Research Article

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The accuracy of 3D structure-from-motion models for assessing underwater coral health

Abstract

A fundamental problem with using human observations in marine ecology is that it is often fallible. This study monitored coral to compare the accuracy of traditional visual surveying and 3D structure-from-motion models in assessing coral health. In a pilot study, objects of known dimensions were rendered underwater to assess the accuracy of the 3D models; between the X-Y and Z dimensions accuracies of 93 ±0.09% (mean ±SD) and 93 ±0.04% were observed, respectively. Following this, two surveyors monitored three individual coral colonies over five months at La Mer (Dubai) for the following visual parameters; live, dead and bleached coral. Significant differences were detected amongst surveyors for these parameters only when traditional surveying was implemented. However, 3D modelling had a significant post-processing time. Nonetheless, results suggest that 3D modelling is a more accurate and consistent tool between surveyors over time for monitoring coral colonies. The potential for such technology to be up-scaled to capture complete 3D-coral reefs could allow researchers to more accurately explore long-term changes to these significant ecosystems.

Keywords: photogrammetry, long-term, observation, technology, 3D-software, relocation

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Introduction

Coral reefs around the globe have been undergoing severe and rapid decline due to human-induced climate change.[1,2] Consequently, this exacerbates over-exploitation of key marine species and other anthropogenic stressors, which are driving coral reefs to functional collapse.[3] Mega-reclamation projects, such as the three Palm Islands, has put Dubai into the spotlight of tourism.[4] However, such activities result in direct removal and/or burial of marine habitats, such as coral reefs, with a poor understanding of the temporal and ecological implications.[5,6]

These activities have visible symptoms on coral reefs, which are commonly used in traditional coral surveys to assess coral health. Many studies suggest a strong correlation between live and dead coral in hermatypic coral reefs, which influence fish abundance[7–9] and its ecological functionality.[10] Hence, changes of visual percentage cover over time and between surveyors and survey types is a critical parameter. Furthermore, in the last few decades, bleaching has become more prominent due to increasing sea temperatures and climate change.[3] Hence there is an equally vital potential in studies that assess the ecology and health of the coral reef.[11]

Similarly, visual parameters are commonly used for assessing relocated coral health; one of the most common mitigation measures during marine dredging or reclamation activities.[12–14] Although there are a plethora of traditional snorkelling or diving coral monitoring surveys that record health of corals,[15,16] one common limiting factor is measurement accuracy amongst surveyors over prolonged period of time.[17] Even though it is standard practice to quantify measurement errors for parameters such as surface area or rugosity, the majority of long-term studies to date fail to calculate error margins over time and amongst surveyors.[17] Consequently, there is a significant need to compare more technologically advanced methods with traditional coral surveying methods, in order to gain a better insight into their trade-offs.[18]

Previous cost-prohibitive methods, including photogrammetry using Structure from Motion (SfM), are now becoming accessible[19] and have recently started gathering momentum in the coral reef monitoring field.[20,21] SfM is an image processing technique that matches features in successive overlapping images to construct accurate and manipulable virtual 3D models.[22] SfM is not a novel approach; other studies have already used it for coral reef monitoring.[17,23] Raoult et al.,[17] study have looked at the accuracy of surface area and volume data over time on coral bommies. Their study did not find any significant difference volume and surface area for 3D models captured by different surveyors over 12 days. Whilst, a study by Young et al.,[23] compared the *in situ* measurements and underwater 3D models for rugosity found the a strong match between the two, further reinforcing that 3D modelling results are transferable with traditional survey methodologies.

This study determines whether ecological parameters such as live, dead and bleached coral cover in individual coral colonies is more accurate compared with data collected by traditional visual methods or 3D coral modelling over time. Prior to the main study, we included a pilot study to evaluate the accuracy of surface area and dimensions of submerged objects of known dimensions when translated into a 3D render. Hence, establishing potential errors when rendering objects of unknown dimensions such as coral colonies.

