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LAPM: a tool for underwater Large-Area Photo-Mosaicking

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Abstract

This paper presents a new tool for large-area photo-mosaicking (LAPM tool). This tool was developed specifically for the purpose of underwater mosaicking, and it is aimed at providing end-user scientists with an easy and robust way to construct large photo-mosaics from any set of images. It is notably capable of constructing mosaics with unlimited ~~amount~~ of images and on any recent computer. The mosaicking process can rely on both feature matching and navigation data. This is complemented by an intuitive graphical user interface, which gives the user ~~full control over the~~ feature matches between any pair of overlapping images. Finally, mosaic files are given geographic attributes that ~~allow~~ direct import into ArcGIS. So far, the LAPM tool ~~was successfully~~ used to construct geo-referenced photo-mosaics with photo and video material from several scientific cruises. The largest photo-mosaic contained more than 5000 images for a total area of about 105 000 m^2.

1 Introduction

Low visibility in the deep-sea constrains images of the seafloor to be taken from a very short distance (< 10 m) to the ~~scene~~. Such low altitude severely limits the field of view of individual images. Hence, ~~imaging extended areas~~ requires many images.

Photo-mosaicking consists ~~in~~ aligning and stitching photographs together to form a large composite picture. ~~S~~imilar technique is widely used in photography for the production of panoramas. However, ~~the~~ interest in mosaics to map deep-sea environments is growing among the scientific community, and several works have focused on developing algorithms to reliably build underwater mosaics (Gracias and Santos-Victor, 2001; Eustice et al., 2002; Pizarro and Singh, 2003; Vincent et al., 2003; Allais et al., 2004; Ferrer et al., 2007; Escartín et al., 2008). Indeed, traditional panorama-dedicated programs usually fail to cope with underwater imagery correctly. The deep sea is a very challenging environment, and the reasons for failure are manifold; moving camera, strong lighting heterogeneities, low contrasts, perspective distortions, poor accuracy of camera positioning data, or adverse camera motions due to bottom currents are many hindrances to the construction of large ~~and low-distorted~~ photo-mosaics.

Efforts have been made in several institutes of physics, robotics or computer vision sciences to develop tools to generate photo-mosaics of the seafloor, and impressive results were achieved (Eustice et al., 2002; Pizarro and Singh, 2003; Ferrer et al., 2007; Escartín et al., 2008). However, applying those techniques often requires strong mathematics, physics and programming skills, which the end-user of deep-sea mosaics does not necessarily possess. Indeed, published works about mosaicking techniques are generally aimed at improving known techniques rather than on developing a robust end-user product for ~~potential~~ deep-sea scientists. For instance, recent mosaicking works now concentrate on 3-D imaging and mosaicking techniques (Nicosevici et al., 2006, 2009; Brandou et al., 2007; Pizarro et al., 2009), but no freely available tool exists for end-users to routinely produce 2-D areal mosaics based on robust feature-matching techniques. Escartín et al. (2008) proposed a *MosaicViewer* software to assemble mosaics, which relied on geo-referencing information for each image, but it did not include any feature-matching capability.

The large-area photo-mosaicking tool (LAPM tool) was developed to ~~palliate this lack. It was written from a marine scientist's perspective and by the mosaic end-users themselves (Marcon et al., 2013a,b), with as objective to meet the needs of deep-sea scientists rather than to improve the current state-of-the-art techniques. Nevertheless, to reach that goal, the LAPM tool~~ bring~~s~~ together several functionalities for the first time. The main strength of this tool lies in its ability to combine image geo-referencing data and robust feature-matching techniques, and to generate photo-mosaics of any size and on virtually any recent computer. Furthermore, mosaic files are given geographic attributes and can be directly imported into a geographic information system (GIS). Finally, the mosaicking process can be fully controlled through a graphical user interface (GUI), which makes it easy ~~to use~~ for end users without requiring detailed mathematics, physics and programming knowledge.

This is the first article to present and to provide a finished and functional program to construct large geo-referenced photo-mosaics of the seafloor using feature detection and matching techniques. It also presents concrete examples of photo-mosaics produced with the LAPM tool.

2 Computer requirements

The LAPM tool was developed and compiled in Matlab, and is able to run on Windows, MacOS and Linux operating systems. No particular computer requirements other than those of the Matlab runtime are necessary. Currently the program does not implement any multicore parallelization. Nevertheless, it worked flawlessly on a 64 bit Windows 7 platform running on a 1.30 GHz Dual-Core Processor with 4 GB RAM, which is the minimum configuration the LAPM tool was tested with.

3 Mosaicking with the LAPM tool

3.1 Background

During the photo-mosaicking process, images are aligned together onto a single 2-D plane of the mosaic. The projection and alignment of an image onto the 2-D plane of the mosaic is called image registration (Zitová and Flusser, 2003). For underwater applications, images can be registered in different ways. First by geo-referencing each individual photograph based on navigation (easting, northing, and altitude) and ~~attitude~~ (pitch, roll, and yaw) data of a remotely operated vehicle (ROV) or autonomous underwater vehicle (AUV). The method is fast and ~~low demanding in terms of computing resources~~, but the quality of the mosaic suffers from ~~the~~ inaccuracies ~~of~~ the navigation data (Fig. 1a). Another method consists ~~in~~ using ~~pictorial information~~ to infer the motion between two images. Such feature-based method requires each image to overlap with the next and has higher computing requirements, but it generally yields more accurate results (Fig. 1b). However, it may not be able to register images if the overlap area is too small, if the scene is featureless, or if the relief is too sharp.

A robust underwater mosaicking tool should rely on feature tracking methods to ensure best registration accuracy. However, it should also be able to use navigation data in areas ~~were~~ feature tracking fails or is not possible. With the LAPM tool (Fig. 2), mosaics can be constructed in three different ways, depending on the user requirements and on the data available: with feature tracking and navigation data, with feature tracking only, or with navigation data only.

