Evaluating Linear Coral Growth Estimation Using Photogrammetry and Alternative Point Cloud Comparison Methods

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Abstract:
Corals are critical reef-building organisms, providing essential habitat and ecosystem services. Tracking coral growth over time indicates coral reef health, which can be measured using various established techniques. Several coral growth-related studies have successfully applied photogrammetry to a particular coral of various types. While the focus of previous work was on standardised data processing and, to a certain degree, on the assessment of different point cloud comparison methods (Lange et al. 2022), little attention has been given to the impact of camera calibration. This study measured the annual linear extension of five *Acropora* spp. colonies using photogrammetry and evaluated all stages of imagery processing. A high focus was given to the analysis of the camera calibration method and the validation of camera parameters derived using an in-situ calibration of coral images with scale bars placed in the camera's field of view. We demonstrate that this method is as reliable as the calibration using a calibration frame. This study also examined the impact of the different point cloud comparison methods for *Acropora* spp. More specifically, the derived point clouds are compared by applying the point-to-point and point-to-model methods and manually selecting 12 coral branch tips. Histograms derived from the comparison methods were analysed and deemed a suitable and efficient alternative approach for measuring the maximum growth rate of mature colonies over shorter time periods (1 year or less).

1. INTRODUCTION

Corals are important reef-building organisms, providing essential habitat and ecosystem services. Environmental changes influence coral reefs' health and function; hence, monitoring coral reef health is essential to understand potential impacts that may occur with a changing climate. Tracking coral growth over time (i.e., quantifying growth rate) indicates coral reef health, which can be measured using various established techniques. However, many traditional methods can be inaccurate, destructive, labour intensive, require specialised equipment or are limited to specific coral morphologies (Browne 2012; Browne et al. 2021).

The use of photogrammetry techniques to study corals has become increasingly popular as it presents a non-invasive approach that, due to advances in software, makes the production of 3D models relatively straightforward (Kikuzawa 2018; Lange & Perry, 2020). The ability to use commercial-grade cameras and processing software that are either free or low-cost has facilitated the production of cost-effective datasets (Agudo-Adriani et al., 2016; Aston et al., 2022). The resulting accuracies and precisions for photogrammetry productions have been researched specifically for, or adjacent to, growth studies, and all validate the process for reef and individual scales (Combs et al., 2021).

Since there are many considerations to the photogrammetry approach, efforts have been made to create a standardised workflow to allow better comparisons between independent studies (e.g. Aston et al., 2022). However, standardisation may impose limits on how studies are performed and constrict the deployment of more effective or appropriate steps. While the focus of previous work was on standardised data processing and, to a certain degree, on the assessment of different point cloud comparison methods (Lange et al. 2022), little attention has been given to the impact of camera calibration.

This study aimed to assess the impact of in-situ camera calibration and point cloud comparison methods on the accuracy of underwater photogrammetry in coral reef applications, with a case study of determining linear extension rates of a corymbose coral (*Acropora* spp.). Each step of the data processing was carefully evaluated to analyse measurement accuracy, and recommendations are made for improvements to the photogrammetric and comparison workflow.

This manuscript is structured as follows: In the next section, background and related work on the topic are presented, including a summary of traditional methods for assessing coral growth. This is followed by data collection and the methods used for this study. The results of calibrations, model productions, and differences in growth determinations are then presented. The paper closes with a conclusion.

2. BACKGROUND

Coral growth rates are commonly measured in terms of linear and/or radial extension (Kikuzawa et al., 2018; Lange & Perry, 2020). Acroporid corals generally have the highest rates of linear extension (Pratchett et al., 2015). These measurements can include basic dimensions, area, volume, and weight (Aston et al., 2022; Lange & Perry, 2020; Pratchett et al., 2015).

Dimensions can be observed by directly measuring the coral in the field. This can be further supported by capturing imagery,

including an object for scaling in the camera's field of view (Lange & Perry, 2020). Staining can also be effective in marking a baseline from which to determine the growth (Morgan and Kench, 2012). Some methods attempt to model a coral by wax casting physically (Aston et al., 2022; Million et al., 2021). Another traditional methodology is tagging; whereby measurements are taken from the tag to the growth extension (Anderson et al., 2012; Simpson, 1988). The tag method is simple in the field, but the tag constricts the coral causing reduced growth due to an interrupted flow from the main body to the branch tip (Lange & Perry, 2020; Pratchett et al., 2015).

