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3D photogrammetric surveys on coral reefs in the Maldives

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***Abstract* – The global increase in seawater temperature is causing irreparable damages to coral reefs all over the world. Frequency of coral bleaching episodes and mass mortality is increasing and coral reefs have not enough time to recover after these impacts. The present study concerns this phenomenon in the context of the Maldives. In this scenario, monitoring activities are very important to check the health of coral reefs, and the adoption of specific parameters such as reef rugosity and accretion of corals provides important measures of the ability of reefs to recover after bleaching. Moreover, the use of photogrammetry allows speeding up the on-site measurements, enlarging the scale and the reliability. The input data are the images traditionally taken by operators for visual analysis, paying attention to the achievement of photogrammetric principles.**

I. INTRODUCTION

Coral reefs result from the dynamic equilibrium between bioconstruction and erosion. Bioconstruction is predominantly undertaken by hermatypic scleractinian corals, which deposit a calcium carbonate ($CaCO_3$) structure that persists after their death. Reef accretion results from vertical growth of the coral framework and is mainly controlled by the rate of sea level rise. The capacity of reefs to maintain physical 3D structures and positive vertical accretion is indicative of their health. Mass mortality of bioconstructors following major disturbances may stop, or hamper the process of bioconstruction and facilitate erosion of carbonate structures.

Global increases in seawater temperature have triggered extensive coral bleaching episodes worldwide, which resulted in mass coral mortality events with catastrophic losses in both coral cover and reef 3D structure [1]. Between 2014-2016, water temperatures raised enough to trigger wide-scale bleaching in most tropical regions [2]; 72% of the reefs bleached [3] and coral mortality has been among the worst ever observed [4]. The Maldives have also been impacted severely in April-June 2016 during this global bleaching event [5] (Fig. 1).

Topographical heterogeneity of coral reefs is difficult to estimate and there is no consistent theory for its measure [6]. In this scenario, photogrammetry is intended to improve the workflow providing metrical data with an offline procedure, based on the images traditionally taken by the operators for visual analysis, obviously paying attention to the achievement of photogrammetric principles [7, 8]. This technique permits to obtain reliable measurements without increasing the diving time on site. A post-processing phase is required to generate the 3D model of the surveyed site and to manage it [9].

In this study, photogrammetric surveys have been conducted on coral reefs of the Maldives in May 2019, to evaluate the status and the 3D structure of reefs after the mass bleaching event of 2016. In particular, results on reef rugosity obtained from photogrammetry have been compared with data obtained through the application of the Rugosity Index during the same surveys using the chain transect method [10].