3.2 Feature tracking

If used, feature tracking is the first step of the mosaicking process. It consists ~~in~~ detecting and matching features within each consecutive pair of the image sequence. The feature tracking is based on the VLFeat toolbox (Vedaldi and Fulkerson, 2008, 2010), which includes an open-source implementation of the Scale Invariant Feature Transform (SIFT) method (Lowe, 1999, 2004). With this method, a set of features is computed for every image and tracked onto the next consecutive image in order to compute the transform matrix, or homography, that explains the motion. In addition, an outlier rejection (Pizarro and Singh, 2003) is performed in order to remove erroneous matches outliers) from the set of positive matches (inliers), which ensures that the best possible homography is computed.

In some cases, the feature tracking may ~~also~~ fail to compute matches. This happens generally if the overlap between the images is insufficient, if the scene is featureless, or if the relief causes perspective distortions. Such failure can be overcome by user intervention, i.e. by creating a few links between the unmatched images (Fig. 3). Alternatively, navigation data can be used to estimate the motion between unmatched images.

3.3 Initial topology and crossover

In mosaicking terms, the topology is the estimation of the position and orientation of every image onto the 2D plane of the mosaic (Gracias and Negahdaripour, 2005). Computing the topology is the next ~~main~~ step of the mosaicking process and a prerequisite for the actual construction of the mosaic. The ‘initial topology’ step of the LAPM tool consists ~~in~~ estimating the position of each image onto the mosaic plane from the homographies (Fig. 4). In this step, the image registration is done successively from the first image to the last in the order of the image sequence.

In such context, minor registration errors tend to add up from ~~a~~ pair to the next and to lead to a larger global error. The use of overlaps between non-consecutive images can help limiting the error by providing additional positioning constraints (Fig. 5), also known as crossover points (Fleischer et al., 1996, 1997; Fleischer and Rock, 1998). Crossover points are used in the computation of the initial topology after the pairwise registration of all images has been estimated. Starting again from the first image, whenever a crossover point is found, the registration parameters of all images within the loop are recalculated backward until the beginning of the loop or until the previous crossover point. The principle of this technique is comparable to the smoother-follower technique described by Fleischer et al. (1996).

Concretely, implementing crossover points consists in computing or manually adding additional matches between pairs of adjacent (but non-consecutive) images. Crossover points have been used in previous mosaicking efforts, and in some cases in a fully automatized and iterative fashion (Pizarro and Singh, 2003). In contrast, the LAPM tool gives ~~to~~ the user full control over crossover matches. It includes graphical interfaces to display all existing matches and to identify potential crossover points.

The use of crossover points can significantly improve the quality of the topology and of the final mosaic (Fig. 6). Crossover points can also be used to compensate for inaccuracies in the navigation data. However, to take advantage of crossover points, overlaps between non-consecutive images must be planned at the image acquisition stage, by preparing an adequate trajectory (Fig. 7).

3.4 Global registration

The global registration consists in computing ~~for each image~~ the optimal transformation matrix in order to obtain the smallest possible global error at the scale of the mosaic. This operation, also known as bundle adjustment (Pizarro et al., 2004), is done by minimizing a cost function, which simultaneously takes into account all matches from every matched pair of images.

The LAPM tool uses the cost function presented by Pizarro and Singh (2003) to compute homographies. It is solved in one iteration by linear least squares and presents the advantage of computing the global minimum. The global registration solves for affine (i.e. 6 degrees of freedom) homographies; hence, it results in a finer estimation than the initial topology.

3.5 Mosaic construction

After all images have been registered, they are merged together to build the actual mosaic. Several methods exist to optimize the rendering of the overlaps, which can be divided in two categories: clipping and blending methods (Burt and Adelson, 1983; Marks et al., 1994; Eustice et al., 2002; Pizarro and Singh, 2003; Ferrer et al., 2007; Lirman et al., 2007; Gracias et al., 2009). Clipping methods consist in taking into account the pixels from one image only out of all overlapping images; they are usually fast but clear seams are visible at the intersection between overlapping images. Conversely, blending methods combine pixels from the overlapping images; depending on the blending type, such technique can better render the mosaic, although at a higher computing cost.

Two rendering methods are available with the LAPM tool: a clipping method, in which the pixels that are closest to the center of their image are chosen (Lirman et al., 2007), and a blending method, known as multi-resolution pyramidal blending (Eustice et al., 2002; Pizarro and Singh, 2003). The latter method is significantly slower but produces a quasi-seamless mosaic (Fig. 8).

4 LAPM tool: functionalities

The LAPM tool was developed specifically for the purpose of underwater mosaicking, and its main functions were designed to meet the needs of an end-user scientist interested in building visual maps of the seafloor. Therefore, it has a graphical user interface (GUI) to ensure ease of use without requiring prior knowledge of the techniques involved (Fig. 2). Other main requirements included the abilities (1) to assemble large high-resolution image datasets on any regular computer, (2) to produce geo-referenced mosaics, (3) to give the user full control over feature matches, and (4) to produce mosaics in different resolutions.

4.1 Tiling the mosaic

Due to limited field of view in the deep sea, mosaicking large areas commonly requires hundreds to thousands of images. Most panorama-dedicated programs were usually not designed to cope with such large datasets, and computer resources are often exceeded. For instance, a photo-mosaic ~~image~~ ~~from~~ a set of several thousand high-resolution photographs can easily reach a few hundred million pixels. Most computers and operating systems cannot cope with such large files.

The LAPM tool can generate photo-mosaics of any size and on any recent computer. To achieve such capability, large mosaics are automatically tiled in several square image files (Fig. 9) which are then constructed successively and independently. The size of individual tiles can be defined by the user and is limited by the computing resources available. Therefore, lower computing capabilities result in smaller tiles.

