Sintesi Tesi di laurea magistrale: **Securo Andrea**

“ MULTI YEAR EVOLUTION OF ICE IN CAVES THROUGH SFM-MVS AND GPR TECHNIQUES ”

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INTRODUCTION

This thesis investigates the application of a terrestrial structure from motion – multi view stereo (SfM-MVS) approach combined with ground penetrating radar (GPR) surveys for monitoring the surface topographic change of three permanent ice deposits in caves located in the Julian Alps (south-eastern European Alps). This method allows accurate calculation of both seasonal and annual mass balance, estimating the amount of ice inside caves. The ground based SfM approach represents a low-cost workflow with very limited logistical problems of transportation and human resources and a fast acquisition time, all key factors in such extreme environments. SfM-MVS allows sub-centimetric resolution results and makes the use of classical terrestrial laser scanner survey technique less convenient and helpful. Fourteen SfM acquisitions were made between the 2017-2020 ablation seasons (i.e. July-October) while 2 GPR surveys were acquired in 2012. The obtained dense point clouds and digital terrain models made possible a reliable calculation of topographic changes and mass balance rates during the analysed period. The combination of SfM-MVS and GPR surveys provided comprehensive imaging of the ice thickness and the total ice volume present in each of the caves, proving to be a reliable, low cost and multipurpose methodology ideal for long-term monitoring.

Ice caves are defined as permanent (i.e. > 2 years) ice deposits in caves or lava tubes (1) and for this reason are recognized by most of the authors as an evidence of permafrost (2, 3, 4). Ice bodies in caves are suffering significant mass losses worldwide and it is therefore extremely urgent to study these sources of paleoenvironmental information that will be soon obliterated (5). Long-term mass balance measurements are rather common on glaciers both in mountains and polar environments and in the last decades' new methodologies such as LiDAR, terrestrial/aerial photogrammetry and pseudo 3D ground penetrating radar improved the reliability of the surveys. This is not the case of permanent ice deposits in caves where only scattered and short-term mass balance records exist (6, 7). Moreover, in all such cases, mass balance measures refer to specific punctual locations as for instance in the Eisriesenvelt ice cave (Austrian Alps) where an ultrasonic ranger continuously monitored ice thickness changes (6) or in the Leupa ice cave (SE Alps) where surface topography changes are monitored by using 2 fixed benchmarks since 2011 (4).

METHODS

Structure from motion multi view stereo (SfM-MVS) is not a stand-alone technique but rather a workflow combining different algorithms coming mainly from computer vision, dense image matching and partially from photogrammetry. The used algorithms differ from traditional photogrammetry because camera positions, orientation and the entire scene geometry are retrieved simultaneously without any geo-referencing (8). However, the acquisition does require references such as ground control points (GCPs) or even the camera positions to improve the overall accuracy of the final output, making it a reliable base for further spatial analysis (8). The proposed methodology allows obtaining a resolution comparable with those achieved by using the TLS in the creation of a digital terrain model (DTM) (9). Moreover, the approach reduces the instrumental cost making easier the improvement of temporal resolution by repeating surveys, which is fundamental in multi-temporal analysis such as long-term mass balances. Another advantage is the applicability range of spatial scales, making possible to focus on small details (e.g. bediéres, sediments, cryoconites) or the whole cave area without altering the processing flow (e.g. the approach is reliable from 10^{-2} to 10^{6} m^2). The easy data acquisition and the lightweight instrumentation are even more useful in particularly remote and not-easily-accessible environments such as ice deposits within caves. To our best knowledge, the SfM-MVS method has never been used in ice caves for detecting multi-annual ice surface topography variation and mass balance calculation.

Ground Penetrating Radar (GPR) is a widespread technique in several glaciology-related surveys thanks to the peculiar dielectric properties of frozen materials and ice which both exhibit low intrinsic attenuation and, therefore, the EM waves can reach depths conspicuously higher than in common geologic materials. Other key aspects that are making GPR a widespread solution for glaciological surveys are the relatively fast acquisition times and the high lateral and vertical resolutions, which are in the order of some centimeters, at least for the shallower applications. Recent application of GPR techniques on ice bodies in the Julian Alps area are numerous and usually related to glaciers (10) while there are only a few examples around the world of GPR in underground ice bodies (11, 12).