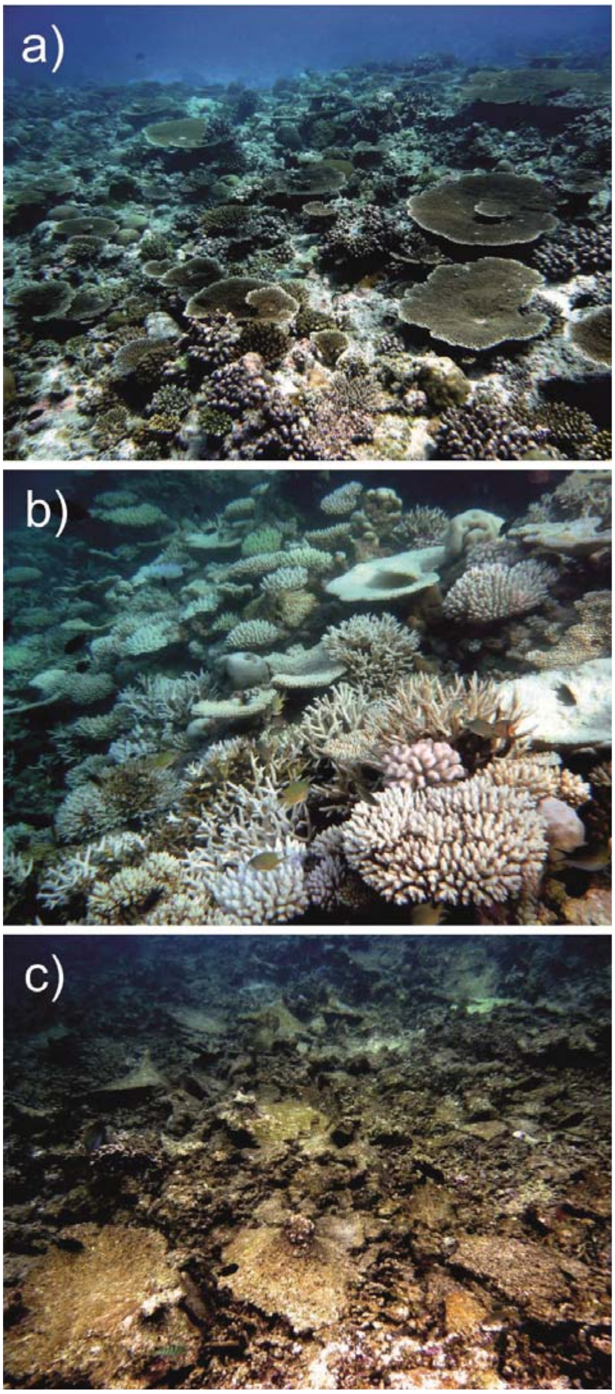

Fig. 1. State of shallow coral reefs in the Maldives in 2015 (a), 2016 (b) and 2017 (c). The 2016 thermal anomaly, mass bleaching and consequent mass mortality of corals is evident. Photos collected by M. Montefalcone during annual scientific cruises in the Maldives in 2015, 2016, and 2017.

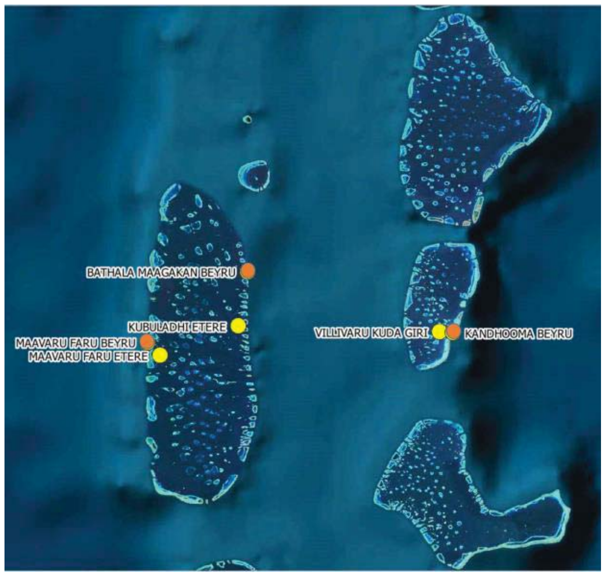

Fig. 2. Location of the six sites investigated during the scientific cruise in the Maldives in May 2019. Orange and yellow dots indicate the ocean and the lagoon reef sites, respectively.