However, because the amount of tiles is unlimited, photo-mosaics of any size can be constructed on any computer.

For instance, computers equipped with 4 GB and 64 GB RAM could build blended mosaic tiles with up to 100×10^6 pixels ($10\,000 \times 10\,000$) and 1.6×10^9 pixels ($40\,000 \times 40\,000$) respectively. Even larger tile sizes can be constructed if the blending option is not used.

4.2 Geo-referencing the mosaic

If the navigation data is used, photo-mosaics can be geo-referenced. The geo-referencing data is written in a world file, which allows mosaics to be imported into a geographic information system (GIS) such as ArcGIS ~~directly.~~ A world file is created for every tile of the mosaic. The global photo-mosaic can be visualized entirely by loading each tile into GIS (Fig. 9). Therefore, spatial analyses can be performed directly on the entire mosaic, instead of separately on each individual tiles.

A world file can also be produced when full navigation data is not available. In such case, the geo-referencing information is estimated from the position and orientation of the first image of the mosaic, as well as from the average field of view of one image. Therefore, such method only gives a crude approximation of the true geographical data; its accuracy depends strongly on the morphology of the surveyed area and on the motion of the camera.

4.3 Editing feature matches

Although robust, feature tracking methods are not foolproof and they sometimes fail to detect matches between overlapping images. This is generally the case if the overlap is too small, the mapped area featureless or the perspective distortions too strong.

Therefore, the LAPM tool includes graphical interfaces that provide the possibility to visualize current matches (Fig. 10) and to manually edit them (Fig. 3). If necessary, the user can select and delete individual links, or create new ones between any pair of images. This function is particularly useful when reliable navigation data is not available and that feature tracking fails. It is also very efficient to force the implementation of crossover points even between very low overlapping images.

4.4 Lowering the resolution

The LAPM tool can produce the final mosaics at several different resolutions. Lowering the resolution reduces computing times significantly. Indeed, the construction of a high-resolution photo-mosaic can a very computer-intensive and slow process, and it may sometimes be advantageous to lower the resolution in order to speed up the process. For instance, building large and accurate photo-mosaics can be an iterative process, for which the construction of low-resolution intermediary mosaics may be beneficial; a preliminary mosaic is indeed an efficient way of identifying crossover points in a set of images.

For example, the construction of a 5.7 billion pixel mosaic, on a computer equipped with a 3 GHz CPU, required computing times of about 24 h without blending and about 4 days with multifrequency blending option. Dividing two times the resolution allowed constructing a fully blended mosaic within a day.

5 Results

The LAPM tool ~~was~~ used to create maps of several deep-sea features. In particular, it produced photo-mosaics with image~~s~~ datasets from different underwater vehicles (ROV and AUV) and from both video- and photo-cameras.

5.1 Helgoland mud volcano

The Helgoland mud volcano, in the ~~Back~~ Sea, was visited in 2010 during the MSM15/2 cruise (Bohrmann et al., 2011). High-resolution images of the volcano center were acquired with a Canon Powershot G10 camera mounted on the MARUM ROV

Quest 4000. The surveyed areas included both sharp topography and featureless areas, and reliable ROV-navigation data was not available. Nevertheless, photo-mosaics could be successfully constructed with the LAPM tool. The results include ~~in particular~~ a 400 m^2-large photo-mosaic of the center of the volcano (Fig. 11). The perfect alignment of linear features (mud flows) indicates that the images were accurately registered.

5.2 Regab pockmark

The Regab pockmark is a cold seep structure located at 3160 m water depth in the Congo deep-sea fan. It was intensively studied during the WACS cruise (2011) and large video and photo surveys were conducted with the Ifremer ROV Victor 6000 (Marcon et al., 2013b). Datasets also contain hybrid navigation information from both Doppler Velocity Log (DVL) and ultra-short baseline (USBL) sensors.

Results include notably a 105 000 m^2-large photo-mosaic of the most active area of the pockmark (Fig. 9). Photos were obtained with the high-sensitivity OTUS camera (Simeoni et al., 2007) from an altitude of 8 m above ~~seafloor.~~ Further photo-mosaics could also be constructed from the video materials. To do so, individual frames were extracted at regular interval (1 s) from the video files. Video images are usually of lower quality than photos from still cameras; however, the high frequency of frames (25 fps for PAL cameras) ensured large overlap areas between consecutive images. Therefore, two very high-definition mosaics could be constructed, with areas of 14 000 and 5800 m^2 (Fig. 12). All mosaics were geo-referenced and could be imported into ArcGIS for spatial analyses.

5.3 Håkon-Mosby Mud Volcano

The Håkon-Mosby Mud Volcano (HMMV) is a 1.4 km-wide circular structure located at about 1250 m water depth in the Barents Sea (Jerosch et al., 2006). The HMMV has been intensively surveyed since its discovery, and high-resolution micro-bathymetry and transects of video-mosaics are already available (Jerosch et al., 2006, 2007).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| | |▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Additional photo-mapping surveys were carried out during cruise MSM16/2 (Boetius et al., 2010), with the Sentry AUV from the Woods Hole Oceanic Institute. The largest of these surveys contains more than 5500 photos. The final photo-mosaic was built using both AUV navigation data and feature tracking, and almost fully covers a 75 000 m^2-large area of the volcano (Fig. 13). It is geo-referenced and spatial analyses and area calculations can be performed ~~in GIS.~~

6 Performance and limitations

The LAPM tool is based on some of the most robust feature tracking techniques (Lowe, 1999, 2004) currently available as well as some commonly-used registration techniques (Pizarro and Singh, 2003). Achieved results show indeed that the LAPM tool can efficiently and accurately register all images into a single mosaic. This is particularly shown by the perfect fits of linear features in some of the mosaics presented.