The use of photogrammetry techniques for studying corals has become increasingly popular, as it presents a non-invasive and cost-effective approach (Agudo-Adriani et al., 2016; Browne et al., 2021; Ferrari et al., 2017; Ferrari et al., 2021; Lange & Perry, 2020; Palma et al., 2019; Veal et al., 2010). In addition, the images represent a permanent record, facilitating repeated or additional measurements, which is impossible using traditional field-based methodologies. The resultant accuracies and precisions have been reported in manuscripts on reef and individual scales (Combs et al., 2021; Figueria et al., 2015; Lange & Perry, 2020; Million et al., 2021; Palma et al., 2019).

3. DATA COLLECTION

The coral colonies captured in this study were located at two locations off Enderby Island in the Dampier Archipelago, Western Australia (Figure 1). A fast-growing coral (*Acropora* spp.) was chosen for this case study to ensure growth rates could be accurately measured over short time periods (i.e. months instead of years). A Canon G7X MkII camera (per Lange and Perry (2020)), was used for the data capture, with images captured in orbits around coral colonies.

Figure 1: Satellite map visualising the Dampier Archipelago, Western Australia (Google Maps). The arrow indicates sampling locations.

A total of five *Acropora* spp. coral colonies were monitored over three epochs: November 2020, March 2021, and November 2021. Only colonies one and two were captured at all three epochs, while the remaining coral colonies were only captured in epochs 1 and 2 (Table 1).

Colony	Epoch 1 (E1), Nov 2020	Epoch 2 (E2), Mar 2021	Epoch 3 (E3), Nov 2021
1	X	X	X
2	X	X	X
3	X	X	-
4	X	X	-
5	X	X	-

Table 1: Colonies and epochs of data capture.

Tag points (yellow cattle tags, Figure 2) were installed permanently around the coral as reference markers and kept in place for this case study's epoch. Although difficult to install, the bolts used to anchor the cattle tags permanently enable the alignment of processed images between epochs. These permanent anchor points allow for the alignment of point clouds across epochs using known reference points rather than natural features on the surrounding reef, which may change over time. Temporary scale bars were additionally placed in the camera’s field of view when capturing imagery (Figure 2).

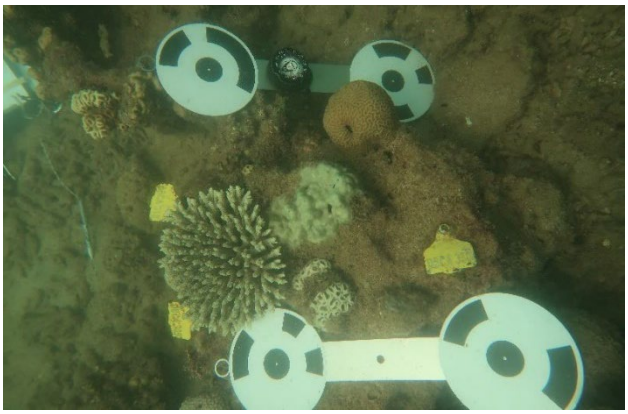

Figure 2: A coral colony and referenceable scale bars.

4. METHOD

The image processing was broken into three steps: camera calibration(s), image processing per colony dataset, and growth analysis. Camera calibration and image processing were performed using Bentley's ContextCatpure software. The growth analysis was conducted using CloudCompare.

The growth analysis focused on measuring maximum linear growth, given that corymbose corals primarily grow at branch tips (Lange and Perry 2020), allowing for comparison with other studies. Other common measures, such as radial extension rates or growth in the horizontal plane, are not suggested for corymbose corals (Lange and Perry 2020) and are therefore not discussed in this manuscript.

4.1 Camera Calibration

Images were processed using a typical photogrammetric workflow (Luhmann et al., 2014). Camera calibration parameters were calculated using two different methods: in-situ and using a calibration frame. Both methods solved for the same set of interior orientation parameters (IOP) of the cameras using the Brown camera model (Brown, 1971): focal length (principal distance, *c*), principal point offset (*xp, yp*), radial lens distortion parameters (*k1, k2, k3*) and decentring distortion parameters (*p1, p2*).