Methods

Study site

The La Mer beachfront development is located at the Jumeirah Open Beach in the Jumeirah 1 area of Dubai (United Arab Emirates). The development consists of a partially enclosed bay with two reclaimed peninsulas at the northern and southern extents of the Project site. The central headland that separates the two beaches has an older protruding breakwater on its west with a relatively dense coral community, dominated by the coral genus *Platygyra* spp. Dense low biodiversity of coral reefs on breakwaters are well documented in Dubai.[24]

The developer (Meraas) granted access to site prior to conducting fieldwork. Two PADI-qualified divers haphazardly selected three individual *Platygyra* spp coral colonies to monitor over a period of five months. These three colonies were tagged as small (40 cm), medium (55 cm) and large (100 cm) and were all located at similar depths

(3.8 ± 0.7 m), about 75 m off public beach on west seaward facing breakwaters of the La Mer development (latitude: 25.2285, longitude: 55.2555). The same two surveyors recorded visual observations on these corals on three occasions (22nd March, 02nd May and 01st July 2019).

The GPS locations of these tagged corals were marked using a hand-held GPS in a waterproof casing at the surface. However, surveyors took note of permanent land structures to better aid locating the survey site (Figure 1). Surveys were conducted during calm sea state conditions; -2 or below on the Beaufort scale.[25]

Figure 1 Location coral on the breakwater western bay of La Mer (UAE).

Pilot study

A pilot study was conducted to ensure that the 3D models were proportionally accurate to real life objects prior to modelling corals. This was to measure the relative accuracy of 3D models against known objects and dimensions. GoPro™ Hero 6 cameras used the same setting as the study site survey (discussed later) on two objects: a dive fin and a 1L jar. Three rounds of photos were taken, each yielding 50 -100 images. Mesh lab was used to analyse the 3D models using two metrics: point-to-point distances and surface area.

Traditional coral survey

The visual coral monitoring aspect of the survey covered the following ecological parameters: live, dead and bleached coral cover. Each of these parameters was selected to determine and understand trends of coral health. Dive surveyors visually estimated the percentage cover of the parameters discussed above using the categories for percent coral cover from English et al.[26] For consistency, the surveyors were trained to estimate percentage of objects on land prior to the surveys.

3D coral modelling survey

Each surveyor had one GoPro™ Hero 6 camera. These were set to capture images (12 MP JPEG) continuously at one-second intervals within the standard flat port GoPro™ underwater housing casing. Camera settings were kept at default, excluding field of view –narrow (to reduce distortion caused by the fish eye lens) and sharpness medium (to reduce the prominence of coral). Due to the shallowness of the site, ambient light provided sufficient illumination. A PVC pipe was marked out with white electrical tape at 10 cm intervals and laid down next to each coral as a reference object for the scaling of the 3D model.

Dive surveyors took photos of the desired coral, starting from the bottom and moving upwards in a circular pine-like motion, adapted from House et al.[27] This was done for 2.5 minutes, producing 150 photos per coral, whilst keeping camera orientation and distance consistent. Water visibility of approximately 1.0 m was required to take clear photos so the distance between the corals and the camera was kept at approximately 1.0 m, allowing for successful rendering of the 3D model. The aim was to obtain between 60 –80% overlap between images, facilitating better image alignment and processing to avoid issues with reconstruction of the 3D model.[27,28]

3D Model generation

Construction of the 3D models was generated using Context Capture Desktop edition Update 9 –v.4.9.516. This is the first instance of the Context Capture program being used for an *in situ* coral study.

All models were rendered in Context Capture following standard protocol procedure, as outlined in the Context Capture user manual.[28] Photos were imported into the Context Capture program for aero triangulation. The relative scales of each 3D model were defined by two tie points, which were manually selected on two or more photos, using the PVC pipe as a scaling point for reference. Therefore, all automatically generated tie points during aero triangulation followed the manually inputted scale constraint. This provides the program with better ground truthing ability for the rendered model.

Once aero triangulation was completed, a draft 3D view of the model was used to verify its orientation relative to 3D space, after which the 3D model was rendered. Final 3D models were rendered as a wavefront format (OBJ) file, which was exported to Meshlab (v2016.12) and transformed into a Polygon File Format (PLY) file for further analysis.