However, such accuracy can only be achieved in areas where feature matching (either manual or automatic) is possible. If not, the imprecisions of the navigation data are reproduced in the image alignment. Furthermore, since the LAPM tool solves homographies for affine transforms, it intrinsically constructs mosaics with the assumption that the scene is planar. In areas of uneven terrain, relief may cause changes in perspective and in field of view between overlapping images. The program will be able to construct the mosaic anyway, but such changes are likely to cause registration inaccuracies and to impact the quality of final mosaics. Therefore, further analyses based on mosaics of relief areas should be performed knowledgeably. Nevertheless, the same planar scene assumption applies to all homography-based photo-mosaicking techniques (Gracias and Santos-Victor, 2001; Eustice et al., 2002; Pizarro and Singh, 2003; Ferrer et al., 2007; Escartín et al., 2008), which are also subject to comparable inaccuracies.

The LAPM tool was optimized for efficiency over speed. The structure of the code allows generating mosaics of any sizes without running into memory overflow errors, although at the cost of greater computing times. Furthermore, the LAPM tool does not include multicore parallel computing capability and cannot make full use of recent processors. Nevertheless, not all applications require full-resolution blended mosaics, and processing times can be greatly speeded-up by deactivating the blending option or by reducing the resolution.

7 Conclusions

The large-area photo-mosaicking ~~tool~~ was presented in this work. It allows end-users to effectively construct large geo-referenced photo-mosaics without requiring in-depth knowledge of the technical aspect of the mosaicking process. The tool can be used with any image~~ry~~ data, but its interface and functions were tailored specifically for the purpose of underwater mosaicking. Although based on the current state-of-the-art feature tracking algorithms and on ~~some~~ commonly-used registration techniques, the LAPM tool does not claim to compete with all other photo-mosaicking techniques. The development of this tool was instead motivated by the current lack of end-user underwater photo-mosaicking tools freely available to deep-sea scientists interested in seafloor mapping.

It is fully functional and has already been used successfully with photo and video material from several scientific cruises for the production of high quality and high-resolution photo-mosaics. ~~However, given the absence of similar end-user tools, the quality and accuracy of the results could not be compared.~~ The LAPM tool is available for download in its current version at http://doi.pangaea.de/10.1594/PANGAEA.808960 (DOI registration in progress). It will be subject to continuous improvements with notably the ability to correct images for geometric distortions, to solve homographies with 8 degrees of freedom (projective transformations), and to use multicore parallel computing.

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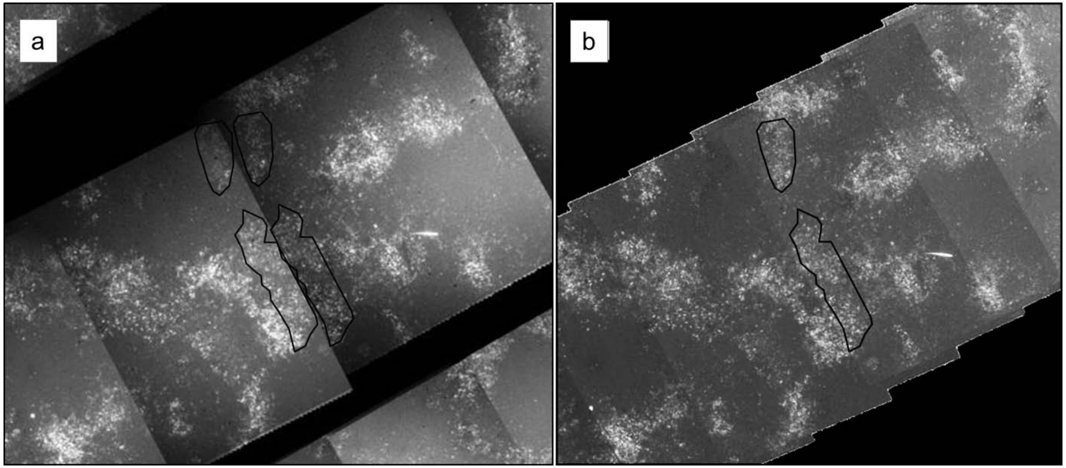
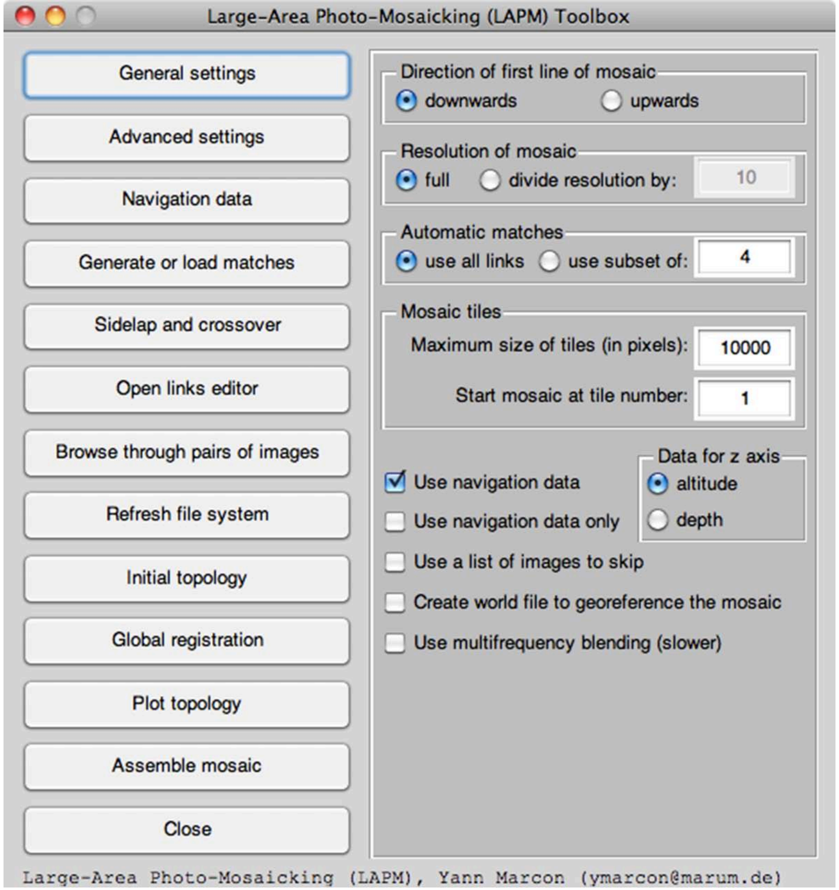