4.1.1 In-situ calibration. Camera calibration was performed based on the images captured of the corals. The scale bars placed next to the coral (Figure 2) were used to constrain the least squares adjustment. At least two (sometimes three) scale constraints were placed using the distance between the main circular targets. Additional points on the scale bar were observed, and the distance between these additional points was photogrammetrically derived, enabling an independent accuracy assessment. RMS values were then calculated using the true distance between those points.

4.1.2 Pre-calibration using a calibration frame. Every day before performing the data capture for the colonies, a calibration cube was photographed (as described by Helmholz et al., 2016). The cube has 53 ground control points in a known local coordinate system which were determined under laboratory conditions. The images were collected by placing the cube on the sea floor and capturing the images in orbits, allowing the camera to reliably be calibrated. Eight well-distributed points on the frame were used as ground control points (GCPs) which were manually observed in several images. The camera calibration was constrained using two methods:

- coordinate (using the coordinates of the 8 GCPs) and
- scale (using 4 distances derived from the 8 GCPs)

Another 8 well-distributed points were used as checkpoints (CPs) to perform an independent accuracy assessment of the camera calibration. The coordinates of the CPs and derived scales were used to calculate RMS values. Both calibration frame methods were compared to the in-situ calibration method.

4.2 Photogrammetric Image Processing per Colony Dataset

The production process per colony refers to the processing of the images of a colony in one epoch. It includes applying prior calculated camera calibration parameters if the in-situ calibration is not used, the orientation of the camera stations and adding scaling constraints. For each of the constructions, at least two scale bars were visible.

A dense point cloud is the most common photogrammetric production for coral growth analysis (Agudo-Adriani et al., 2016; Lange & Perry, 2020). Meshes are not recommended for this kind of study as they are sensitive to the presence of data gaps. Hence, a dense 3D reconstruction of the coral colonies was performed after the images were successfully processed.

4.3 Growth Analysis

The final step was to compare each colony's point clouds of different epochs. The permanently installed bolts were used to align the point clouds (Figure 2). Typically, a fine alignment using the Iterative Closes Point (ICP) method would be used. However, due to the nature of the coral with many local optima, the ICP decreased the accuracy of the alignment. Hence, alignment was only performed using the permanently installed reference points.

After the point clouds were aligned, point clouds of the same coral from different epochs were trimmed to remove non-colony data, such as the surrounding scenery. The aligned and trimmed point clouds were compared using a point-to-point comparison (P2P), and a point-to-model comparison using least squares matching of neighbourhood points to estimate a surface (P2M-LSLM). For the P2M-LSLM, the *k*- numbers of neighbours used were varied (k=6 and k=12). The earlier epoch was always used as a reference. An example of such a comparison is presented in Figure 3.

For each of these datasets, 12 spaced-out points at branch tip extremities of the *Acropora* colonies were chosen as the basis for the comparison (Figure 3). An initial top-down view was used to divide the approximately circular shape into eight perimeters, and four centrally located points. From there the view was manipulated to ensure the most suitable selection per tip was made. Points were selected in the same manner across all epochs. For these 12 points, the difference between the epochs was calculated using the results of P2P and P2M- LSLM comparison. As the models were scaled to mm, the difference is also observed in mm. The 12 distances are averaged for the further assessment.

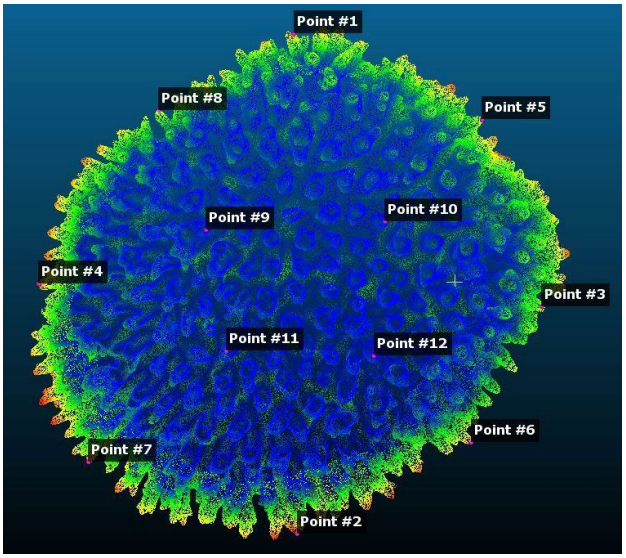

Figure 3: Epoch 1 (E1) and Epoch 2 (E2) comparison for colony 3 demonstrating the intended distribution of the twelve points on the colony.