Correction of 3D models

Of the 18 rendered coral models, 6 required further correction. The two issues that were observed on these models were flaking of sections and/or missing sections of critical areas. Flaking areas were corrected by the addition of manually selected tie points, prior to aero triangulation. Flaking was a result of poor overlapping photos or darker sections of the coral not being detected automatically by the SfM algorithm. Missing sections were a result of insufficient overlapping photos due to blurry images. This was resolved by using the Close Holes function on Mesh labs. It is important to highlight that the closed section did not have the same surface detail as the surrounding coral (Figure 2).

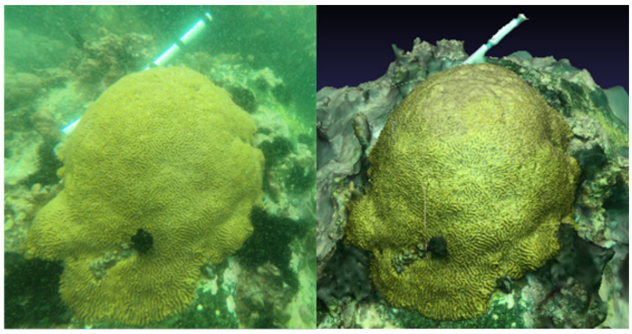

Figure 2 Left: Medium *Platygyra* spp coral. Right: Final 3D renders using Context Capture. Black tape was used to mark 10 cm intervals on the PVC to calibrate scale on the 3D-coral model.

Pilot study: point–to-point distances

The pilot study looked at two man-made objects (a dive fin and a 1L jar) which were photographed 50 - 100 times, on three separate occasions (Figure 3). These were used to produce three 3D models which were compared to the objects of known dimensions (ground truths). The objects stood out relatively well against the reef backdrop, including objects of mute colour, an observation which differed from

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the observations in Young et al.[23] The known dimensions of the objects ranged from 4.0 –87.5 cm in the X-Y plane and 10.0 –14.5 cm in the Z plane. Accuracy was measured using the following formula[23]

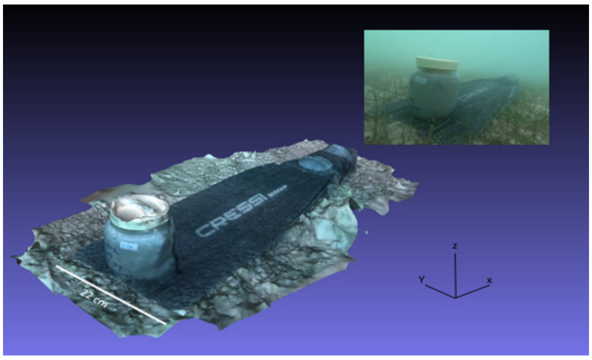

Figure 3 Left: Objects with known dimensions were rendered underwater three times. Inset is an image of the underwater scene. The two objects were: (1) Cressi 2000 free dive fin and (2) a 1L jar.

$$\text{Accuracy} = -1\frac{(\text{Underwater 3D Model} - \text{Grouth Truth})}{\text{Ground Truth}}\%$$

This metric was used to measure distance between the known 10 cm intervals on the PVC pipe to ensure the model scale was not changed during the file transferred into Mesh labs. The pilot study dataset was found to violate the parametric assumption after conducting the Levene's test for normality. Therefore, the Wilcoxon matched pairs test was used, followed by the Root Mean Square Errors. All statistical analyses were conducted in SPSS (Version 23.0.0.2).

Actual study: surface area

The aforementioned methodology was also used to measure accuracy in the actual study. Quantification of ecological parameters (i.e. live coral cover) on the traditional coral survey method were measured as a percentage. These parameters were manually highlighted on Mesh lab and therefore needed to be converted from surface area (mm^2) into a percentage value for comparison with the traditional survey results. The formula below was used:

$$\frac{\text{Surface area of live coral}}{\text{Total surface area of coral}} = \%\,\text{Live coral}$$

Surface area on the actual survey were analysed using either an Independent *t*-test or a Mann-Whitney *U* test if Levene's test for normality showed that assumptions for the former were violated. These statistical analyses were conducted using SPSS (Version 23.0.0.2).