Fig. 1. Two photo-mosaics of a same area, constructed with different methods. **(a)** Navigation-based photo-mosaic; mismatches occur between consecutive images. **(b)** Feature-based photo-mosaic; better fit between consecutive images; however, more images are required to cover the same area.



Direction of first line of mosaic
● downwards ○ upwards

Resolution of mosaic
● full ○ divide resolution by: 10

Automatic matches
● use all links ○ use subset of: 4

Mosaic tiles
Maximum size of tiles (in pixels): 10000
Start mosaic at tile number: 1

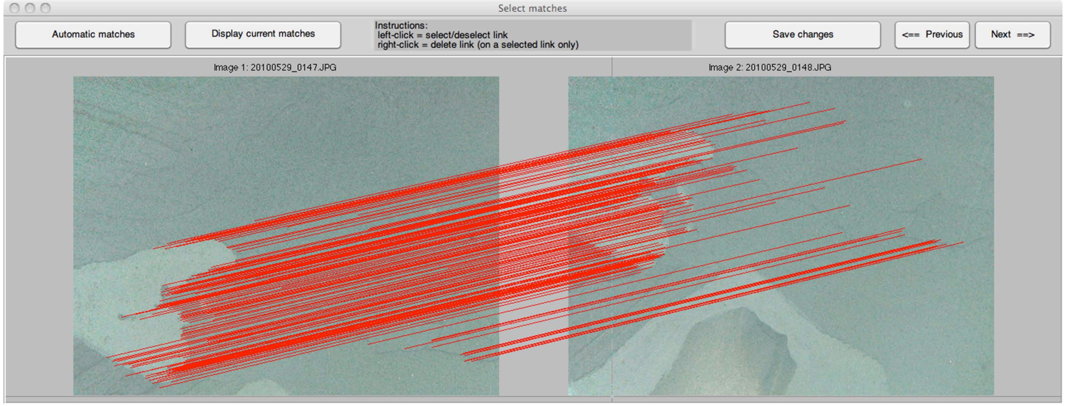
☑ Use navigation data
☐ Use navigation data only
☐ Use a list of images to skip
☐ Create world file to georeference the mosaic
☐ Use multifrequency blending (slower)

Data for z axis
● altitude
○ depth

`Large-Area Photo-Mosaicking (LAPM), Yann Marcon (ymarcon@marum.de)`

Fig. 2. Graphical user interface (GUI) of the large-area photo-mosaicking (LAPM) tool; the column of buttons is designed to guide the user through the mosaicking process. Several menus allow ~~to~~ fully control the tool.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion



Instructions:
left-click = select/deselect link
right-click = delete link (on a selected link only)

Fig. 3. The interface of the match selector allows ~~browsing~~ through each pair of images and ~~visualizing~~ the computed matches; erroneous matches can be removed and new matches can be manually created.

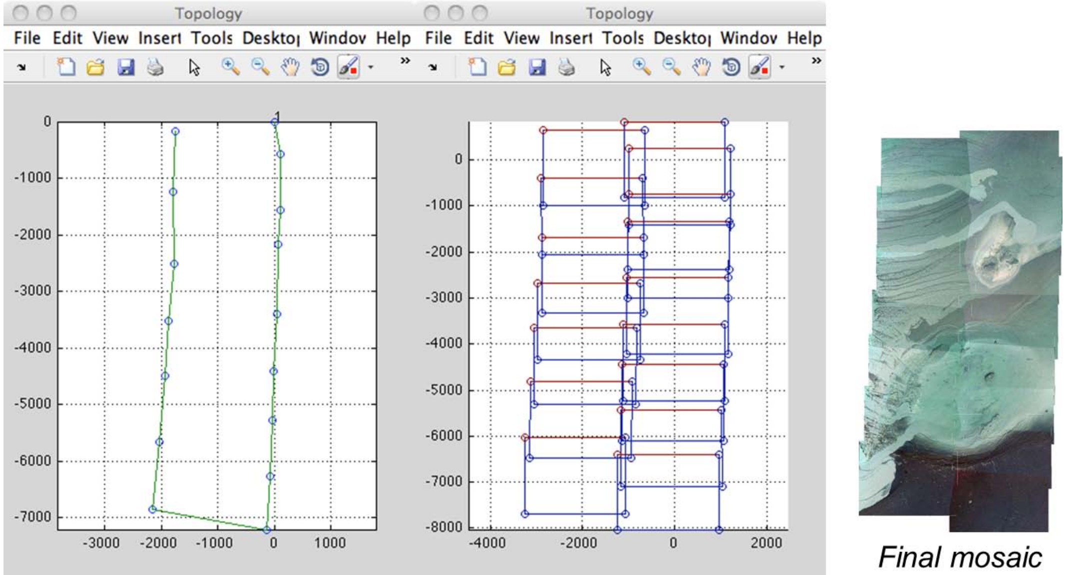


Fig. 4. Illustration of the initial topology. Left panel: estimation of the center position of each image. Middle panel: estimation of the projection of the image frames onto the 2-D plane of the mosaic. Right panel: corresponding mosaic.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

