European Commission

Sensor Tracking and Mapping (STeAM)

Release 2.3.3

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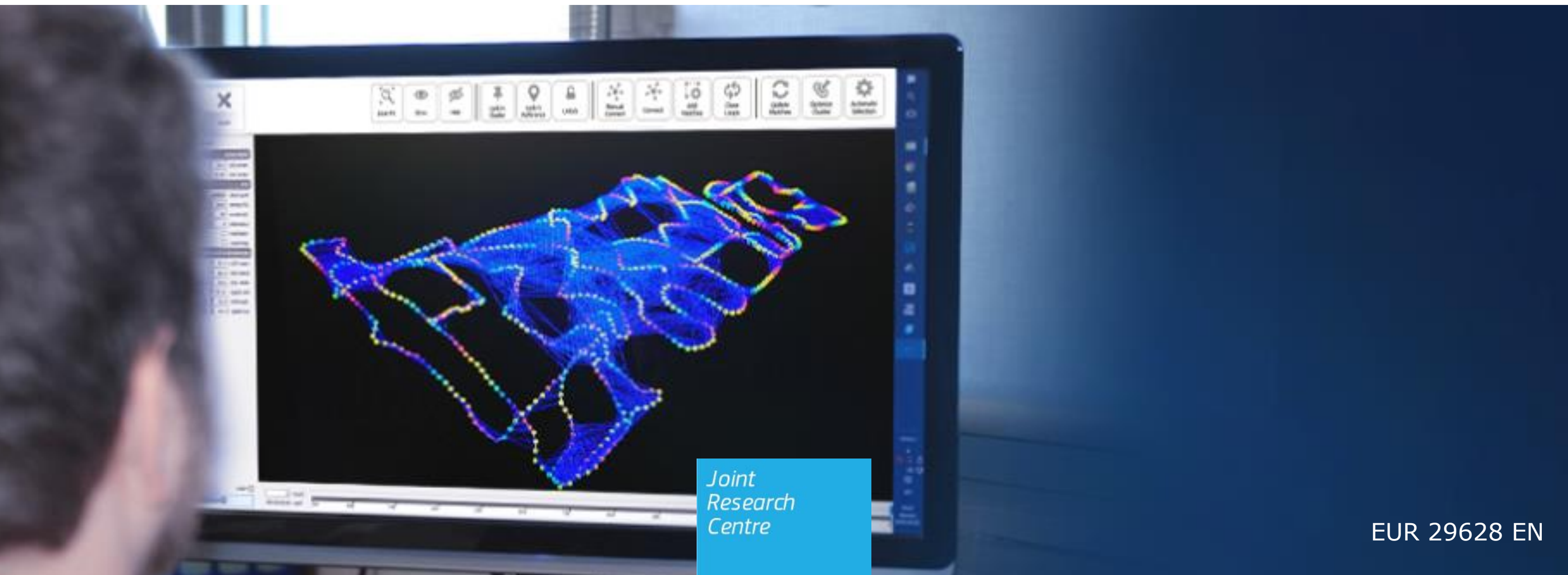
2018



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Abstract

STeAM (Sensor Tracking and Mapping) is a software suite developed at the JRC, which is used to operate its Mobile Laser Scanning Platform (MLSP) and to process the scan data acquired by the system. MLSP/STeAM are used by nuclear safeguards inspectors during on-site inspections and it is commercially available for non-nuclear applications through a JRC license agreement.

This report provides an overview of the STeAM software and the new features introduced in STeAM 2.3.3.

1 Introduction

JRC's *Mobile Laser Scanning Platform* (MLSP) acquires a 3D model of the environment using a real-time 3D laser scanner mounted on a backpack. STeAM is the related software suite that was developed to operate MLSP and process the acquired 3D scan data.

Figure 1: User carrying the STeAM backpack.

MLSP/STeAM is based on 3D SLAM (Simultaneous Localization and Mapping) technology: the laser scanner acquires several 3D scans per second; by aligning consecutive scans to each other, it is possible to build a 3D map as the sensor moves through the environment [1]. In addition to the 3D map, SLAM generates the trajectory of the sensor, which allows to location-tag any auxiliary information collected during the acquisition. STeAM operates in two modes: the *Mapping* mode is used to generate a 3D map of a previously unknown environment. In the *Tracking* mode, the acquired data is aligned in-real time with a pre-loaded reference map; any geometrical changes with respect to the reference are highlighted to the user. One of the key benefits of the system is that it does not rely on global positioning sensors, so it can work in GPS-denied environments (i.e. indoor or underground environments).

STeAM comprises three main components:

- **STeAM Server** runs on the integrated MSLP backpack PC, controls the MLSP sensors, receives the data and stores them on the local disc. It carries out basic data processing to generate initial results that are sent to the *STeAM Live* client for preview and analysis purposes.
- The **STeAM Live** client is the graphical user interface running on the tablet PC during data acquisition, which allows the user to send commands for controlling the server (e.g. start/stop) and receive feedback from the acquisition. When working in *Tracking* mode, the live client performs and visualizes the change detection analysis results in real-time.
- The **STeAM Desktop** application is a post-processing software to refine the live results provided by the MLSP. It aligns scan data acquired with the backpack and corrects the drift that is accumulated over time. STeAM Desktop can also import point clouds from other sensors, such as static laser scanners or drone-based photogrammetry, and merge all sources into a single point cloud.

STeAM/MLSP has been developed for nuclear safeguards applications, e.g. for design information verification and change monitoring and is being used by Euratom and IAEA inspectors, for example in the Finish underground repository for the disposal of spent nuclear fuel [2].

