistorted images are saved with a suffix ('_u') relative to the original names, preserving the original images unchanged.

2.3 Image I/O

The *Image I/O* module is responsible for reading and writing images, including pixel and metadata information. AragoJ accepts images in jpg, gif, bmp, and png formats natively. Support for other image formats can be added through plugins, consisting in simple Java library projects packaged in a JAR file. Guidance on how to create plugins is available on the GitHub repository. A plugin adding support to over 150 microscopy file formats, using the Bio-Formats library released by the Open Microscopy Environment Consortium (<http://openmicroscopy.org>) is included in AragoJ distributions after version 0.61, which can also be used as an example for the creation of additional plugins.

The application reads and presents the metadata inscribed in digital images EXIF information (JEITA 2002), which is useful for finding and using relevant information (geolocation, date and time, camera and image specifications, custom information from sensors, etc.). Metadata entries can be individually selected for exporting (Fig. 3), as well as be directly imported in some of other AragoJ tools.



Figure 3: Graphical User Interface showing the Metadata tab. Some of the picture metadata are visible, while other are hidden under the EXIF and Derived headers. Metadata entries that were selected for exporting are signaled with an 'e' symbol before the metadata tag.

2.4 Measuring

AragoJ includes tools for linear, area, and angle measurements (Figure 1). The linear measurement tool accepts any number of segments, allowing for the measurement of irregular and curved shapes. Additionally, linear measurements can be made at user-specified angles from a reference line (Fig. 1), helping to easily take parallel or perpendicular measurements (or at any other angle).

Apart from angles, all measurements are taken in pixel units prior to scaling (see below). AragoJ allows sub-pixel values, and three pixel selection options are available: free (line segments can start and end at any position inside a pixel), 0.5 pixel (line segments can start and end either at the center or the edge of a pixel) and 1.0 pixel (line segments can only start and end at the edge of a pixel). These options allow controlling for unrealistic precision.

Polygon area is calculated from coordinate geometry, using equation (1)

$$Area = \left| \frac{(x_1y_2 - y_1x_2) + (x_2y_3 - y_2x_3) + \dots + (x_ny_1 - y_nx_1)}{2} \right| \quad (1)$$

with x_n and y_n being the coordinates of vertex n . Since the method is not applicable for area calculation of self-intersecting polygons, these are first decomposed using the Java class `FlatteningPathIterator`.

All measurements are recorded and named automatically, as 'layers', and presented in the *Layers tab*, under the *Info* panel. The user can easily rename layers, in order to standardize the output data table fields.

2.5 Scaling and Unit Conversion

The *Scaling and Unit Conversion* module is responsible for scaling measurements from pixel to metric units. For convenience, the module also includes a tool to convert from metric to other units. Two methods are available for scaling measurements taken on the photographs: 1) reference-based (Figure 4), using fiducial marks imprinted in the image; or 2) distance-based (Fig. 1), using the camera sensor size and focal length, combined with distance to object, to calculate the scaling factor applying the similarity of triangles principle (Kraus 2011).

Reference-based scaling is calculated using equation (2):

$$M_{cm} = \left(\frac{M_{px} \times S_{cm}}{S_{px}} \right) \quad (2)$$

where M_{cm} stands for the scaled trait measurement in centimeters (cm), M_{px} the length of the same trait in pixel units, S_{cm} the true length of the scale in cm, S_{px} the length of the scale in pixel units.

In distance-based scaling, the calculation of the scaling factor uses equation (3):

$$M_{cm} = M_{px} \times \left(\frac{Sw \times (D + \beta) \times 100}{Fl \times imW} \right) \quad (3)$$

where M_{cm} stands for the scaled trait measurement in cm, M_{px} the same trait measured in pixel units, Sw the width of the camera sensor in millimeters (mm), D the distance of the camera to the object (cm), Fl the focal length (mm), and imW the image width in pixel units (which is automatically obtained from the metadata). β is a correction factor for the camera to object distance. For example, the height reported by barometric altimeters used in drones is referenced to the take-off location and can differ from the true height relative to the location where the image was taken; if that difference is known, β can be used to correct for that. Fl and Sw can often be obtained directly from camera manufacturers. Alternatively, a vast database of sensor specifications is maintained by OpenMGV (<https://github.com/openMVG>).