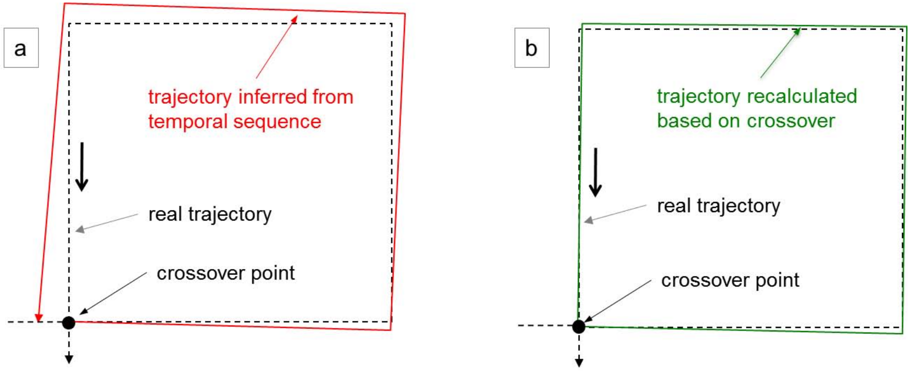


Fig. 5. Illustration of the contribution of crossover points in limiting registration errors. **(a)** Small positioning errors add up along the trajectory and grow unbounded. **(b)** By forcing the trajectory to cross itself at a given point, the position of each point within the loop can be recalculated backward; the registration error of each image is reduced.

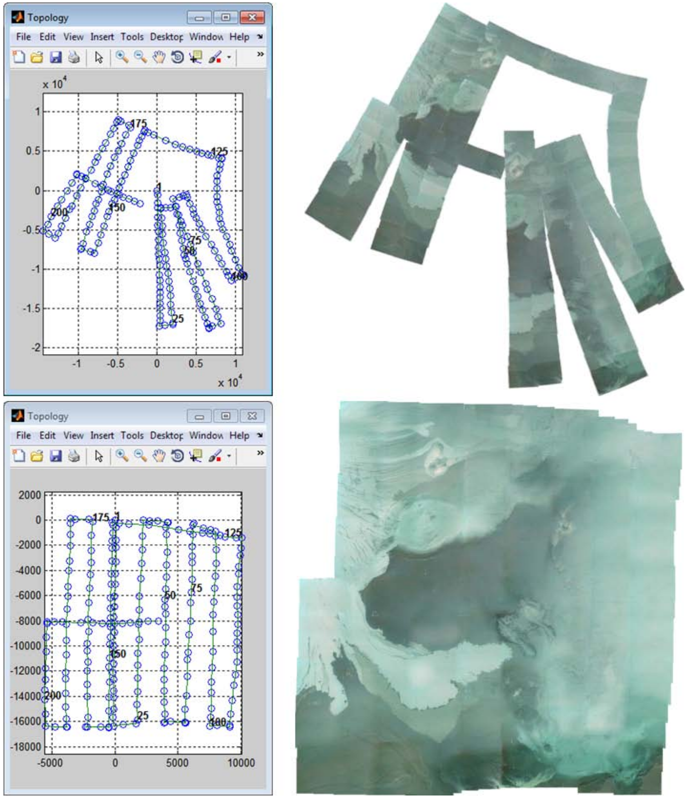


Fig. 6. Illustration of the benefits of using crossover points. Top panels: pairwise registration errors add up and lead to a huge global error. In this example, the right line of the mosaic corresponds to a featureless area, and the pairwise image registration is impacted by large errors. Bottom panels: the use of crossover points allows constraining the error. The final mosaic is consistent.

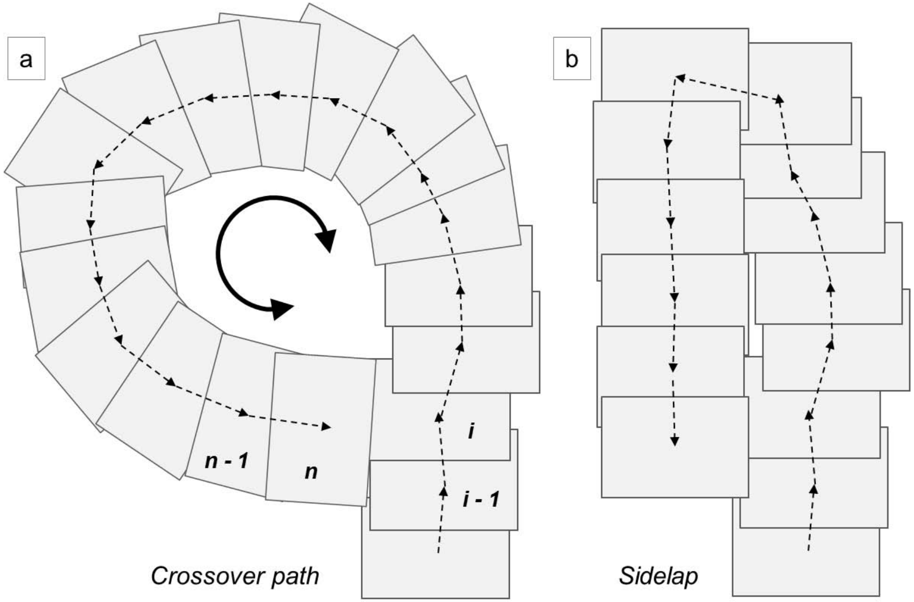


Fig. 7. Examples of crossover trajectories. **(a)** A crossover path is a trajectory, in which the camera crosses its own trajectory and surveys a same point several times; adapted from Fleischer et al. (1996). **(b)** Side-overlap, or sidelap, occurs when parallel lines of mosaic overlap.