Additionally, a logistic regression model using the Firth method was run on the data using R studio (Version 1.1.463). The sparse dataset collected from the actual study resulted in quasi-complete separation data, which caused errors as a result of strongly biased parameter estimates diverging to ±∞ in logistic regression.[29] Therefore, a stepwise method[30] was used to build two-predictor logistic regression model with the Firth method[31] using the R package, *logistf*. This used a penalised likelihood method to correct bias in a small data set.[31,32]

Results

Pilot study: point–to-point distances

We found no significant differences between the median of the 3D model and the known underwater objects for the X–Y (n =9, R^2 =0.98; p =0.214; Wilcoxon matched pairs test test) and Z planes (n =6, R^2 =0.94; p =0.01; Wilcoxon matched pairs test), The root mean square errors (RMSE) of the models were 1.54 cm in X-Y and 1.04 cm in Z. There was a high degree of accuracy of the X-Y and Z dimensions, at 93 ±0.09% (mean ±SD) and 93 ±0.04% respectively.

Pilot study: surface area

The models' surface area lined up well with their true surface area (n =6, R^2 =0.99; p =0.249; Wilcoxon matched pairs test). Regression plots of surface area suggest slight underestimation of the models' surface area (Figure 4). The RMSE of the models was 1156 cm^2 for surface area which is relatively low, hence providing a more accurate model to predict surface area from.

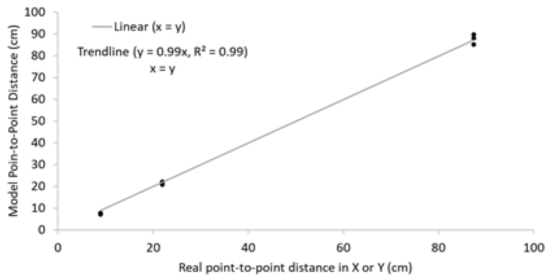

Figure 4(A) Accuracy of 3D model for point-to-point distances on the X or Y dimension.

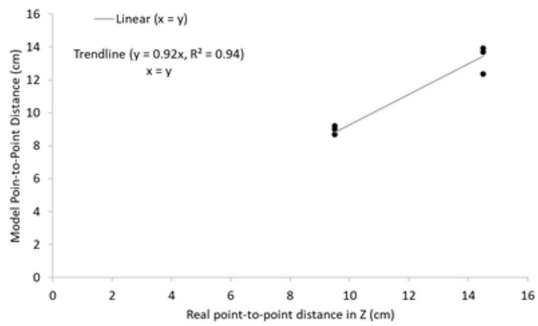

Figure 4(B) Accuracy of 3D model for point-to-point distances on the Z dimension.

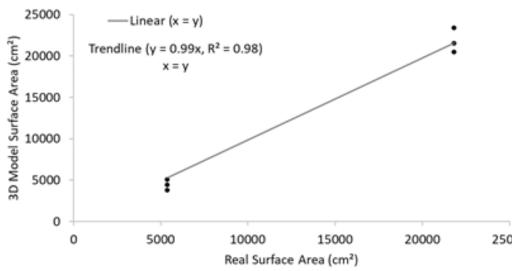

Figure 4(C) Accuracy of 3D model for surface area.

Differences between surveyors and survey methods (Over time)

The traditional survey was associated with a significantly larger live coral cover for the small coral colony (*t* =6.80, *p* =0.001, independent samples) and large coral colony (*U* <0.001, *p* =0.002, Mann-Whitney

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U test), while the inverse was found for the 3D survey on dead coral cover for the small coral colony (t =-6.47, p = 0.001, independent samples) and large coral colony (U =0.00, p =0.003, Mann-Whitney *U* test), as illustrated on Figure 5.