STeAM is also used for the documentation and characterization of JRC's nuclear facilities which currently undergo decommissioning. Present activities focus on the alignment of static scan data, the use of mobile scan data is foreseen for the future.

MLSP/STeAM has applications in many other domains. JRC has patented MLSP/STeAM [3] and concluded a license agreement with an Italian SME (Gexcel Srl), which covers the commercialization in non-nuclear applications (under the product name *Heron*[1]).

The remainder of this note provides an overview of STeAM and lists the new features of version 2.3.3, which was released to internal and external customers during the summer 2018.

[1] https://gexcel.it/en/solutions/heron-mobile-mapping

2 MLSP Hardware

In the standard configuration, the laser sensor is mounted on a backpack and the data is acquired while the user walks through the environment. A 360 panoramic camera captures colour information which is geometrically and temporally aligned with the 3D data. An Inertial Measurement Unit (IMU) is integrated to support the data processing. The backpack includes a single-board PC running the STeAM server software.

A tablet PC is connected to the backpack through an Ethernet cable. It runs STeAM Live and serves as interface to the user.

After the data acquisition, the raw data is transferred to a processing PC which runs the STeAM Desktop software for generating the final 3D map.

Figure 2 shows the components of the standard MLSP configuration and illustrates the data exchanged between them.

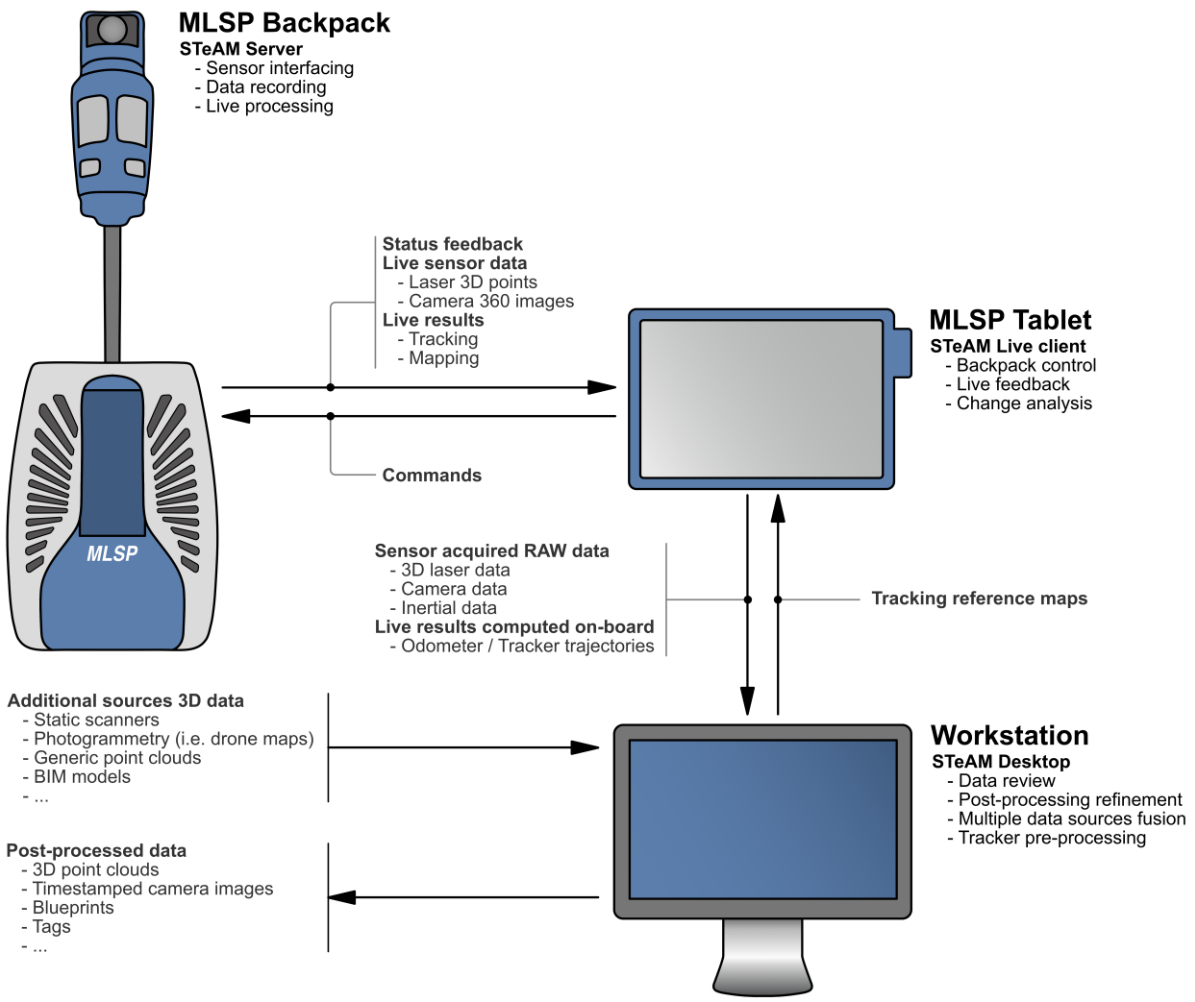

Figure 2: Overview of MLSP components and related data exchange.