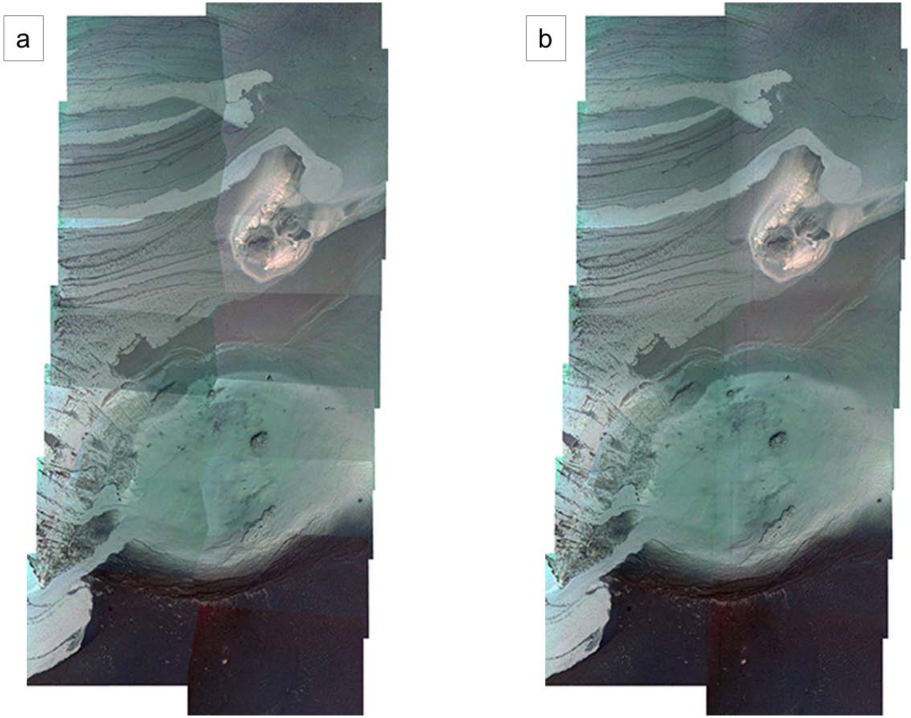


Fig. 8. Illustration of the two rendering options of the LAPM tool. **(a)** Clipping method: clear seams mark the transition between images. **(b)** Blending method: seams are barely visible but computing times are longer.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

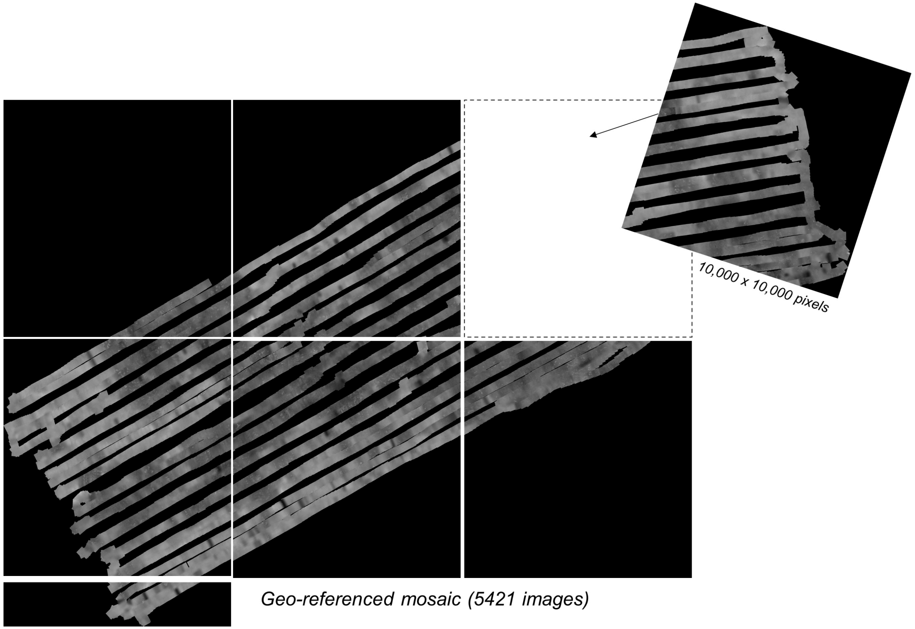


Fig. 9. Illustration of the mosaic tiles as produced by the LAPM tool; in this example, each square tile covers about 100 000 m^2. Individual tiles are constructed separately in order not to exceed the computing resources; tiles are geo-referenced, hence, loading them into a GIS allows displaying the photo-mosaic entirely.

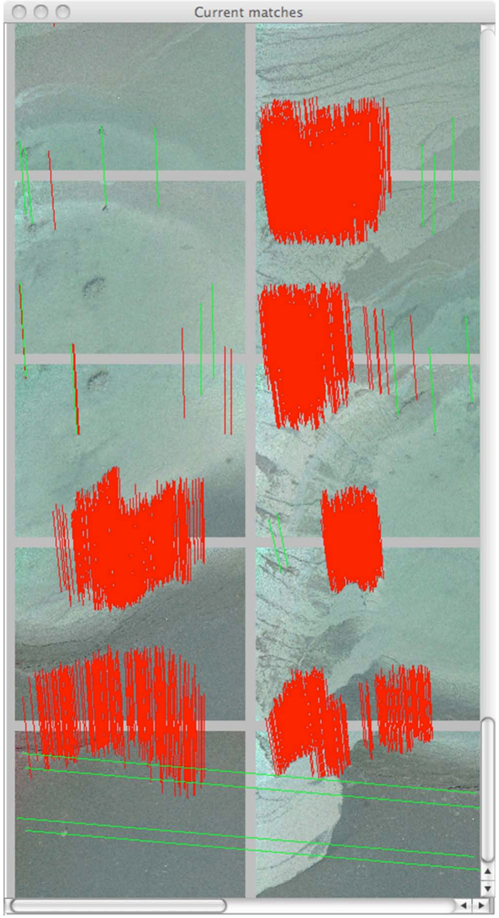


Fig. 10. View of the link editor of the LAPM tool; it gives the possibility to visualize all matches and to identify potential unmatched overlapping images.