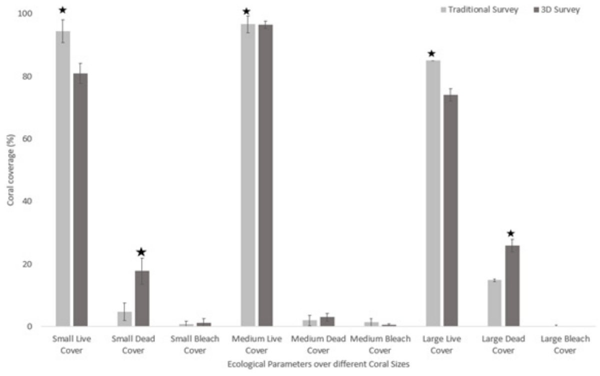

Figure 5(A) Differences between traditional and underwater 3D surveys of individual corals, in terms of average ecological parameters with standard deviation error bars (* - indicating a significant difference at the 5% level).

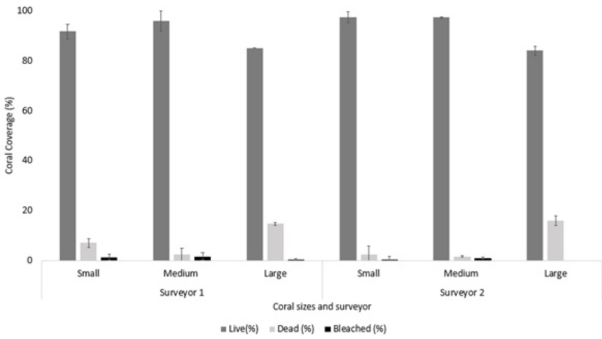

Figure 5(B) Average difference between surveyors for different ecological parameters over the three survey events.

Bleached coral cover

Bleached coral cover was observed to drop over time for the small and medium coral colony, whilst bleaching was not observed on the large coral colony. However, differences in bleached coral cover between the two surveyors and survey types were low. As such, the observed trend did not yield any significant differences or interactions over time from the logistic model, suggesting that minor deviances over time or coral colony remain accurate between surveyors and survey type.

Live coral cover

Generally, higher estimated values were recorded for live coral cover on the traditional method when compared to 3D model results. Results between surveyors remained relatively consistent over time and within the same survey type. However, there was a significant difference (p <0.001) between survey types (Table 2). Interestingly, an interaction between survey types over time was detected for March (p <0.001) and May (p <0.001). Greenland et al.,[33] suggests that penalised predictions (including the Firth method) on regression models may delete important cofounders when analysing causal effects and may therefore add another source of bias. Consequently, a post hoc analysis was not conducted to differentiate the interaction between survey type and time as the results may not be robust for either live or dead coral cover.

Dead coral cover

Higher values were recorded for dead coral cover with the 3D modelling method compared to traditional survey results, which is to be expected as live coral cover was the inverse of this observation. Significant differences between survey types were found (p <0.001) with a similar explanation to the ones discussed in the live coral cover section above. However, a significant difference between surveyors (p <0.001) was only observed for dead, but not live, coral cover (Table 2).

Table 1 Summary of all differences between traditional and underwater 3D surveys between individual corals in terms of ecological parameters

Coral size	Ecological parameter	Levene's Test	Statistical analysis
Small	Live◆◆	$F(6) = 0.69$, $p = 0.685$	Independent t test, $t(6) = 6.80$, $p = <0.001$
	Dead◆◆	$F(6) = 0.31$, $p = 0.308$	Independent t test, $t(6) = -6.47$, $p = <0.001$
	Bleach	$F(6) = 0.81$, $p = 0.390$	Independent t test, $t(6) = -0.73$, $p = 0.483$
Medium	Live	$F(6) = 1.14$, $p = 0.311$	Independent t test, $t(6) = 0.88$, $p = 0.399$
	Dead	$F(6) < 0.001$, $p = 0.951$	Independent t test, $t(6) = -1.16$, $p = 0.273$
	Bleach◆	F 6) = 7.6, p =0 .020	Mann-Whitney U test, $U(6) = 10.00$, $p = 0.191$
Large	Live◆/◆◆	$F(6) = 83.21$, $p = <0.001$	Mann-Whitney U test, $U(6) < 0.001$, $p = 0.002$
	Dead◆/◆◆	$F(6) = 44.33$, $p = <0.001$	Mann-Whitney U test, $U(6) < 0.001$,$p = 0.003$
	Bleach◆	$F(6) = 6.25$, $p = 0.031$	Mann-Whitney U test, $U(6) = 15.00$, $p = .317$

◆- Parameters that violate the Levene test for homogeneity of variance; therefore, a Mann-Whitney U Test was conducted, which demonstrated a significant difference between the two survey types.