One caveat with both scaling methods is the square pixels assumption, which in some rare cases is violated (Manthey & Kowerko 2019). Nevertheless, the vast majority of modern digital camera sensors utilize square pixels (Godding 2007).

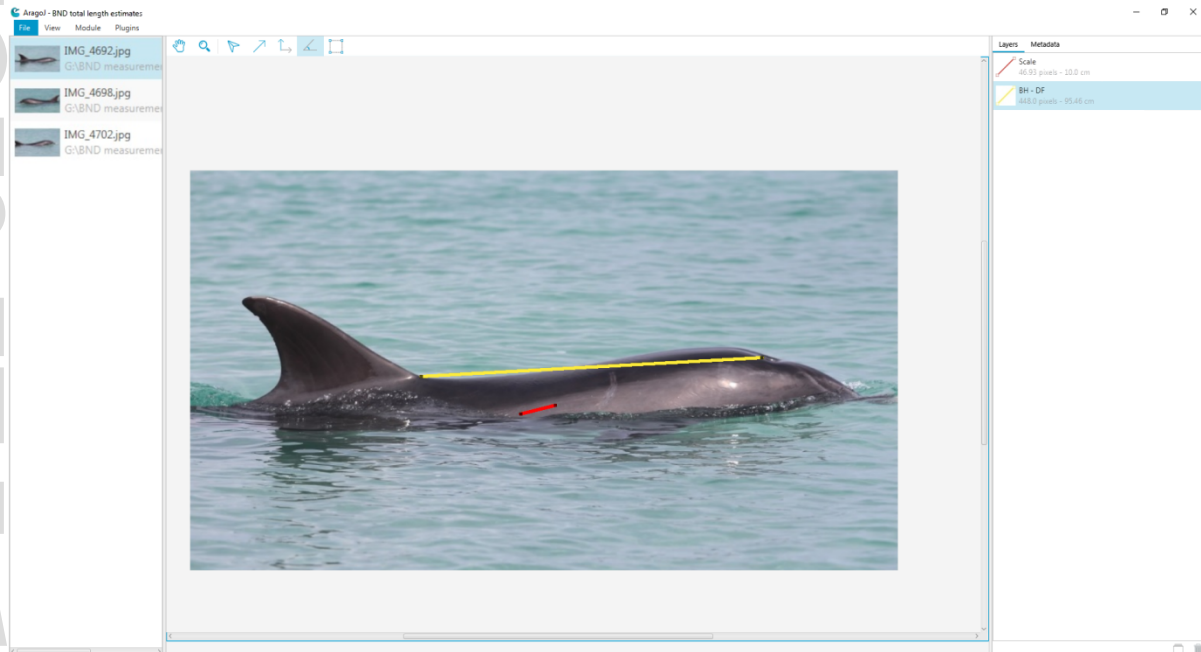


Figure 4: Example of reference-based scaling in AragoJ. Parallel lasers are projected on the body of a free-swimming bottlenose dolphin (*Tursiops truncatus*) creating a scale (shorter line segment, in red) of known size, that is used by AragoJ to scale other measurements (longer line segment, in yellow). Results from conversion from pixel to metric units can be seen in the *Info* panel, on the right side of the image.

2.6 Mathematical Expressions

AragoJ includes a module for creating and storing mathematical expressions that can be called inside the software and produce results using the measurements made over an image as variables. This is useful to quickly calculate derived variables, for example, using allometric relations.