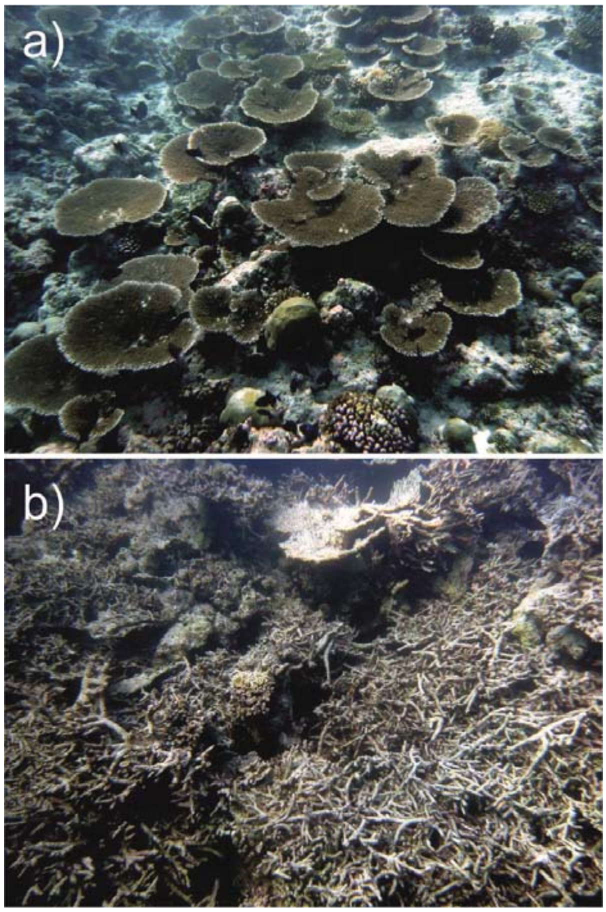

Fig. 3. Examples of the aspect of a Maldivian healthy ocean reef (a, Maavaru Faru Beyru in Ari atoll) and an unhealthy lagoon reef (b, Maavaru Faru Etere in Ari atoll) at about 5 m depth, surveyed during the 2019 scientific cruise. Photos collected by M. Montefalcone.

II. METHODS

The Maldives form the central part of the Laccadive-Maldives-Chagos ridge in the central Indian Ocean. In May 2019 a scientific cruise took place and six sites have been surveyed across the atolls of Ari, North Malé, and South Malé (Fig. 2).

Three were ocean reef sites, which are ocean-facing sides (fore reefs) of the atoll rims, and three were lagoon reef sites, which are lagoon patch reefs or lagoon-facing sides (back reefs) of the atoll rim. During the 2019 scientific cruise, some of the reefs result healthy, others unhealthy (Fig. 3).

The position of each site was recorded using a GPS. At each site, all data (described in more detail below) were collected by SCUBA diving at depths between 3 and 5 m, on the reef flat.

Reef rugosity at each site was computed using 12 replicate 2 m long chain transects [6, 10] laid randomly on the bottom parallel to the reef edge, following the substrate and organisms contour with the chain links as far as possible. An index of substrate rugosity was calculated dividing the length of the chain deployed on the substrate by the length of its horizontal projection, measured with a meter.

3D structure of the six reefs investigated was derived from photogrammetric surveys done on the same reefs at the same locations where the chain transects have been laid. The images collection has been planned taking into account as constraints the features of the available cameras (Canon EOS 600D and Panasonic Lumix DMC-FX30) and the distance from the reef. Fixing these parameters, the number of photos and the baseline have been established considering the needed overlapping. Moreover, the Ground Sample Distance (GSD), i.e. the dimension of the image pixel content, has been computed to evaluate the reachable accuracy and resolution. In Table 1, a resume of the planned parameters is reported.

Table 1. Photogrammetric planning parameters.

Camera	Canon EOS 600D		Panasonic Lumix DMC-FX30	
Relative distance [m]	3		5	
Longitudinal overlapping [%], baseline [m]	70	1.2	60	0.4
Transversal overlapping [%], baseline [m]	70	0.8	60	0.3
Focal [mm]	17		28	
GSD [mm]	0.5		0.2	

After the on-site shooting phase, the post-processing of data has been performed in laboratory by means of the photogrammetric suite Agisoft Photoscan© (now Agisoft Metashape©) [11].

The images have been relatively oriented and a 3D point cloud has been produced for each site. The models have been scaled using scale bars, thanks to the presence of a tape measure. Finally, the so-obtained point clouds have been managed using CloudCompare and Autodesk™ AutoCAD® 2019 [12, 13], in order to extract sections and measurements. Note that point clouds do not have absolute positioning and orientation, as it was not possible to acquire GPS points on site. This means that their azimuthal and zenithal orientation is uncertain, mainly leading to uncertainty about the definition of the reef slope.