From the P2M-LSLM comparison methods results, a histogram of the distances between the two epochs was used as an alternative means for measuring maximum linear extension. The histogram was used to calculate the distance within which 95% of the measurements were. Using the 95th percentile of the histogram as a measure of coral growth removes the requirement to manually select individual points at the end of the coral tips. For the rest of the paper, we refer to this method as P2M-LSLM 95%.

To summarise, the following comparison methods are used:

1. Distance of 12 manually selected points using P2P as input Referred to **P2P** for the rest of the paper.
2. Distance of 12 manually selected points using P2M-LSLM and k = 6 as input Referred to **P2M-LSLM *k* – 6** for the rest of the paper.
3. Distance of 12 manually selected points using P2M-LSLM and k = 12 as input Referred to **P2M-LSLM *k* – 12** for the rest of the paper.
4. 95th percentile of the histogram using P2M-LSLM and k = 12 as input Referred to **P2M-LSLM *95%*** for the rest of the paper.

5. EVALUATION

In this section, results of all the stages of the processing including camera calibration, photogrammetric image processing per colony dataset, and the growth analysis, are presented and discussed.

5.1 Camera Calibration

For this analysis, we focused only on colonies 1 and 2 as these are the only colonies captured during all epochs. The first step of any calibration in this paper was the alignment of the images used for the camera calibration. To assess if the alignment of the images was successful, an analysis of the reprojection errors was performed. The reprojection error is the distance between the extracted tie points observed and the reprojected point after the

camera calibration. The results of the reprojection errors for all calibrations and the number of used images for the calibration, are presented in Table 2. The average reprojection error for all colony **in-situ** datasets was 0.79 pixels. Although this error value is double that expected of in-air applications, this is considered acceptable for underwater applications (based on the authors' experience; (Lange & Perry, 2020). The average reprojection error for the **frame calibration** using the scale constraint was also 0.79 pixels. In contrast, the frame calibration using the coordinate constraint method, achieves an average reprojection error of 1.16 pixels. As the same tie points were used, the only possible reason for the different results is the constraint used during the calibration process.

Epoch	Colony	#images	In-situ calibration Reproj. Error (pixels)	Frame Const.	#images	Frame calibration Reproj. Error (pixels)
1	1	73	0.82	Scale	79	0.82
	2	70	0.8	Coord.	79	1.19
2	1	72	0.79	Scale	79	0.73
	2	59	0.79	Coord.	79	0.96
3	1	91	0.76	Scale	80	0.83
	2	81	0.79	Coord.	80	1.33
Average:			0.79	Average:		0.97

Table 2: Calibration Reprojection Errors for the in-situ calibrations (column 4) and the frame calibrations (last column).

It must be noted that the distribution of automatically extracted tie points for the calibration frame processed images (Figure 4, top) is visually not as good as the automatically extracted tie points for the colony-processed images (Figure 4, bottom). This may be because the frame was placed on a flat sandy area with fewer features than areas around coral colonies. In addition, coral colonies are not flat and offer depth in object space.

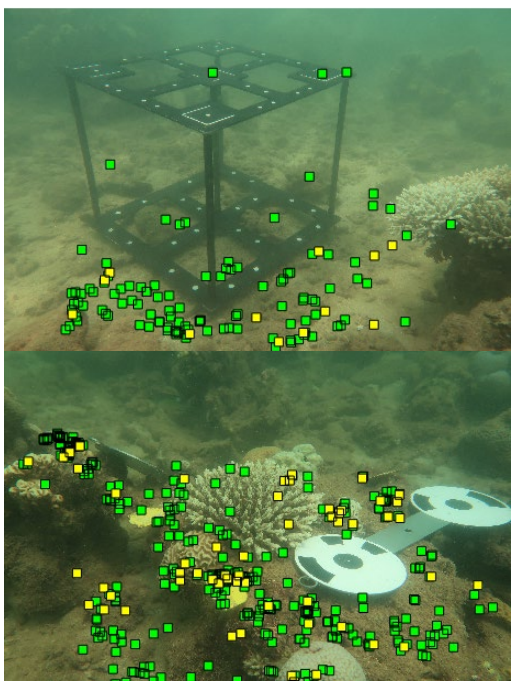

Figure 4: Distribution of automatically extracted tie points for images containing the calibration frame (top) and coral colony (bottom). Green tie points have a reprojection error smaller than 1 pixel, and yellow tie points have a reprojection error larger than 1 pixel.