RESULTS AND CONCLUSION

The dense point clouds and the polygonal meshes reconstructed through SfM-MVS allowed exact reproduction of the three analysed caves with a sub-centimeter resolution. The texturization of 3D models through photographs has also allowed the creation of photorealistic and interactive scenes that can be useful for other scientific application or dissemination activity. The use of opensource software for the comparison of point clouds made it possible calculation of the distribution and entity of topographic changes within the cavities (Fig.1), thus obtaining information also on snow and debris inside them. This has been done both on 2.5D DTM and 3D datasets (Fig. 2), testing different software and algorithm alternatives. The use of geometric features allowed the classification and morphological analysis of point clouds (Fig. 3), although these processing results are not part of this thesis work. The GPR data allowed volume estimations of the ice deposits with high precision (Fig. 4), expanding the time series of available data when older photos usable as reliable references were available.

The Vasto ice cave (VIC) has lost 13.6% of its estimated ice volume from 2012 to November 2020, which equals 134.00 m^3. The Leupa Ice Cave has lost 49.4% of its ice volume from 2012 to November 2020, which equals 180.11 m^3 of ice. There are not enough data to establish how much of its total ice has been lost in the Pecore ice cave (PIC). However PIC lost 66.12 m^3 from 2019 to 2020. The estimated error for the entire methodology is 0.02 m ± 0.01 m on singular points measurements. This value reduces to 0.01 m in the ice deposit areas that are more densely reconstructed. There are also non-estimable errors that come from the limitations of the 2.5D GPR methodology and from some portions of cavities not reconstructed through the SfM-MVS (e.g. part of the PIC).

Further useful information on the time-evolution characterizing these portions of the cryosphere and on the interaction with the external environment can come from the combination of these data and similar future acquisitions with microclimatic data collected on-site, both inside and outside caves. Other implementations of the presented methodology could come from the use of a more refined data referencing for SfM-MVS surveying (e.g. using a total station) combined with georeferenced 3D GPR acquired at the same time.

Absolute georeferencing would also allow more precise calculation of errors by implementing precision maps in M3C2 (Multiscale Model to Model Cloud Comparison) measures through an innovative Monte Carlo method, traditionally used for the qualitative assessment of UAV surveys in the outdoors. Also including larger portions of the caves (e.g. secondary entrances, chimneys, external morphology) in the acquisitions and use these 3D models for simulations similar to those proposed in Bertozzi et al. (7) could lead to a better CAD (Cave Air Dynamics) understanding of these environments.

The results obtained in this thesis might constitute a starting point to a better quantification of ice volume reduction occurring in alpine caves under global warming scenarios. The methodology itself is also applicable to other branches of glaciology. Surveys of this type can be an economical and very effective alternative to UAV SfM-MVS mass balances and it is starting to be used for this purpose, especially where the geomorphology of the glacierized area allows a good overlapping between different photo positions.