From these photogrammetric surveys the reef rugosity was calculated according to the on-site technique of measurement. 12 sections for each site have been extracted from the photogrammetric point cloud at almost regular length intervals of 1 m, in both longitudinal and transversal directions with respect to the transect development. For every extracted section, a portion with projection of 2 meters has been taken into account. Nevertheless, the ratio between the section length and its known projection has been normalized, to be coherent with the use on-site of a chain of fixed length.

III. RESULTS

The analysis has been deepen for two cases study, localized in Maavaru Faru Beyru (healthy ocean reef) and Kubuladhi Etere (unhealthy lagoon reef). The areas under study by photogrammetry have an extension of 10m x 3m while the chain transects method was applied on a longer areas, moving parallel to the reef edge for about 30m.

The 3D models of corals and reef were derived by photogrammetric surveys of 150-200 pictures per site. Fig. 4 shows the nadiral view of healthy (a) and unhealthy (b) portions of the coral reefs. Some holes in the point clouds are present mainly due to corals covering the seabed from sight.

Examples of longitudinal and transversal sections of the 3D models are shown in Fig. 5 and 6, respectively.

The mean value of the index of rugosity obtained from the chain transects in the lagoon reef was 1.25±0.12, while that in the ocean reef was 1.20±0.16 (Table 2). The indexes of rugosity evaluated by photogrammetry were 1.52±0.17 in the lagoon reef and 1.45±0.14 in the ocean reef (Table 2).

The mean values evaluated in both methods are significantly different, the photogrammetric one higher than the chain one. This was expected, due to the differences in the area covered and in the measurement technique.

Although this difference, both methods showed consistently the highest values of reef rugosity in the lagoon reef than in the ocean reef.

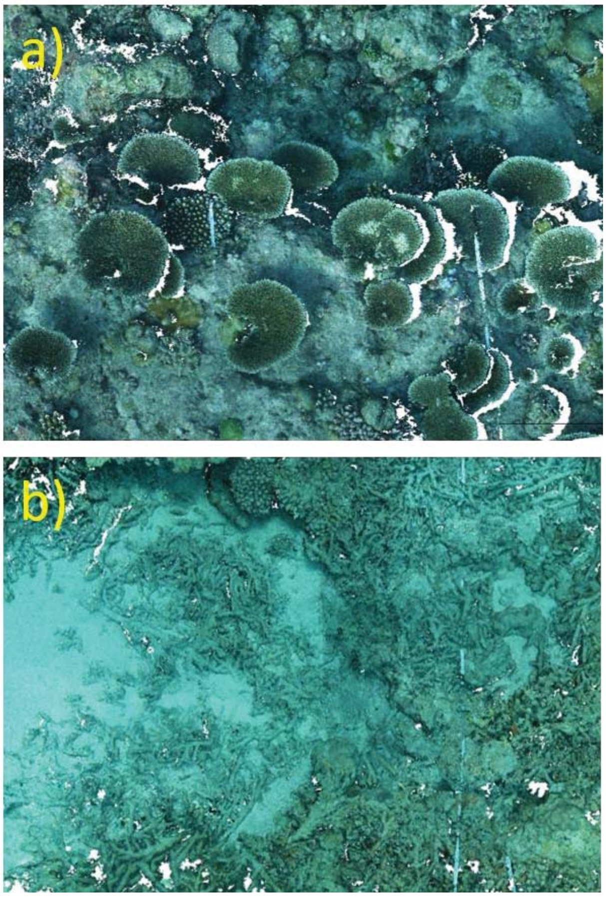

Fig. 4. Nadiral view of the photogrammetry 3D point cloud. Example of healthy (a) and unhealthy (b) coral reef. Holes in the seabed surface, mainly due to corals covering the seabed from sight, are in white.