The RMS values for the in-situ calibration as well as the checkpoint (CPs) and check scales RMS values of the frame calibration are presented in Table 3. The average of the RMS values using the in-situ calibration is less than 1 mm. In contrast, the RMS value for the frame method is over 150% of this value and larger than 1.5 mm. Possible reasons can be that the RMS values for the colony data were based on 2 to 3 check scales, whereas, for the calibration method, 4 check scales were used. More observations can lead to a larger standard deviation. However, this should mean that the RMS values based on checkpoints (calibration frame coordinates constraint) should be larger, too, which is not the case. A more detailed analysis is required; however, this was outside the scope of this study.

Epoch	Colony	In-situ calibration RMS [mm]	Frame Const.	Frame calibration RMS [mm]
1	1	1.05	Scale	2.33
	2	0.87	CPs	1.39
2	1	0.11	Scale	2.02
	2	1.30	CPs.	1.31
3	1	1.09	Scale	2.12
	2	1.34	CPs.	1.23
	Average:	0.96	Average	1.74

Table 3: Calibration RMS (independent assessment) for the in-situ calibrations (column 3) and the frame calibrations (last column).

Special focus was given to the radial lens distortion, as it is the distortion with the largest magnitude. For epoch 1 (E1) the radial distortion profiles for the colony data and frame data are shown in Figure 5. The distortion profile of the frame-processed images using the coordinates of the GCPs to constrain the adjustment is very different to all other radial lens distortion profiles. The distortion profile of the frame-processed images using the scale constraint is very similar to the profiles derived from the coral images. All other epochs show the same trend. Such a significant difference is not expected, and further investigations are required to ascertain the cause. Therefore, for the rest of the paper, we proceeded using only the scale constraint method.

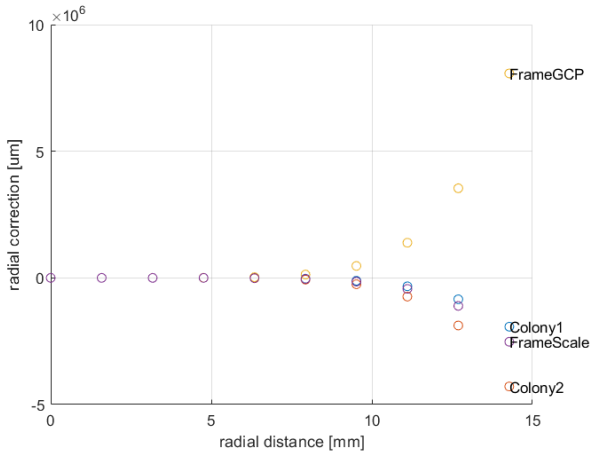

Figure 5: Radial lens distortion plots for epoch1 of the calibration based on the colony images and the frame images.

The final comparison is the comparison of the radial lens distortion profiles of different epochs. For this comparison, only the frame-processed images with the scale constraint are used. Even though the same camera was used for all epochs, the profiles are very different. The E1 profile is larger in magnitude compared to E2 and E3, and the profiles of E2 and E3 are very similar in magnitude. E1 was captured in November

(spring/summer), while E2 and E3 were captured in March (summer/autumn). Temperature loggers deployed during epochs 1, 2 and 3 recorded a mean daily temperature of 28.9, 29.0 and 31.2°C, respectively. Extreme variations in turbidity can also occur depending on the tidal cycle, wave action and season (Semeniuk et al, 1982). These differences could cause changes in the IOPs, as they depend on the medium and the condition in which the images are taken.