3 STeAM Server

STeAM Server runs on the MLSP backpack. It connects to the sensors and receives and stores the raw data for later post-processing. The following sensors are included:

- A 3D laser scanner which provides the central data source for the SLAM processing. Two different models are currently supported: Velodyne HDL-32E and Velodyne-Puck. In the current configuration, the scanners acquire 12 scans per second.
- An Inertial Measurement Unit (IMU) which aids the SLAM algorithm. Currently, STeAM supports the XSens MTi 10 and 100 series.
- A 360° panoramic camera to provide colour information that is aligned with the 3D data. STeAM uses the UVC (USB Video Class) streaming protocol. In combination with a video capture card, it is possible to support all cameras streaming over USB or HDMI connection. The current setup uses a Garmin Virb 360°. The temporal and spatial resolution is configurable and has to be selected in order not to exceed the bandwidth limitations of the backpack PC. The standard setting acquires 12 images per second (approximately one image per scan) at FullHD.

STeAM server also performs basic processing to provide feedback to the user: if the system is running in *Tracking* mode, the sensor position is tracked by aligning the current scan with the reference map. In *Mapping* mode, STeAM runs an *Odometer* algorithm to compute the trajectory of the sensor by aligning successive scans to each other. In order to comply with real-time constraints, this preview trajectory is computed with low accuracy and might be subject to drift over time.

STeAM Server communicates with STeAM Live over a TCP/IP connection:

- STeAM server sends preview information to STeAM Live: the raw 3D and colour information (in reduced format to limit the required bandwidth) and the results of the data processing, i.e. the current pose of the sensor according to the tracking/odometer results.
- It receives command messages from STeAM Live, e.g. to start/stop an acquisition, to load a reference map for the *Tracking* mode or to add tag information to the acquired data.

STeAM Server creates a folder for each acquisition where it stores all acquired data in a pre-defined structure. STeAM Live is responsible for transferring the data after the acquisition (see next section).

4 STeAM Live

STeAM Live runs on the tablet PC that is used to control the acquisition and display live feedback. It can run in *Mapping* and *Tracking* mode:

In *Mapping* mode, *STeAM Live* receives the real-time 3D scan data and corresponding pose information from STeAM server. The scans are visualized in a common coordinate frame and the map is being built up as the user walks through the environment. It also receives and displays the image stream acquired with the panoramic camera. STeAM Live allows to start and stop an acquisition and to insert localized tag information that is stored on the backpack (see Figure 3).

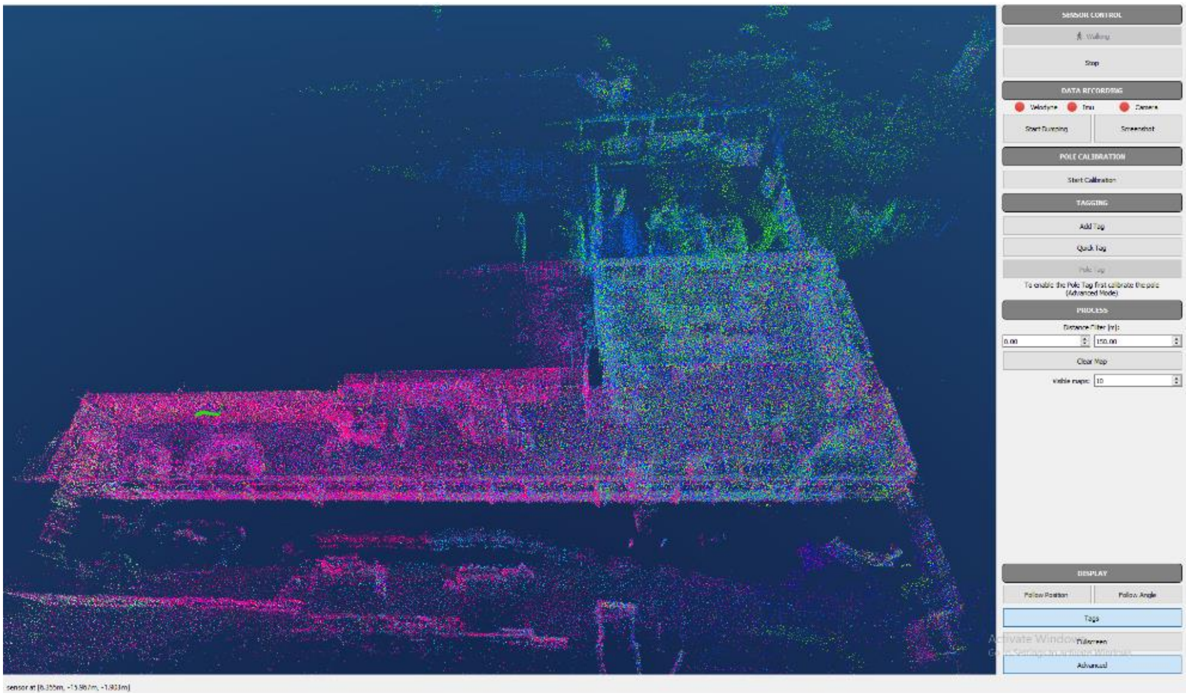

Figure 3: Snapshot of the MLSP interface as it is provided to the user in real-time for the Mapping use case. The main window shows a preview of the acquired point cloud; the panel on the right contains the buttons for controlling the backpack.

In *Tracking* mode, *Steam Live* receives the real-time scan data in the same coordinate frame as the reference map and calculates - for each scan point – the distance to the closest point in the reference map. The points are then colour-coded according to the distance. The result is a 3D change map, where points that have changed with respect to the reference map are shown in red, points that have not changed are shown in green as shown in Figure 4. See [4, 5] for technical details.