Table 2. Rugosity data obtained from photogrammetry (Ph) and chain transects (Ct).

Case study	**Kubuladhi Etere (lagoon reef)**		**Maavaru Faru Beyru (ocean reef)**	
	Ph	Ct	Ph	Ct
Mean rugosity	1.52	1.25	1.45	1.20
Dev. std.	0.17	0.12	0.14	0.16

The standard deviations of the observed rugosity indexes, both by photogrammetry and by chain transects, highlight the significance of only the first decimal value of the index.

The variability of the rugosity index obtained by means of the in-situ chain is obviously affected by the uncertainty of the measurement, which can be evaluated of the order of 2-4 cm. It follows that the expected standard deviation associated with the evaluation of the index with chain can be evaluated of the order of 0.04. Instead, the expected standard deviation of the rugosity index obtained by photogrammetry is negligible, of the order of 0.001, being the uncertainty of the measurement of the order of 1 mm.

The observed standard deviation is obviously higher than the expected one, because of the large area analyzed and the measured environment.

IV. DISCUSSIONS

After the 2016 bleaching event and the severe loss in living coral cover, all lagoon and some of the ocean Maldivian reefs shifted from a net accretion to a net erosive state [5]. This notwithstanding, the 3D structure of the reef was still preserved in May 2019, most of the dead coral colonies being in place.

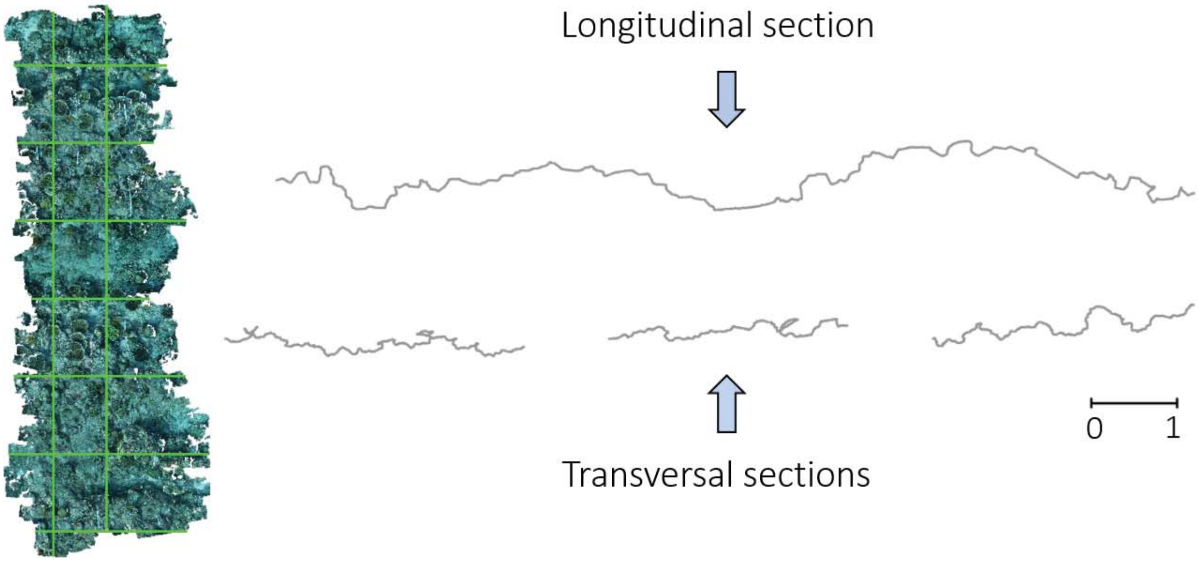

Fig. 5. Location of longitudinal and transversal sections in Maavaru Faru Beyru (ocean reef) and examples of their trend. The scale bar at the right bottom represents 1 m.