◆◆ - Parameters that demonstrated a significant difference between the two survey types.

Table 2 Logistic regression (with Firth Method) output of the main effects and interactions for the dependent variable dead coral cover against the independent variables; surveyor, survey type and time

Dead variable against the independent variable	Logistic regression (Firth method)				
	SE Coefficient	**Lower-95**	**Upper-95**	**Chi square**	***P* value**
Main effects: Surveyor	1.64	-7.89	2.98	10.55	<0.001
Main effects: Survey type	1.82	-10.78	1.11	67.40	<0.001
Interaction: Survey type:Time (March)	3.62	-5.98	10.26	31.58	<0.001
Interaction: Survey type:Time (May)	3.70	-6.38	9.87	24.02	<0.001

Discussion

This study demonstrates that ContextCapture[28] was a viable program to be utilised for *in-situ* 3D coral modelling with accurate results for underwater objects of known dimensions. Furthermore, there was a significant different found between traditional and 3D coral modelling over time, as well as between surveyors.

Pilot study

The point to point distance results were similar to the (RMSE) in this study were 1.54 cm in X-Y and 1.04 cm in Z, similar to the finds reported by Young et al.,[23] at 1.48 cm in X-Y and 1.35 cm in Z. Regression plots on Young et al.,[23] indicate that models in their study underestimated both X-Y and Z dimensions, while this study only found extremely marginal underestimations (Figure 4). This, however, could be due to a lower sampling number used on this study for X-Y and Z dimensions, compared to Young et al.,[23] which were n =48 and n =25 respectively. On the other hand, there was a high degree of accuracy of the X-Y and Z dimensions, at 93 ±0.09% (mean ±SD) and 93 ±0.04% respectively. Results from this study were more accurate when compared to results from Young et al.[23] The likely cause for this is their cameras were not calibrated and did not manually identify ground control objects. However, it is important to highlight that the rendering software used in this study was different to to that Young et al.,[23] which used Agisoft PhotoScan, which may have introduced other unknown program variables.[34]

Results from this study demonstrate that the 3D model surface areas were similar to their true surface area (Figure 4). This is further reinforced by the accuracy of the surface area (90% ±0.1%). Similarly, surface area was also found to be more accurate when compared to another study looking at the same metric for underwater models.[35] They used underwater 3D coral modelling and surface area accuracy ranged from 2% -18% depending on the morphology of the coral with the surface area of massive coral morphology type (to which the *Platygyra* spp. used in our study belong) overestimated by 17.4% (±6·3%).[35]

This pilot study looked at smooth and structurally non-complex objects, which are expected to render better as they stand out more from the seabed. Overall, results from the pilot study indicate that underwater 3D models can be treated with a high degree of confidence.

Differences between surveyors and survey methods (Over time)

Bleached coral cover

A recent long-term study suggests elevated sea temperatures increases bleaching in shallow water coral.[11] Interestingly, the monitor period for this research started in winter (March) to early summer (July), with the bleaching trend corresponding inversely to the Brown et al.,[11] study and following a similar trend described in LaJeunesse et al.,[36] Cold-water temperatures causing bleaching are less well known but have been documented.[36] Whilst, the observed trend did not yield any significant differences or interactions over time from the logistic model, suggesting that minor deviances over time or coral colony remain accurate between surveyors and survey type, bleached coral cover was observed to drop over time for the small and medium coral colony reinforcing the findings from LaJeunesse et al.,[36] Bleaching was not observed on the large coral colony.