STeAM Live also includes the functionality to export the acquired data to an external drive for post-processing in STeAM Desktop and to import the reference maps that are required for the *Tracking* mode.

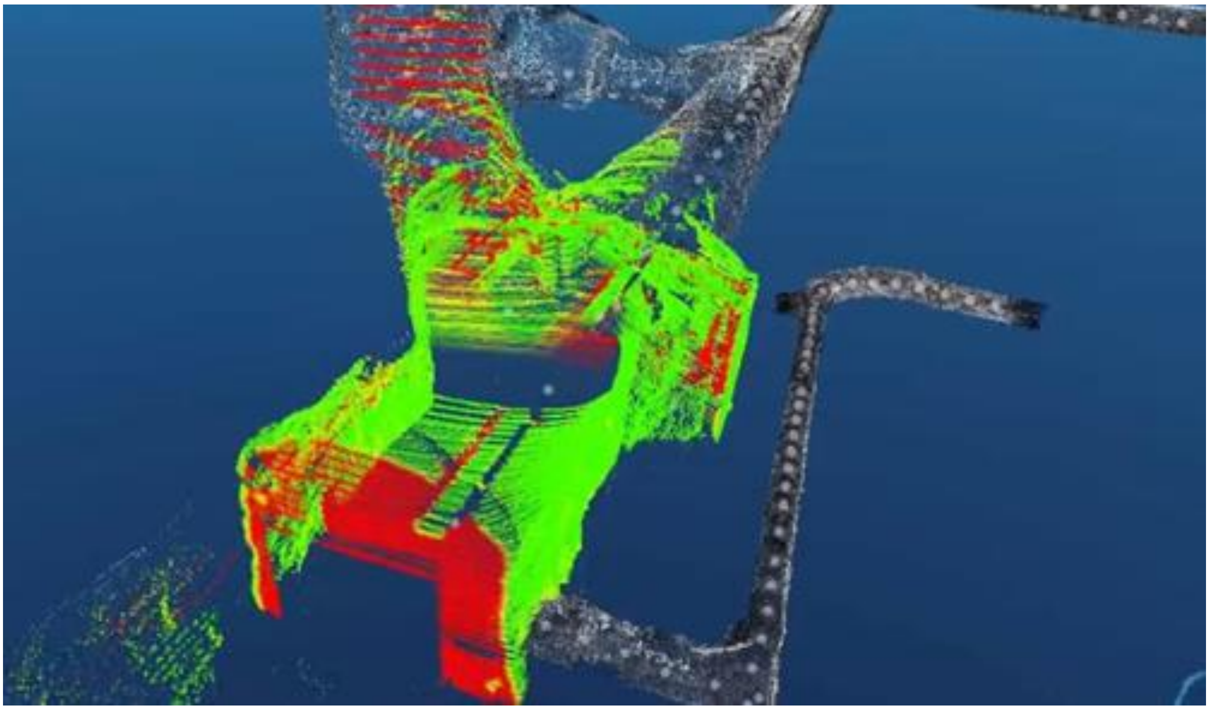

Figure 4: Snapshot of the MLSP interface as it is provided to the user in real-time for the change analysis in a tunnel environment. The reference map is shown in grey. The live data is color-coded as follows: green corresponds to objects that already existed in the reference (i.e. the main tunnel excavation); red corresponds to changes (e.g. the fire door that was constructed after the reference map was acquired).

5 STeAM Desktop

The main task of STeAM Desktop is the registration of scan data to generate a final 3D point cloud. Initially, it was developed to process the mobile scan data acquired with MLSP, but it has now been extended to include also other point cloud data acquired for example with static 3D laser scanners or with drone-based photogrammetry. The processing pipeline consists of following steps: *Odometer*, *Local Maps*, *Global Optimization*, *Export*. Depending on the complexity of the acquisition and the environment, the steps can be executed in a completely automatic batch process or, if necessary, as an interactive process. The remainder of the section explains the processing pipeline (see Figure 5) and other, optional functionality.