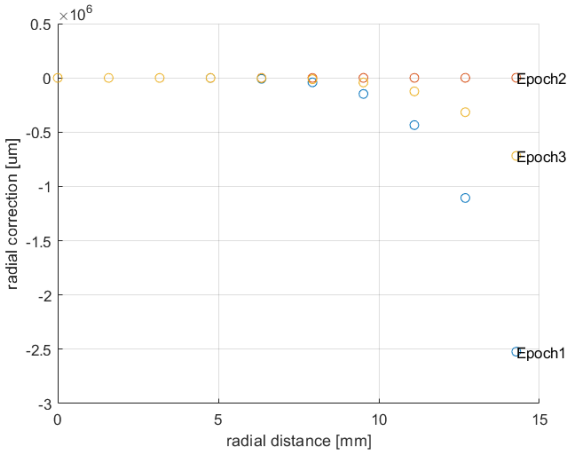

Figure 6: Radial lens distortion plots for epochs 1, 2 and 3 using the frame images with scale constraint.

To conclude, considering time, logistics of transportation, the mechanical stability of the portable calibration frame in daily field operations, and the overall performance of the in-situ calibration, the in-situ calibration should be the preferred method for field data collection. In-situ calibration also would ensure that the working distance and associated focusing for the calibration and coral capture are identical, including the covered field of view and compensate for different water characteristics, including temperature impact.

5.2 Photogrammetric Image Processing per Colony Dataset

Further quality assessment was performed on the point cloud data. The scale bars, which were placed in the field of view of the camera, were manually measured in the derived point cloud data. The differences between the true distance and the distance derived from the point cloud data are presented in Table 4. In E1, colony 5 has the largest difference with 2 mm. In E2, colony 4 has one high scalebar error. This high observation was made for a scale bar that is relatively far away from the coral (Figure 7) and should not impact the coral's analysis. The scale bar errors for colonies 1 and 2 in epoch 3 were deemed acceptable.

Global RMS	Epoch 1	Epoch 2	Epoch 3
Colony 1	0 mm 0 mm	0 mm 0 mm	0 mm 1 mm
Colony 2	0 mm 1 mm	0 mm 0 mm 4 mm	-1 mm 0 mm
Colony 3	0 mm	-1 mm 1 mm 0 mm	-
Colony 4	-1 mm 1 mm	1 mm 1 mm	-
Colony 5	0 mm 2 mm	0 mm 0 mm 1 mm	-

Table 4: Scale bar errors in the derived point cloud. If more than one value is listed, more scale bars were available for the test.

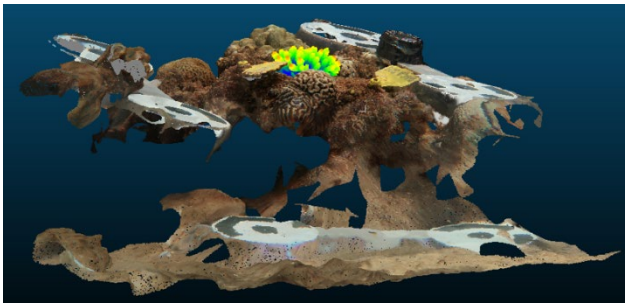

Figure 7: Point cloud of colony 2 in epoch 2.

5.3 Growth Analysis

The growth analysis was performed first estimating the growth between the epochs using the absolute values derived from the point clouds. This will be done for E1 compared to E2, E2 compared to E3 and E1 compared to E3. After this, the manuscript will report on the mm/year growth rate.

5.3.1 Epoch 1 (E1) to Epoch 2 (E2). Lange and Perry (2020) note that the growth rate variance is an aspect to be considered when analysing the growth rate of corals. The average growth rate calculated for all colonies between E1 and E2 using 12 distributed measurements of the P2P comparison and their derived standard deviations are presented in Table 5. Please note, that colony 1 was split into two sub-colonies (1a and 1b). The standard deviation is around 10% of the growth and is smaller than the reported standard deviations by (Lange and Perry, 2020). Similar results were achieved for the other epoch comparisons.

[mm]	Average growth E1 – E2	Stand. Deviation
Colony 1a	19.6	1.8
Colony 1b	21.7	2.0
Colony 2	21.3	1.6
Colony 3	18.5	2.3
Colony 4	14.5	2.6
Colony 5	17.8	2.2

Table 5: Average growth rate based on 12 disturbed measurements and their standard deviations for all corals between E1 and E2 using the P2P method.