2.7 Session Handling

The *Session Handling* module is responsible for saving session information to a file, and managing sessions throughout the lifecycle of the application. A session is akin to a 'project' in image editing software, referring

to all work done by the user that can be saved. This module specifically handles two cases: 1) opening and saving session information; and 2) exporting measurements, calculations and selected metadata to a CSV file.

3. CONCLUSIONS AND FUTURE WORK

We believe that AragoJ is a seamless, convenient and efficient software package to undertake a wide range of 2D photogrammetry studies within one application, without being tailored to a particular task. This makes AragoJ highly versatile in its uses for CRP across multiple disciplines. In fact, despite having been developed as a tool aimed at helping in ecological studies, the principles and workflow involved are equally applicable in architecture, anthropology, forensics, archaeology and paleontology studies.

The software utilizes some well-known libraries (such as OpenCV) to manipulate and obtain quantitative information from images. These were chosen for being robust, with well-established and tested methods. These libraries are well documented, enabling the user to understand how some of the more complex tools (such as camera calibration and distortion correction) work, and to account for any biases that may apply. The architecture of AragoJ allows taking full advantage of these libraries with the aim of optimizing the workflow involved in 2D CRP, in order to improve efficiency and reduce processing time and errors. Additionally, it can be easily extended with new functionalities through the creation of plugins.

AragoJ was created as a stand-alone and portable application so it can be used in most situations, and shared easily. We feel that these are strong qualities and intend to maintain them in future releases. However, we are aware that AragoJ and ImageJ (Abramoff, Magalhães & Ram 2004) are complementary in many ways. Thus, an AragoJ plug-in for ImageJ is planned for those users who prefer to work with the latter software. Similarly, we also plan to create a mobile version of AragoJ, to improve its utility in fieldwork situations, including direct import capabilities from mobile device cameras.

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AUTHORS' CONTRIBUTIONS

RP conceived the software, led the preparation of the manual and participated in testing beta versions. FA led the development of AragoJ software. SO played a key role in testing beta versions, and provided substantial contributions to the manual. LS and PN mentored FA and supported software development. All authors participated in the preparation of the manuscript.

DATA AVAILABILITY STATEMENT

AragoJ is developed through GitHub at <https://github.com/AzWhaleLab/AragoJ>. The source code for v0.6.1, described here, is available under the Apache License, Version 2.0, and is deposited in zenodo (<https://doi.org/10.5281/zenodo.3660975>).

REFERENCES

- Abramoff, M., Magalhães, P. & Ram, S.J. (2004) Image processing with ImageJ. *Biophotonics International*, **11**, 36-42.
- Balletti, C., Guerra, F., Tsioukas, V. & Vernier, P. (2014) Calibration of action cameras for photogrammetric purposes. *Sensors*, **14**, 17471-17490.
- Birgfeld, C.B., Saltzman, B.S., Luquetti, D.V., Latham, K., Starr, J.R. & Heike, C.L. (2013) Comparison of two-dimensional and three-dimensional images for phenotypic assessment of craniofacial microsomia. *The Cleft Palate-Craniofacial Journal*, **50**, 305-314.
- Bouguet, J.Y. (2015) Camera Calibration Toolbox for Matlab. http://www.vision.caltech.edu/bouguetj/calib_doc/. Assessed 30/07/2019.
- Bradski, G. (2000) The OpenCV library. *Dr Dobb's J. Software Tools*, **25**, 120-125.
- Bradski, G. & Kaehler, A. (2008) *Learning OpenCV: Computer Vision with the OpenCV Library*. O'Reilly Media.
- Breuer, T., Robbins, M.M. & Boesch, C. (2007) Using photogrammetry and color scoring to assess sexual dimorphism in wild western gorillas (*Gorilla gorilla*). *American Journal of Physical Anthropology*, **134**, 369-382.