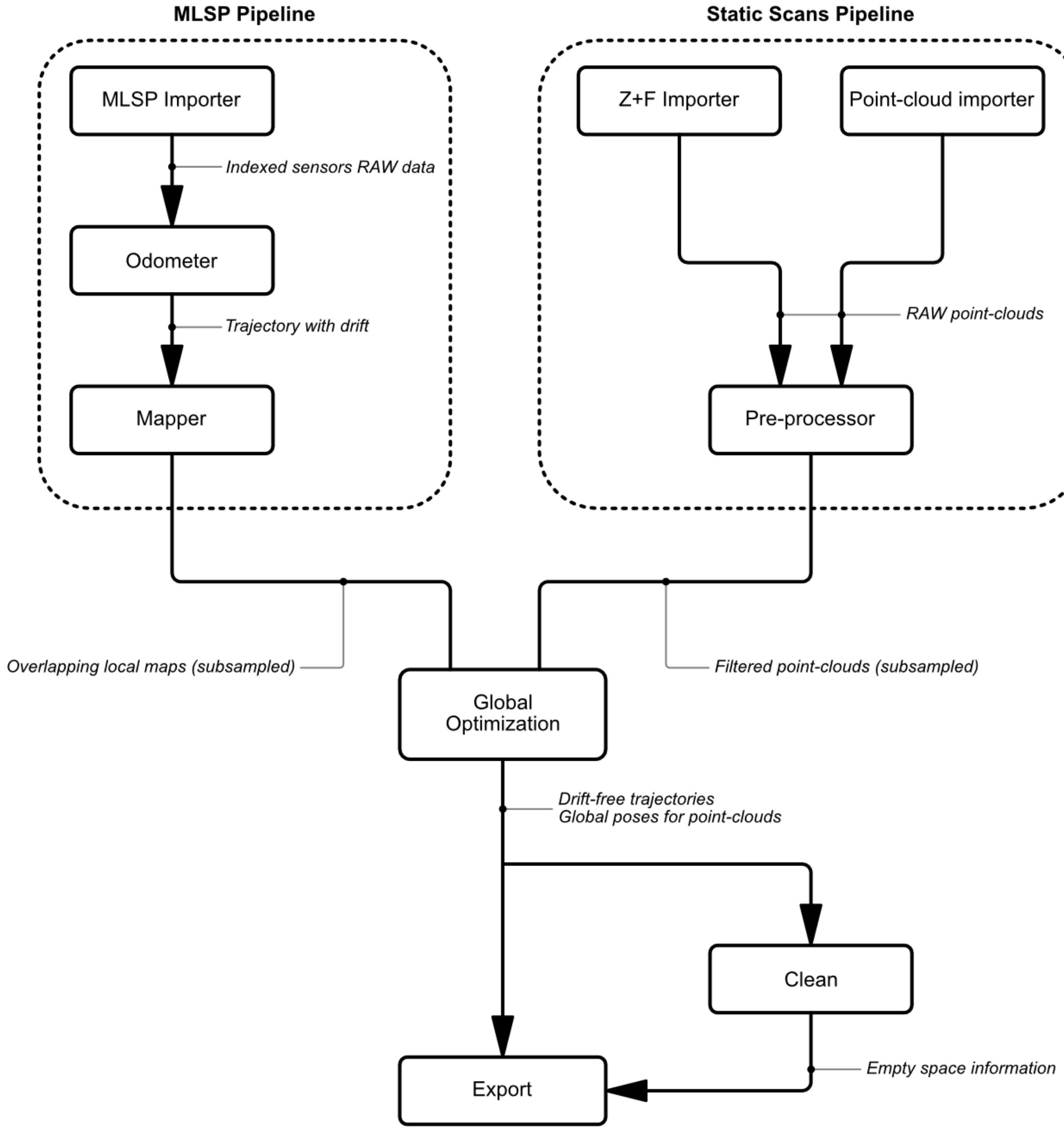

Figure 5: STeAM Desktop processing pipeline.

5.1 Odometer

The Odometer is applied to the mobile scan data acquired with the MLSP. Each 3D scan is consecutively aligned with the previous ones to construct the trajectory of the sensor during the acquisition and therefore the 3D map of the environment. Figure 6 illustrates the Odometer process.

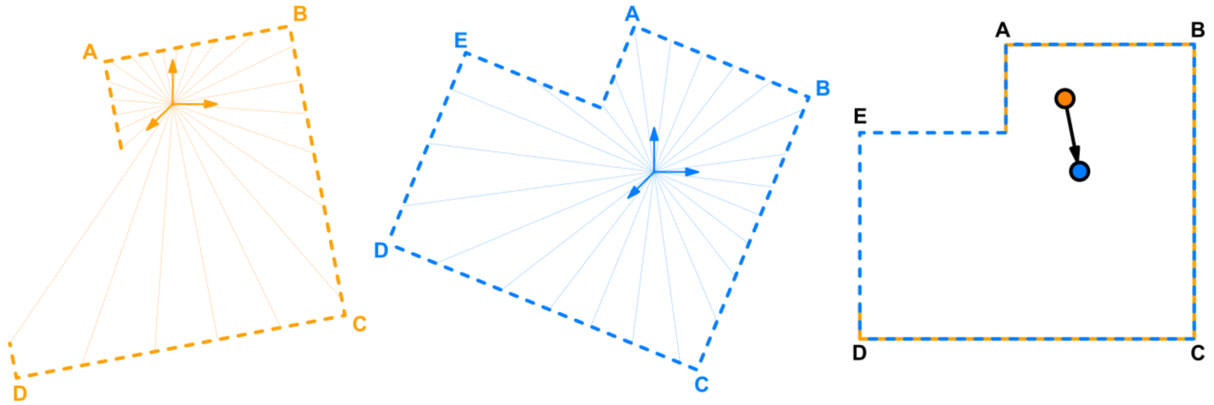

Figure 6: Illustration of the odometer process. (left) 3D scan acquired by the MLSP at a given time. Room corners are named with letters. (middle) 3D scan acquired by the MLSP at the subsequent location. (right) both 3D scans geometrically aligned and trajectory computed by the odometer from the alignment transformation (black arrow connecting the orange and blue circles)

The *Odometer* is equivalent to the process executed during data acquisition on the STeAM Server; however, it uses different parameters to improve robustness and minimize the drift over time as it is not constrained by the real-time requirements. Some drift does nevertheless remain and is addressed during the sub-sequent optimization process.

5.2 Local Maps

The *Global Optimization* aims to remove the drift that accumulates during the *Odometer* process. It is based on the assumption that the drift is locally negligible and only creates significant errors over longer time periods. Therefore, the trajectory is divided in small (partially overlapping) segments and a *Local Map* is created for each of them by cumulating the 3D points observed by the laser sensor during the time interval covered by each segment. Figure 7 shows several *Local Maps* created for one acquisition with different colours. Each *Local Map* is treated as a rigid point cloud in the following process.