E1 and E2 are 114 days apart. Estimates of coral growth between E1 and E2 for the five colonies, using the different comparison methods, are shown in Table 6 and ranged between 13 and 22 mm (which is equivalent to 42 to 70 mm/year). This is within the range expected for this genus (Pratchett et al. 2015). However, these growth rates are likely somewhat inflated given corals tend to grow faster over the summer months (Simpson 1988). The growth estimates were very similar for the P2P and all P2M LSLM methods. All growth distances between methods were within a millimetre (Table 6). Small differences are likely due to the different point spacing. Using a higher point spacing is likely to lead to even smaller differences between the methods. As the differences between the methods are a maximum of 1 mm, any of the methods could be used for further processing. We decided to select the P2P-LSLM k=12 method to assess the histogram approach results. This is the method that will be used for further analysis.

E1-E2 [mm]	P2P	P2M-LSLM k=6	P2M-LSLM k=12	P2M-LSLM 95%
Colony 1a	19	18	19	21
Colony 1b	21	20	20	22
Colony 2	22	21	22	21
Colony 3	18	17	17	17
Colony 4	14	13	13	14
Colony 5	18	17	17	15

Table 6: Coral growth between E1 and E2. Comparison of the P2P, P2Ms and the P2M LSLM 95% approach.

5.3.2 Epoch 2 (E2) to Epoch 3 (E3): E2 and E3 are 351 days apart, hence much more growth is expected than between E1 and E2. For E3, only two colonies were available (colonies 1 and 2). As previously mentioned, colony 1 has two sub-colonies (1a and 1b). Table 7 represents the growth estimates between E2 and E3. The results between the P2M-LSLM *k*=12 and the P2M-LSLM 95% for colony 1 are within 15 mm (equivalent to 16 mm/per year) which is between 17 and 20%. This contrasts with colony 2 where the difference between the methods is only 5mm (equivalent to 5 mm/per year, below 10%). As for E1-E2, these growth rates are within the range expected for this genus, however, are likely more accurate reflections of actual yearly growth given the growth period spans a full year (i.e. full range of seasonal temperature conditions).

E2-E3 [mm]	P2M-LSLM k=12	P2M-LSLM 95%	Diff.	Diff. (%)
Colony 1a	55	69	14	20
Colony 1b	58	69	12	17
Colony 2	49	54	5	9

Table 7: Coral growth between E2 and E3 for the two colonies Comparison of P2M-LSLM (k =12) and P2M LSLM 95%.

5.3.3 Epoch 1 (E1) to Epoch 3 (E3): E1 to E3 were captured 465 days apart. The differences between the corals using the P2M LSLM (k=12) and the P2M LSLM 95% method are shown in Table 8. The histogram-derived measure overestimates the growth for all colonies. The higher differences are all experienced by the dual colony 1. This leaves colony 2 with an 8 mm or 10% difference.

E1-E3 [mm]	P2M-LSLM k=12 [mm]	P2M-LSLM 95% [mm]	Diff. [mm]	Diff. [%]
Colony 1a	75	92	17	19
Colony 1b	79	92	13	14
Colony 2	71	79	8	10

Table 8: Coral growth between E1 and E3 for the two colonies Comparison of P2M-LSLM (k =12), and P2M LSLM 95%.

5.3.4 Overall growth analysis: Figure 8 shows colonies 1 (left) and 2 (right) at all three epochs (E1, E2, E3 – top to bottom). The growth between E1 and E2 was not as high as that of E3 compared to E2. For instance, the main colony in colony 1 at the E3 developed an additional growth (bottom left component of Figure 8) compared to previous epochs. This growth impacts the P2M LSLM 95% approach as it considers the whole colony and not only 12 selected branches. Hence, while the 12-point branch tip selection of the P2P and P2M remains relatively consistent, the P2M LSLM 95% approach overestimates the linear growth in this case. Colony 2 growth from E2 to E3 is not as strong as that of colony 1. Hence, the P2M LSLM 95% approach result is closer to the results of the 12-point branch tip selection.