Live coral cover

Vogt et al.,[37] found that overestimation of live coral cover has been recorded on other studies and those findings are supported by this study. The angle at which the observer is viewing the coral, coral overhangs and fragmented growth of the coral can lead to overestimation.

The small coral surveyed was located on a vertical reef wall, hence introducing overhangs and had fragmented growth. The large coral was nested in the reef, hence obstructing visual survey and, as a result, these conditions may have led to an overestimation of live coral cover. On the other hand, the medium and large corals were on flat ground, so the easiest to survey with the least discrepancy between surveyor and survey type. Additionally, a study by Leujak et al.,[38] that compared six coral community survey methods, although, 3D modelling was not one of these, found that *ex -situ* video analysis was the most accurate compared to the other five *in-situ* survey methods. Thus reinforcing the results found on this survey that *ex-situ* survey techniques (3D coral modelling) are more accurate and consistent compared to *in situ* survey techniques.

Significant interactions were observed over time between surveyors and survey types (Table 1). This suggests that even in a relatively short-term monitoring study (5 months), using different surveyors over time can yield significantly different results. Interestingly, an interaction between survey types over time was detected for March and May. However, the interpretation of this interaction may not solely be caused by discrepancies of data recorded between survey types over time but a factor of coral growth over time. *Platygyra* spp tend to have a temperature dependent growth rate, ranging from 5.4 to 9.7 mm per year.[39] Therefore, growth may have been significant with increasing water temperatures in the time period.

Dead coral cover

Higher values were recorded for dead coral cover with the 3D modelling method compared to traditional survey results, which is to be expected as live coral cover was the inverse of this observation.

Significant differences between survey type were found with a similar explanation to the ones discussed on the live coral cover section. However, a significant difference between surveyors was only observed for dead, but not lives, coral cover (Table 2). Clanahan[40] suggests death of massive taxa coral such as *Platygyra* spp. tends to be poorly detected by visual surveys with the highest mortality in high water temperatures, possibly explaining the significant difference. Whilst, live coral cover is likely to be overestimated in a more similar manner between surveyors. This observation in combination with results from the Clanahan[40] study would suggest that higher readings on the 3D survey are likely to be more representative of dead coral cover than the overestimated live coral cover[37] from the traditional survey. This is further reinforced by the accuracy of the rendered 3D models to known objects during the pilot study.[41,42]

Overall, 3D surveying results remained more accurate over time and between surveyors as also found by Raoult et al.,[17] The inclusion of traditional surveying in our study further suggests that smaller changes in ecological parameters over time (i.e. dead and bleached) can be significantly different between surveyors for traditional coral surveying compared to 3D coral modelling. However, ContextCapture[28] is an industrial standard reality modelling program which makes is an expensive program, thus cost prohibitive for most survey work. Whilst, this study's results highlight that ContextCapture[28] is a viable program for *in-situ* 3D coral modelling, cheaper alternative programs 3D model programs, such as Agisoft Photoscan, can be utilised to obtain similar results at a more reasonable cost.[23]

For now, therefore, coral survey method for rapid assessments or time-restricted surveys will fare better in the amount of information that can be gathered with the current state of technology. However, this advantage is very much on a limited timeline with technology advancing rapidly.[43] Although 3D surveying is tedious, it gathers copious amounts of information that was not analysed in this study, such as reef topography, volume and minute growth rates over time. There is no doubt that processing speeds of 3D model programs will shorten in the future, allowing more holistic 3D surveys of entire reefs to be conducted.

The future for this field holds great promise with technologies such as underwater autonomous vehicles are becoming more affordable, in combination with improved cameras for capturing 3D corals would allow for rapid and holistic captures of coral reefs which would not be possible within limitations associated with human divers.[44,45] However, for the time-being the surveyor needs to think about the time and cost aspect relative to the amount of information gathered when setting up a study. Therefore, results yielded from this study would suggest 3D modelling is best utilised for medium-low frequency, long-term in-depth ecological studies of several relocated corals rather than several tens of individual coral colonies with a high monitoring frequency.

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Conflicts of interest

The authors declare that there are no conflicts of interest.

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