- Burnett, J.D., Lemos, L., Barlow, D., Wing, M.G., Chandler, T. & Torres, L.G. (2018) Estimating morphometric attributes of baleen whales with photogrammetry from small UAVs: A case study with blue and gray whales. *Marine Mammal Science*, **35**, 108-139.
- Carbonneau, P.E. & Dietrich, J.T. (2017) Cost-effective non-metric photogrammetry from consumer-grade sUAS: implications for direct georeferencing of structure from motion photogrammetry. *Earth Surface Processes and Landforms*, **42**, 473-486.
- Cardini, A. (2014) Missing the third dimension in geometric morphometrics: how to assess if 2D images really are a good proxy for 3D structures? *Hystrix, the Italian Journal of Mammalogy*, **25**, 73-81.
- Collins, T.J. (2007) ImageJ for microscopy. *Imaging Frontiers*, **43**, S25-S30.
- Dai, F., Feng, Y. & Hough, R. (2014) Photogrammetric error sources and impacts on modeling and surveying in construction engineering applications. *Visualization in Engineering*, **2**, 2.
- Dawson, S.M., Bowman, M.H., Leunissen, E. & Sirguy, P. (2017) Inexpensive aerial photogrammetry for studies of whales and large marine animals. *Frontiers in Marine Science*, **4**, 366.
- Dawson, S.M., Chessum, C.J., Hunt, P.J. & Sooten, E. (1995) An inexpensive, stereophotographic technique to measure sperm whales from small boats. *Report of the International Whaling Commission*, **45**, 431-436.
- Deakos, M.H. (2010) Paired-laser photogrammetry as a simple and accurate system for measuring the body size of free-ranging manta rays *Manta alfredi*. *Aquatic Biology*, **10**, 1-10.
- Durban, J.W., Moore, M.J., Chiang, G., Hickmott, L.S., Bocconcelli, A., Howes, G., Bahamonde, P.A., Perryman, W.L. & LeRoi, D.J. (2016) Photogrammetry of blue whales with an unmanned hexacopter. *Marine Mammal Science*, **32**, 1510-1515.
- Elewa, A.M.T. (2010) Why morphometrics? *Morphometrics for nonmorphometricians* (ed. A.M.T. Elewa), pp. 3-7. Springer-Verlag, Heidelberg Dordrecht London New York.
- Franke-Gromberg, C., Schüler, G., Hermanussen, M. & Scheffler, C. (2010) Digital 2D-Photogrammetry and direct anthropometry - a comparing study on test accomplishment and measurement data. *Anthropologischer Anzeiger*, **68**, 11-20.
- Galbany, J., Stoinski, T.S., Abavandimwe, D., Breuer, T., Rutkowski, W., Batista, N.V., Ndagijimana, F. & McFarlin, S.C. (2016) Validation of two independent photogrammetric techniques for determining body measurements of gorillas. *American Journal of Primatology*, **78**, 418-431.