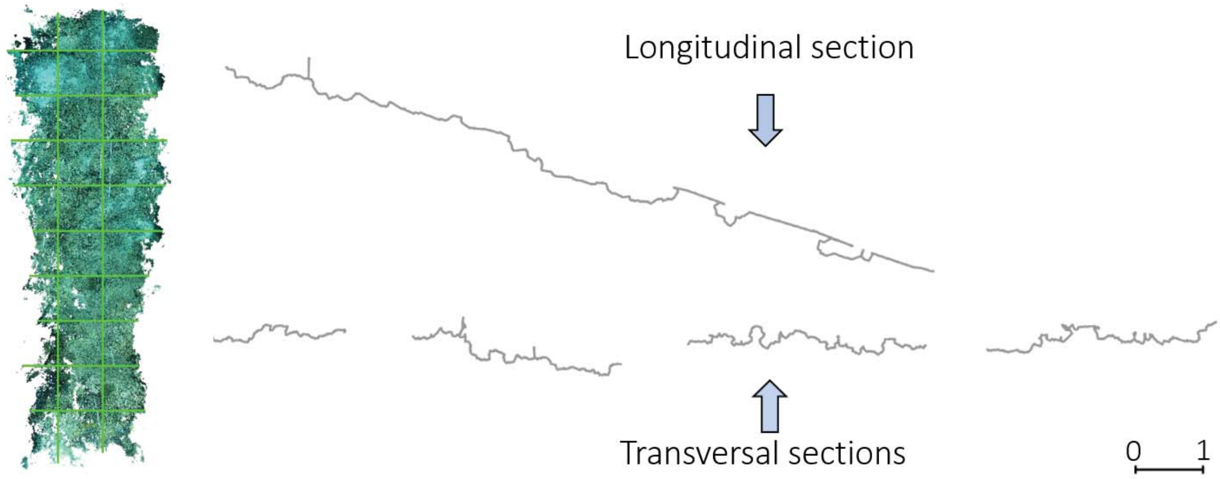

Fig. 6. Location of longitudinal and transversal sections in Kubuladhi Etere (lagoon reef) and examples of their trend. The scale bar at the right bottom represents 1 m.

Rugosity values obtained with both methods showed a higher 3D in the lagoon reef of Kubuladhi Etere, although most of the coral colonies were died. This is consistent with the fact that lagoon reefs, when corals are healthy, have coral cover usually higher than ocean reefs, where the wave beats more. Moreover, lagoon reefs are characterized mainly by branched corals that greatly increase the three-dimensionality of the reef. In most of the reefs studied, the colonies of branched corals in the lagoon reefs were dead. Instead ocean reefs, dominated by massive corals, showed a higher living coral cover (Fig. 3 and 4). However, no erosion already hit the dead coral in the lagoon reefs, that therefore continues to maintain high values of roughness.

In the next years the dead coral colonies will be destroyed by physical and biological erosion. The reduction of the reefs 3D structure due to the breakage of dead colonies, will reduce the reef into rubble and sand: reduction in reef rugosity after the mass coral mortality of 1998 was noticeable [14]. Recovery of corals in the next years will allow gradual aggradation of the reefs during periods of coral colony development.

Bleaching is likely to become a chronic stressor in the coming decades [4], implying repeated coral mortality, reduced reef accretion and risk of drowning following sea level rise [5]. Cover data has been often used as a proxy to estimate carbonate deposition and reef accretion by means of predictive equations [5, 15].

Geomorphological aspects, such as those considered in the present study, have received little or no attention by other studies on coral reefs. Application of photogrammetry in the Maldives suggests that this approach can be effective in following the recovery of reef accretion. In facts, the advantage of the photogrammetric technique is related to the simplification of on-site operations and on the enlargement of working scale and reliability of measurements, useful features for data production and management.