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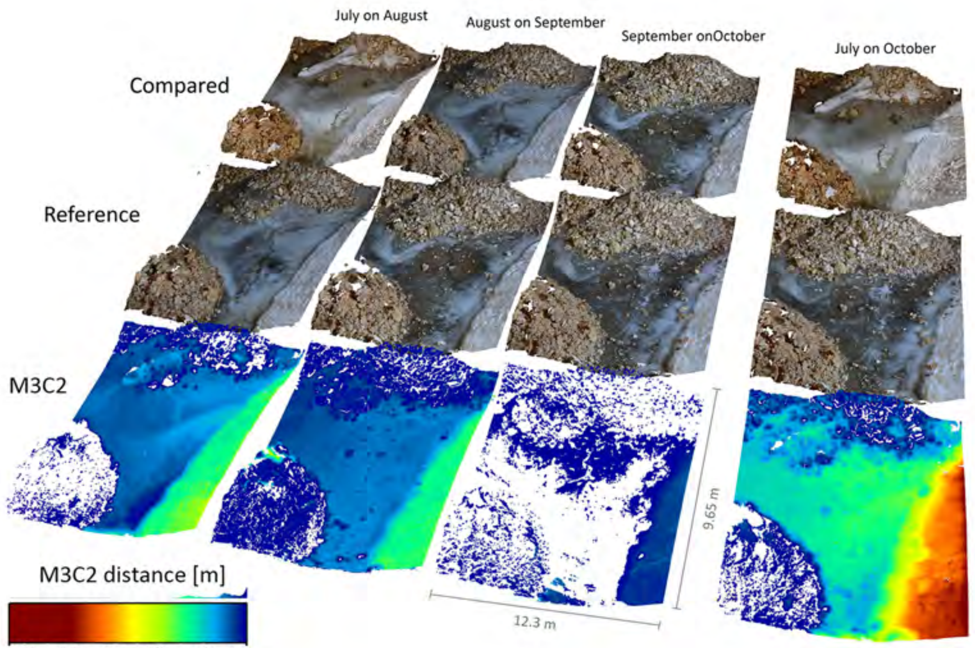
Figures captions

- *Fig. 1* - Example of M3C2 (Multiscale Model to Model Cloud Comparison) distance computations for monthly variations inside a portion of the VIC (Vasto Ice Cave). The dark blue portion (rock debris) resulting in a M3C2 of almost 0m, and the maximum values area (snow entering the cave) can be filtered out working on the histograms of the scalar fields to isolate the ice deposit differences.
- *Fig. 2* – LIC (Leupa Ice Cave) dense point clouds generated after SfM-MVS workflow (a, b). M3C2 distance inside LIC applied only to the permanent ice deposit between July and November 2020 (c).
- *Fig. 3* - Verticality (log scale) inside VIC during 2017-2018 surveys. Ice typically presents the lower values (yellow) being almost flat while the snow that enters from outside the cave has intermediate values (orange). On the rocks, the highest values are reached. The bediéres visualization is enhanced due to the vertical borders of the edges. Holes (white) are all due to the position of the camera stations during acquisition.
- *Fig. 4* - GPR profiles positioning above LIC surface (no ceiling) (a); 3D model derived from 2.5D interpolation (Kriging gridding method) of interpreted bedrock depth in GPR profiles (b); perspective 3D view of LIC (July 2020) with reconstructed bedrock (red) and ice ceiling of the inner cave (yellow) (c).