- Gale, R., Renouf, D. & Worthy, G.A.J. (1994) Use of bioelectrical impedance analysis to assess body composition of seals. *Marine Mammal Science*, **10**, 1-12.
- Gašparič, R., Hyžný, M., Jovanović, G., Čorić, S. & Vrabac, S. (2019) Middle Miocene decapod crustacean assemblage from the Tuzla Basin (Tušanj, Bosnia and Herzegovina), with a description of two new species and comparison with coeval faunas from Slovenia. *Palaeontologia Electronica*, **22.1.9A**, 1-21.
- Godding, R. (2007) Camera calibration. *Handbook of Machine Vision* (ed. A. Hornberg), pp. 333-360. John Wiley & Sons, Germany.
- Grochowsky, J.C., Alaways, L.W., Siskey, R., Most, E. & Kurtz, S.M. (2006) Digital photogrammetry for quantitative wear analysis of retrieved TKA components. **79B**, 263-267.
- Hartley, R. & Zisserman, A. (2004) *Multiple view geometry in computer vision*, 2 edn. Cambridge University Press, Cambridge.
- Hsiang, A.Y., Nelson, K., Elder, L.E., Sibert, E.C., Kahanamoku, S.S., Burke, J.E., Kelly, A., Liu, Y. & Hull, P.M. (2018) AutoMorph: Accelerating morphometrics with automated 2D and 3D image processing and shape extraction. *Methods in Ecology and Evolution*, **9**, 605-612.
- Ivosevic, B., Han, Y.-G. & Kwon, O. (2017) Calculating coniferous tree coverage using unmanned aerial vehicle photogrammetry. *Journal of Ecology and Environment*, **41**, 10.
- Jadejaroen, J., Hamada, Y., Kawamoto, Y. & Malaivijitnond, S. (2015) Use of photogrammetry as a means to assess hybrids of rhesus (*Macaca mulatta*) and long-tailed (*M. fascicularis*) macaques. *Primates*, **56**, 77-88.
- Jeffreys, G.L., Rowat, D., Marshall, H. & Brooks, K. (2013) The development of robust morphometric indices from accurate and precise measurements of free-swimming whale sharks using laser photogrammetry. *Journal of the Marine Biological Association of the United Kingdom*, **93**, 309-320.
- JEITA (2002) Exchangeable image file format for digital still cameras: Exif Version 2.2. Japan Electronics and Information Technology Industries Association, Japan.
- Kannala, J. & Brandt, S.S. (2006) A generic camera model and calibration method for conventional, wide-angle, and fish-eye lenses. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **28**, 1335-1340.
- Kim, W., Choi, B.-J., Hong, E.-K., Kim, S.-K. & Lee, D. (2003) A Taxonomy of dirty data. *Data Mining and Knowledge Discovery*, **7**, 81-99.
- Kraus, K. (2011) *Photogrammetry: geometry from images and laser scans. 2nd edition*. de Gruyter.

- Langlois, T.J., Harvey, E.S., Fitzpatrick, B., Meeuwig, J.J., Shedrawi, G. & Watson, D.L. (2010) Cost-efficient sampling of fish assemblages: comparison of baited video stations and diver video transects. *Aquatic Biology*, **9**, 155-168.
- Letessier, T.B., Juhel, J.-B., Vigliola, L. & Meeuwig, J.J. (2015) Low-cost small action cameras in stereo generates accurate underwater measurements of fish. *Journal of Experimental Marine Biology and Ecology*, **466**, 120-126.
- Leurs, G., O'Connell, C.P., Andreotti, S., Rutzen, M. & Vonk Noordegraaf, H. (2015) Risks and advantages of using surface laser photogrammetry on free-ranging marine organisms: a case study on white sharks *Carcharodon carcharias*. *Journal of Fish Biology*, **86**, 1713-1728.
- Luhmann, T., Robson, S., Kyle, S.A. & Harley, I.A. (2006) *Close range photogrammetry: Principles, techniques and applications*. Whittles Publishing, Caithness, Scotland.
- Manthey, R. & Kowerko, D. (2019) Hexagonal image generation by virtual multi-grid-camera. *Intelligent Human Systems Integration 2019* (eds W. Karwowski & T. Ahram), pp. 17-22. Springer International Publishing, Cham.
- Meise, K., Mueller, B., Zein, B. & Trillmich, F. (2014) Applicability of single-camera photogrammetry to determine body dimensions of pinnipeds: Galapagos sea lions as an example. *PLoS One*, **9**, e101197.
- Micheletti, N., Chandler, J.H. & Lane, S.N. (2015) Structure from motion (SFM) photogrammetry. *Geomorphological Techniques (online edition)* (eds L.E. Clarke & J.M. Nield), pp. 1-12. British Society for Geomorphology, London.
- Monkman, G.G., Hyder, K., Kaiser, M.J. & Vidal, F.P. (2019) Accurate estimation of fish length in single camera photogrammetry with a fiducial marker. *ICES Journal of Marine Science*.
- Muneza, A.B., Ortiz-Calo, W., Packer, C., Cusack, J.J., Jones, T., Palmer, M.S., Swanson, A., Kosmala, M., Dickman, A.J., Macdonald, D.W. & Montgomery, R.A. (2019) Quantifying the severity of giraffe skin disease via photogrammetry analysis of camera trap data. *Journal of Wildlife Diseases*, **Epub ahead of print**.
- Remondino, F., Spera, M.G., Nocerino, E., Menna, F. & Nex, F. (2014) State of the art in high density image matching. *The Photogrammetric Record*, **29**, 144-166.
- Reyment, R.A. (1996) An idiosyncratic history of early morphometrics. *Advances in Morphometrics* (eds Leslie F. Marcus, M. Corti, A. Loy, G.J.P. Naylor & D.E. Slice). Plenum Publishing Corporation, New York and London.