In addition to the measures of rugosity, also the height of corals and reefs could be calculated from photogrammetry, but the strategy is still under investigation. In fact, the seabed surface is highly covered by corals, that prevent the detection of significant portions of it, needed for its surface reconstruction by interpolation. Supervised classification techniques have been used in an attempt to identify the seafloor. Moreover, several mesh reconstruction tools have been tested, in order to infer the surface development from the seabed point clouds identified. Other tests will be performed in the next future.

V. REFERENCES

[1] T.P.Hughes, J.T.Kerry, M.Álvarez-Noriega, J.G.Álvarez-Romero, K.D. Anderson, A.H.Baird, S.K.Wilson, "Global warmingand recurrent mass bleaching of corals", Nature, vol.543, 2017, pp.373-377.

[2] C.M.Eakin, G.Liu, A.M.Gomez, J.L.De La Cour, S.F.Heron, W.J.Skirving, A.E.Strong, "Global coral bleaching 2014-2017", Reef Encounter, vol.31, 2017, pp.20-26.

[3] S.F.Heron, C.M.Eakin, F.Douvere, "Impacts of climate change on World Heritage Coral Reefs: A first global scientific assessment", UNESCO World Heritage Centre, Paris, France, 2017.

[4] T.P.Hughes, K.D.Anderson, S.R.Connolly, S.F.Heron, J.T.Kerry, J.M.Lough, S.K.Wilson, "Spatial and temporal patterns ofmass bleaching of corals in the Anthropocene", Science, vol.359, 2018, pp.80-83.

[5] M.Montefalcone, C.Morri, C.N.Bianchi, "Long term change in bioconstruction potential of Maldivian coral reefs following extreme climate anomalies", Glob. Change Biol., vol.24, 2018, pp.5629-5641.

[6] R.Lasagna, I.Gattorna, G.Albertelli, C.Morri, C.N.Bianchi, "Substrate heterogeneity and relation with coral recruitment in coral reefs of the Maldives (Indian Ocean)", Biol. Mar. Medit., vol.13, 2006, pp.88-89.

[7] J.H.R.Burns, D.Delparte, R.D.Gates, M.Takabayashi, "Integrating structure-from-motion

photogrammetry with geospatial software as a novel technique for quantifying 3D ecological characteristics of coral reefs", PeerJ 3:e1077, 2015.
[8] P.Rossi, C.Castagnetti, A.Capra, A.J.Brooks, F.Mancini, "Detecting change in coral reef 3D structure using underwater photogrammetry: critical issues and performance metrics", Applied Geomatics, 2019, pp. 1-15.
[9] E.Nocerino, F.Neyer, A.Gruen, M.Troyer, F.Menna, A.Brooks, A.Capra, C.Castagnetti, P.Rossi, "Comparison of diver-operated underwater photogrammetric systems for coral reef monitoring", Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W10, 2019, pp.143-150.
[10] C.N.Bianchi, R.Pronzato, R.Cattaneo-Vietti, L.Benedetti-Cecchi, C.Morri, M.Pansini, G.Bavestrello, "Hard bottoms", Biol. Mar. Medit., vol.11, 2004, pp.185-215.
[11] Agisoft PhotoScan©, 2019, www.agisoft.com/ (access on 25th June 2019)
[12] CloudCompare, 2019, www.cloudcompare.org/ (access on 25th June 2019)
[13] Autodesk™ AutoCAD®, 2019, www.autodesk.it/products/autocad/overview/ (access on 25th June 2019)
[14] C.Morri, M.Montefalcone, R.Lasagna, G.Gatti, A.Rovere, V.Parravicini, G.Baldelli, P.Colantoni, C.N.Bianchi, "Through bleaching and tsunami: coral reef recovery in the Maldives", Mar. Pollut. Bull., vol.98, 2015, pp.188-200.
[15] C.T.Perry, K.M.Morgan, "Bleaching drives collapse in reef carbonate budgets and reef growth potential on southern Maldives reefs", Sci. Reports, vol.7, 2017, 40581.