GID

3, 127–156, 2013

LAPM: a tool for underwater Large-Area Photo-Mosaicking

Y. Marcon et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

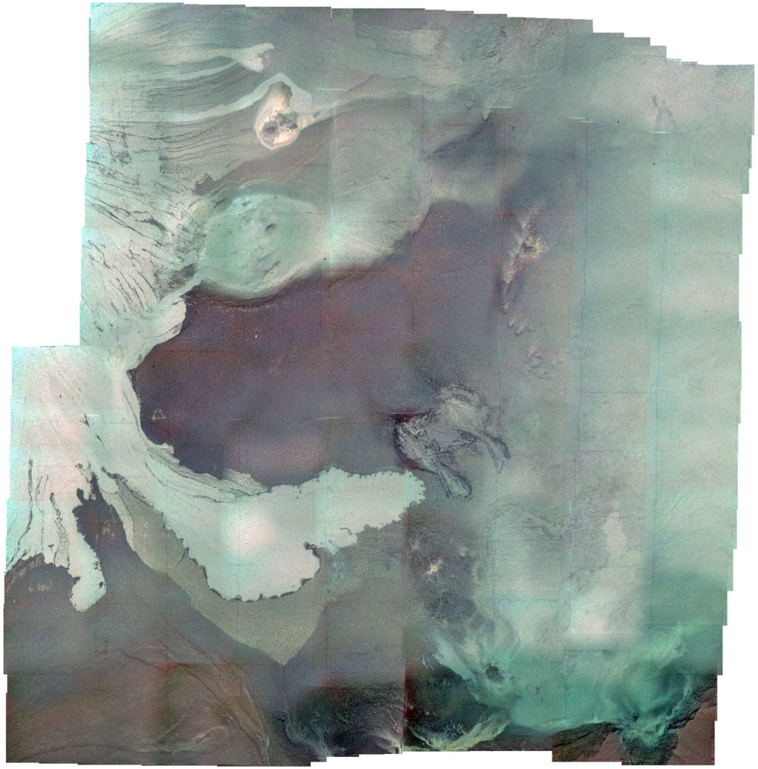


Fig. 11. Photo-mosaic showing mud pool and mud flows at the Helgoland mud volcano; the mosaic was built with 218 images and covers an area of about 400 m^2.

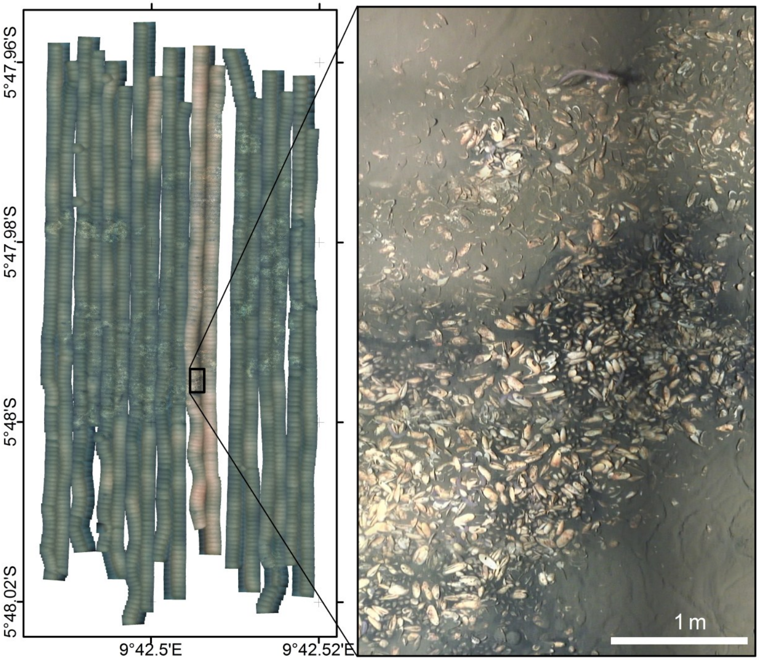


Fig. 12. Geo-referenced photo-mosaic constructed from high-definition video material; the mosaic covers an area of 5800 m^2 with a resolution, which allows ~~distinguishing~~ individual living and dead clams

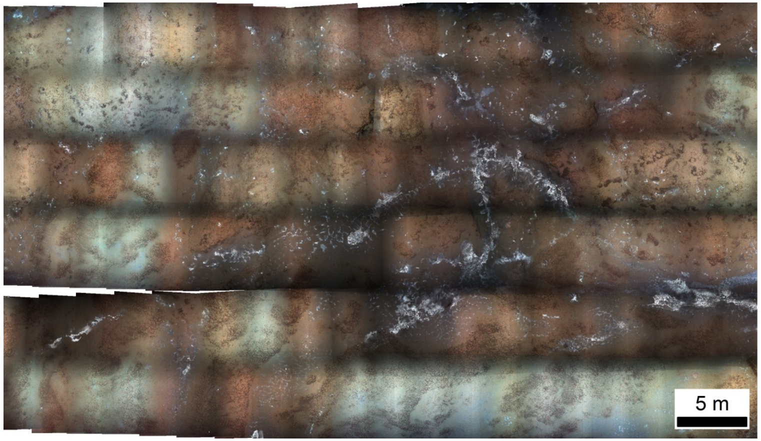


Fig. 13. Excerpt of the photo-mosaic of Håkon-Mosby Mud Volcano; the continuity of the *Beggiatoa* mats (white patches) and pogonophoran (brown patches) distribution across the mosaic indicates that images were accurately registered.