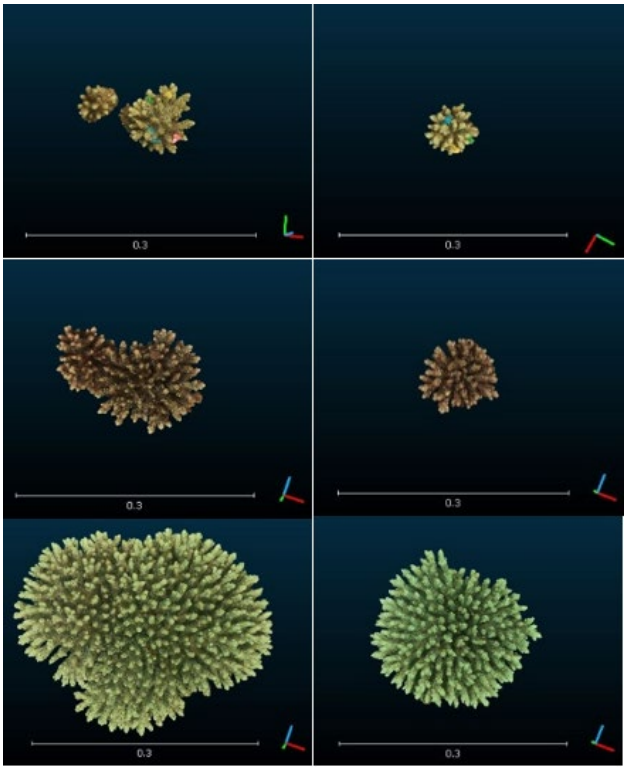

Figure 8: Colony 1 (left) and colony 2 (right) for E1 (top), E2 (middle) and E3 (bottom). The white scale bar on the bottom of the figure indicates a dimension of 0.3m. All figures are presented in the same scale.

The average coral growth (per year) for a juvenile colony (based on E1-E2) and a non-juvenile colony (based on E2-E3) using the P2M-LSLM k=12 is shown in Table 9. It is easily visible that juvenile colonies growth faster than non-juvenile colonies.

Colony	juvenile growth (< 1 year) [mm/year]	Non-juvenile growth (>1 year) [mm/year]	Diff. [mm/ year]
1a	60.8	57.2	3.6
1b	64.0	60.3	3.7
2	70.4	51.0	19.5
3	54.4	-	-
4	41.6	-	-
5	54.4	-	-
Mean	57.6	56.2	8.9

Table 9. Average coral growth between E1-E2 and E2-E3.

6. CONCLUSION

This study aimed at quantifying the application of photogrammetry to coral growth. It carried out an accurate assessment of the stages used to derive coral growth.

Firstly, we focused on the camera calibration and investigated if in-situ calibration using the images captured of the coral, including scale bars, was performed, as well as calibration using a custom-made frame. It can be concluded that the in-situ calibration can achieve comparable results, and indeed outperforms calibration using the frame. The coral provides better surroundings for automatically extracted tie points. The

distribution of tie points in the images of the coral colonies is better (more equally distributed, lower reprojection errors, more depth variation in object space) than in the images of the frame. There are also many practical reasons to opt for in-situ calibration, including time to capture additional images of a frame, logistics of transportation of a large and bulky frame, and stability of the calibration frame during freight and daily field operations. In-situ calibration also ensures that the working distance and associated focusing of the camera and the coral are correct and that the selected field of view is appropriate for the coral capture. Finally, in-situ calibration ensures that all systematic refractive effects are the same for the coral capture and calibration. This is important as our tests could prove that seasonal effects caused by the water temperature are reflected in the radial lens distortion profiles.

After the successful calibration and image processing of the images of the coral colonies, a 3D point cloud was derived for all coral colonies and epochs. The derived 3D point clouds were also accurately assessed by extracting the dimensions of scale bars in the point cloud. The differences were not larger than 1 mm for 24 out of 26 comparisons. Based on those results, we were confident that input to the coral growth analysis was accurate.

Four types of point cloud comparison methods (P2P, P2M LSLM k= 6, P2M LSLM k= 12 and P2M LSLM 95%) were used to assess coral growth. Five colonies of corymbose *Acropora* spp. of various sizes were evaluated. The novel P2M LSLM 95% approach of using a statistical histogram at the 95% level shows a high level of precision and is time-saving for measuring coral growth. It should be noted. However, the initial coral size has a significant influence on the growth rate, whereby smaller colonies tend to grow faster (Cresswell et al., 2020; Madin et al., 2020). Therefore, the P2M LSLM 95% approach is less suitable for linear growth analysis if tracking a coral from juvenile size or over a more extended period (i.e. > 1 year) due to the nature of the coral analysed (heavy branching and growth). If there is a long time between coral survey epochs, the P2M LSLM 95% approach may be used to estimate volume radial growth rather than linear growth.

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