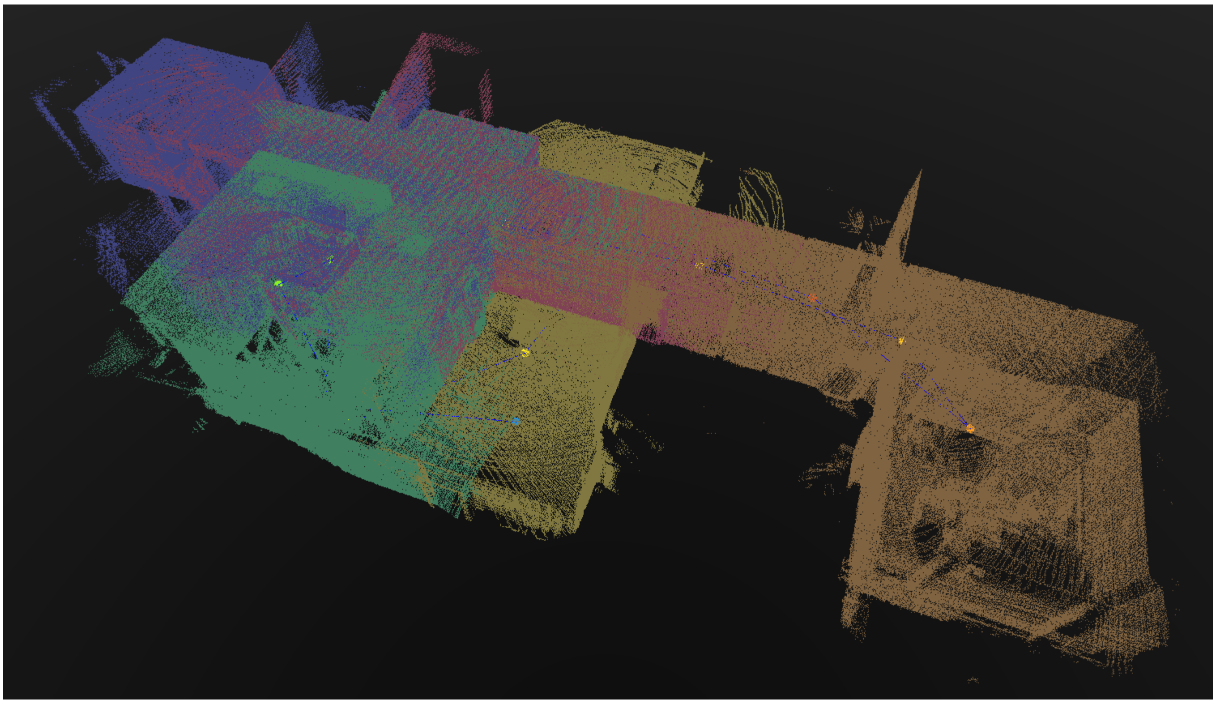

Figure 7: Local maps computed from an odometer trajectory. Big coloured dots represent the centre of each local map, connected with blue lines to express consecutivity.

5.3 Global Optimization

The *Global Optimization* aims to correct the drift error that was accumulated during the *Odometer* process and has two parts: *Loop Detection* and *Loop Closure*.

The *Loop Detection* recognizes if the trajectory re-visits a location that has already been acquired previously. If two *Local Maps* are identified as representing the same location, the algorithm computes the translation and rotation that is required to align the two *Local Maps*, which corresponds to the drift error accumulated by the *Odometer*. At this stage, it is also possible to join several trajectories obtained from different acquisitions.

During the *Loop Closure*, the position of all *Local Maps* is globally optimized so that the sum of the errors between all matching *Local Maps* is minimized. Figure 8 shows a trajectory before and after *Global Optimization.*

Since the *Global Optimization* works on a set of *Local Maps*, i.e. rigid point clouds, it is possible to include arbitrary static point clouds into the optimization process, i.e. the final global point cloud can be an integration of diverse data sources such as mobile laser scanning, static laser scanning or photogrammetry. See [6] for details.

It is also possible to '*lock*' a *Local Map* during the optimization, i.e. its position will remain unchanged. For example, one or more static scans can be geo-referenced in an external application and imported to *STeAM Desktop* with their global position. If those scans are locked during the *Global Optimization*, the remaining (mobile) scan data aligns with the locked scans resulting in a geo-referenced final point cloud.