- Rhee, S.C. (2018) Differences between Caucasian and Asian attractive faces. **24**, 73-79.
- Rohlf, F.J. (1990) Morphometrics. *Annual Review of Ecology and Systematics*, **21**, 299-316.
- Rothman, J.M., Chapman, C.A., Twinomugisha, D., Wasserman, M.D., Lambert, J.E. & Goldberg, T.L. (2008) Measuring physical traits of primates remotely: the use of parallel lasers. *American Journal of Primatology*, **70**, 1191-1195.
- Rupnik, E., Daakir, M. & Pierrot Deseilligny, M. (2017) MicMac – a free, open-source solution for photogrammetry. *Open Geospatial Data, Software and Standards*, **2**, 14.
- Scherz, J.P. (1974) Errors in photogrammetry. *Photogrammetric Engineering*, **40**, 493-500.
- Schneider, C.A., Rasband, W.S. & Eliceiri, K.W. (2012) NIH Image to ImageJ: 25 years of image analysis. *Nature Methods*, **9**, 671-675.
- Shrader, A.M., Ferreira, S.M. & Aarde, R.J.v. (2006) Digital photogrammetry and laser rangefinder techniques to measure African elephants. *South African Journal of Wildlife Research*, **36**, 1-7.
- Tsai, R.Y. (1987) A versatile camera calibration technique for high-accuracy 3D machine vision metrology using off-the-shelf TV cameras and lenses. *IEEE Journal on Robotics and Automation*, **3**, 323-344.
- Wehkamp, M. & Fischer, P. (2014) A practical guide to the use of consumer-level digital still cameras for precise stereogrammetric in situ assessments in aquatic environments. *Underwater Technology*, **32**, 111-128.
- Weisgerber, J.N., Medill, S.A. & McLoughlin, P.D. (2015) Parallel-laser photogrammetry to estimate body size in free-ranging mammals. *Wildlife Society Bulletin*, **39**, 422-428.
- Wenhao, F. (2001) The specific character of limit errors in close range photogrammetry. *Geo-spatial Information Science*, **4**, 50-56.
- Whitehead, H. & Gordon, J.C.D. (1986) Methods of obtaining data for assessing and modeling sperm whale populations which do not depend on catches. *Reports of the International Whaling Commission*, 149-165.
- Whitehead, H. & Payne, R. (1981) New techniques for assessing populations of right whales without killing them. *Mammals in the Sea. Volume 3: general papers and large cetaceans* (ed. J. Gordon Clark), pp. 189-209. FAO, Rome.
- Willisch, C.S., Marreros, N. & Neuhaus, P. (2013) Long-distance photogrammetric trait estimation in free-ranging animals: A new approach. *Mammalian Biology*, **78**, 351-355.

Zhang, Z. (2000) A flexible new technique for camera calibration. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **22**, 1330-1334.

Zou, X., Möttöus, M., Tammeorg, P., Torres, C.L., Takala, T., Pisek, J., Mäkelä, P., Stoddard, F.L. & Pellikka, P. (2014) Photographic measurement of leaf angles in field crops. *Agricultural and Forest Meteorology*, **184**, 137-146.