Fig. 1



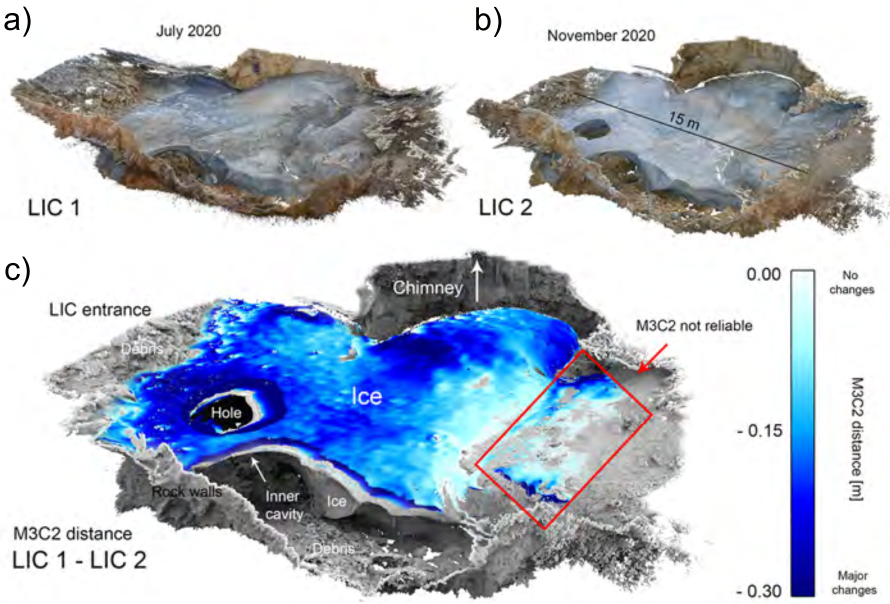


Fig. 2

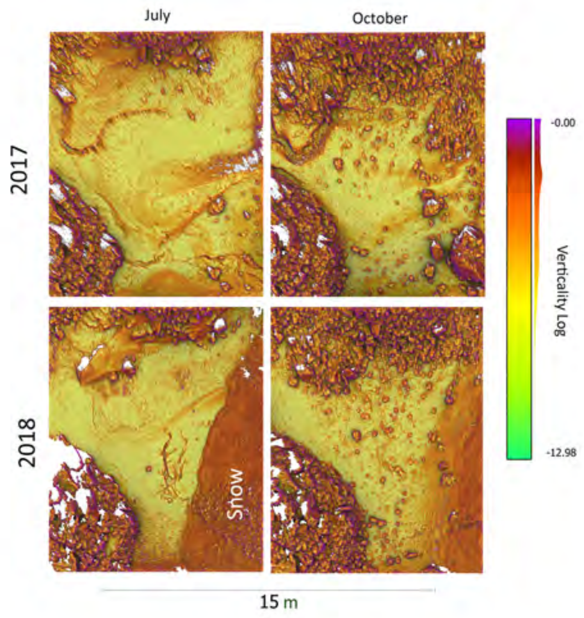


Fig. 3

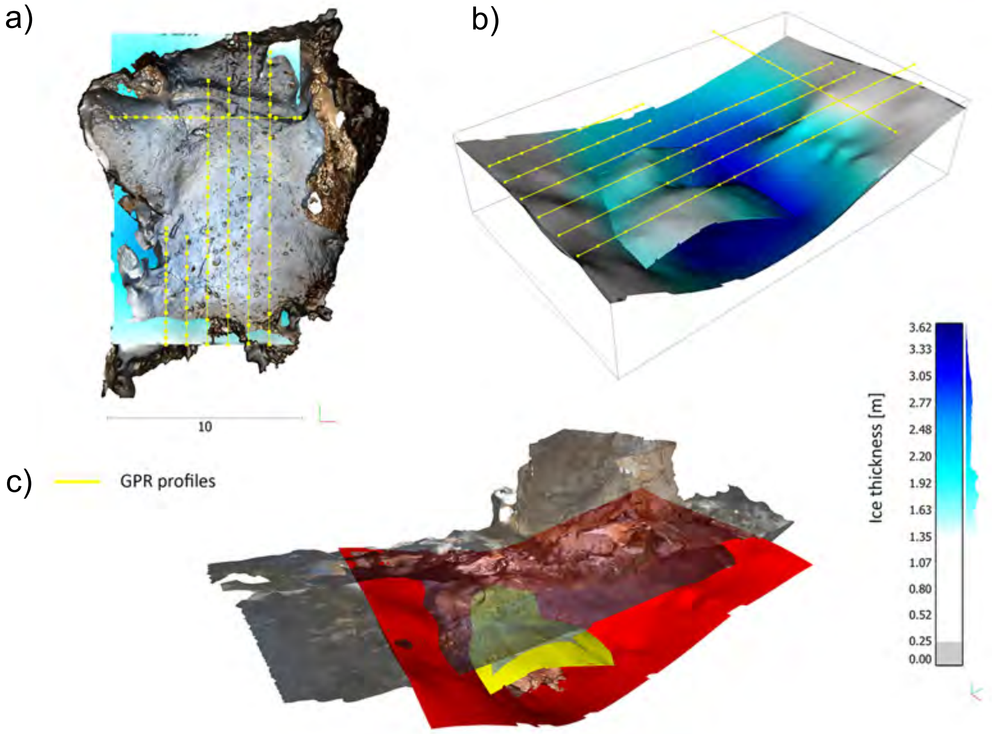


Fig. 4