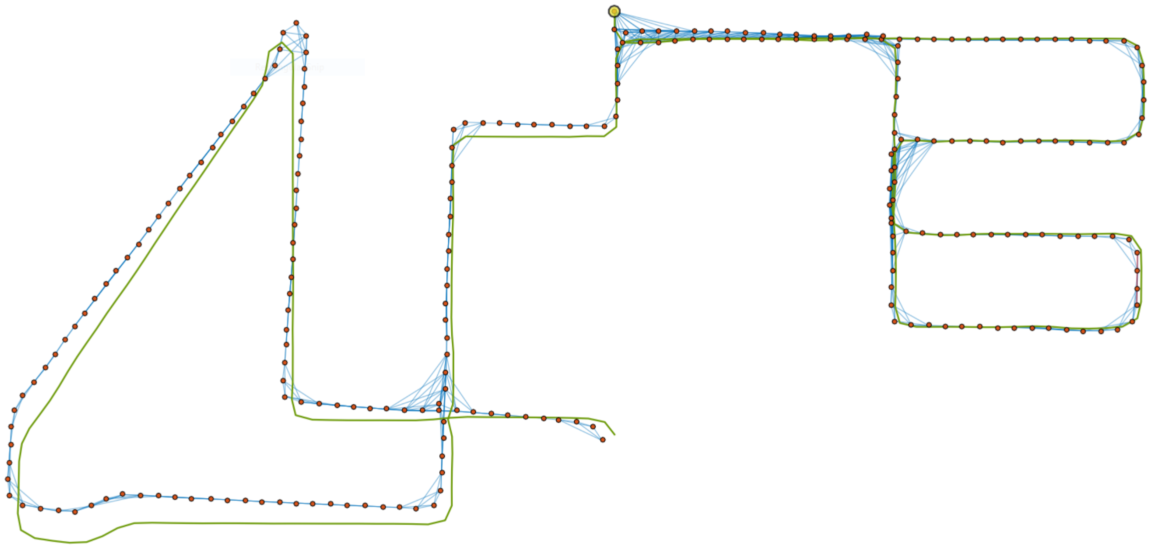

Figure 8: Sample trajectory before (green) and after (sequence of red dots) global optimization. Red dots represent the centres of the local maps used. Blue lines connecting red dots represent the loops detected and included in the optimization process.

5.4 Clean Data

Often it is not possible to avoid persons or cars moving through the environment that is being scanned with MLSP, which can create significant 'trails' in the final point cloud. *STeAM Desktop* contains a *Clean Data* functionality that aims to detect and remove points corresponding to moving objects. It is based on the fact that static objects are seen by the scanner repetitively at the same location while the scanner passes the object. On the other hand, moving objects change position between two consecutive scans, i.e. the location where the object was seen during the first scan is observed as empty during the next scan. Points which are not observed consistently over all scans are marked as '*moving object*' and can be removed from the final point cloud. Figure 9 shows an example of detecting moving points.

Figure 9: Results of the clean data classification. Points shaded in grey are the ones labelled as 'static', whilst red points correspond to 'moving' objects. The trails created by persons walking around during the acquisition were completely detected and, thus, removed in the final point-cloud.

5.5 Export and Data Access

The result of the *Global Optimization* is the trajectory that the sensor followed during data acquisition and – if static scans are part of the project – the scan positions. The final point cloud is generated during the *Export* by merging all the scan data into a single point cloud based on the computed trajectory. In order to reduce the size, the point cloud is voxelized (all points that fall in the same voxel are merged) using a user-defined resolution. The points are colourized using the image information obtained from the panoramic camera.

In order to achieve a tighter integration, third party applications can access directly the STeAM Desktop database, which includes the sensor trajectory (with time and position information) and all time-stamped data acquired with MLSP, e.g. the panoramic images and user-created tags. Using the time stamps and trajectory, third party applications can localize all data in 3D space and implement domain-specific analysis and review tools.

5.6 Create Reference

If a user wants to use a reference map for tracking and change analysis in *STeAM Live*, the corresponding point cloud needs to be pre-processed to create the data structures that allow real-time tracking in *STeAM Live*.

The reference point cloud can be generated with *STeAM Desktop* or can be imported from an external source. It is, for example, possible to generate a point cloud from a CAD/BIM model and use it as a reference in *STeAM Live* to monitor the progress on a construction site.

The pre-processing to create the reference map from a point cloud is a batch process that is launched from *STeAM Desktop*.

5.7 Offline Tracking

The tracking and change analysis is normally carried out in real-time in *STeAM Live*. In some cases, for example when the result of an inspection should be shared a-posteriori, it might however be useful to execute the tracking off-line in STeAM Desktop.

In that case, a reference map and the new MLSP acquisition are loaded into STeAM Desktop. The MLSP acquisition is not processed with the standard Odometer/Global Optimization pipeline, but tracked within the reference map. Differences between the two data sets are visualized for further analysis. The tracking result is a point cloud, which is perfectly aligned with the reference map and can be used to update the map and document changes over time (see Figure 10).

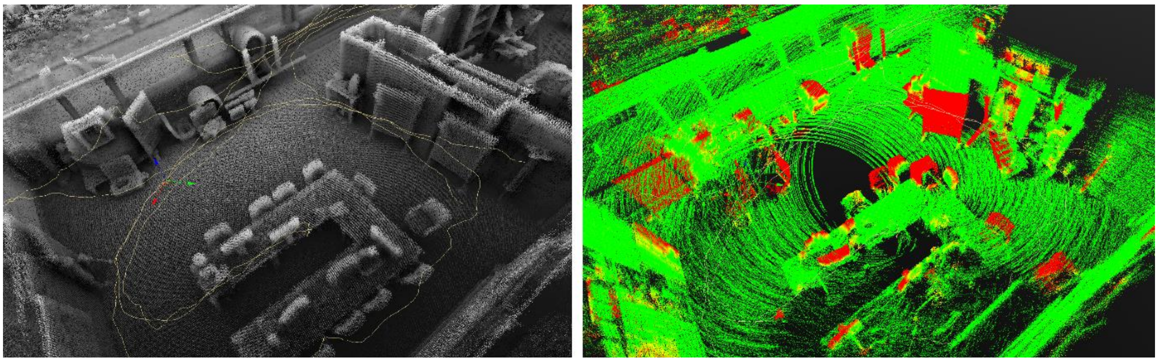

Figure 10: Results of the offline tracking: (left) reference model with the trajectory after tracking the new acquisition inside the map. (right) change detection visualization. Red points correspond to elements that are not present in the reference map, whilst green ones correspond to points observed by the sensor that match the reference map.

5.8 Data Review

Although STeAM Desktop is mainly intended as processing tool (i.e. for aligning scan data acquired with MLSP and external sources), it includes some basic data review tools. In particular, it allows browsing through the image data and user created tags using a time slider. The corresponding position is indicated in the 3D map (see Figure 11).

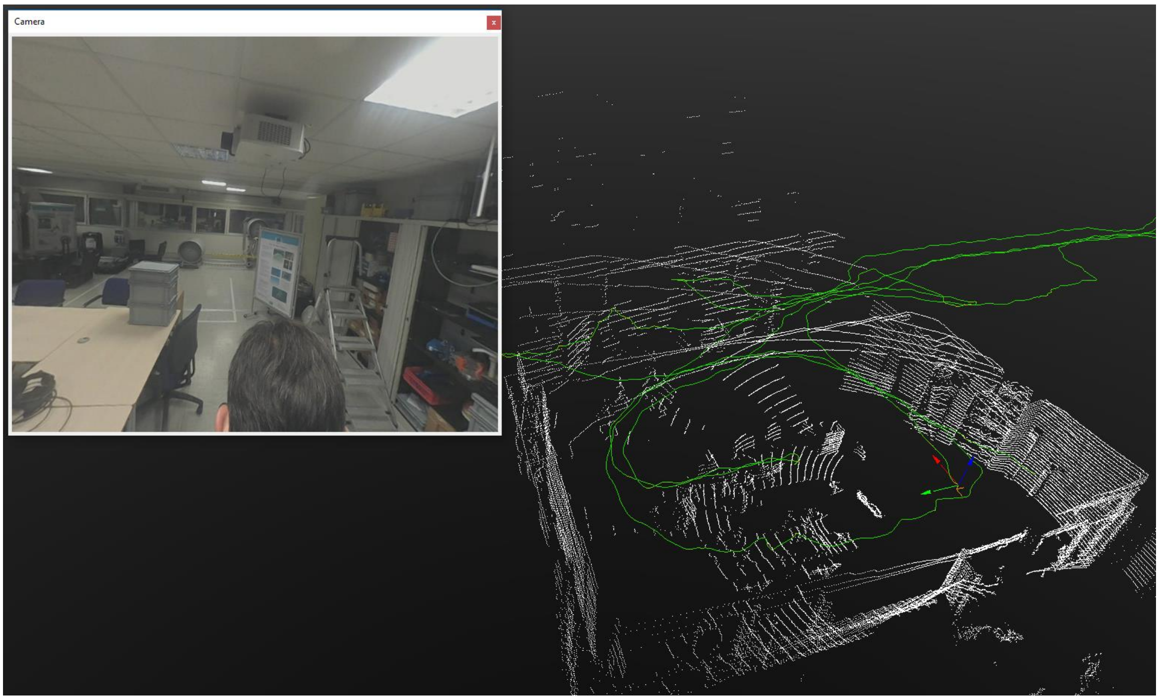

Figure 11: Review of video data. (top-left) spherical image acquired by the camera. (right) 3D point cloud acquired when the image was taken (white points), pose of the sensor at that time (blue/green/red arrows) and trajectory followed inside the building (green line).

6 Summary and Outlook

STeAM is a powerful tool for creating 3D point clouds from scan data acquired with JRC's Mobile Laser Scanning Platform (MLSP) and point clouds acquired with other sensors, such as static laser scanners or (drone) photogrammetry.

JRC developed STeAM for nuclear safeguards applications, in particular design information verification. As it also has numerous applications in the non-nuclear domain, the system has been made available commercially through a license agreement.

In future developments, STeAM will support additional sensors (e.g. two laser scanners to increase the field of view of the system). It is also planned to extend the *Global Optimization* process to include additional constraints, e.g. global reference points, during the optimization.

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Annex 1: New Features in STeAM 2.3.3

STeAM 2.3.3 builds over the STeAM 2.3 architecture, introducing new features and improving the user experience. Main developments in this release are:

- General bug fixing and usability improvements according to the user feedback (European Commision / IAEA personnel) and by Gexcel Srl.

- Added support for static (Z+F) scanners through a direct importer in STeAM Desktop. The functionality was implemented in the context of the collaboration with JRC's nuclear decommissioning activities (JRC G.III.9).

- Improved workflow with static scans in the global optimization module by implementing a pre-alignment global registration technique. Published in the 15th International Conference on Intelligent Autonomous Systems [1].

- Improved registration accuracy when working with high-resolution/accuracy static scans. New implementation of the alignment algorithm (ICP) that benefits from the improved quality of the input point clouds.

- Development of an off-line tracker plugin for STeAM Desktop that allows reviewing and improving previous tracking surveys performed with the mobile system. The functionality will facilitate the DIV inspection at the Finish underground repository for the disposal of spent nuclear fuel: in addition to the life change analysis that is performed by the inspectors, it also enables the *a posteriori* review of the inspection data.

- Formalization of the STeAM Desktop database format in order to allow third party applications to benefit from the 3D registration techniques available in the tool.
    - Development of a bridge between STeAM Desktop and Gexcel Reconstructor to exploit this interface.
    - Integration of STeAM Desktop with the decommissioning technical application (MIDAS), to store registered 3D scans and mobile data into an online database.

- Development of a standalone, general-purpose communication library with the backpack to allow developing custom live clients with extended/simplified functionalities. A sample application has been developed for documentation purposes to illustrate the use of the entire interface of the communications library.

- Development of a STeAM Desktop legacy converter tool to provide backward compatibility with previous versions of the application.

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