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THERMOGRAPHIC ANALYSIS FROM UAV PLATFORMS FOR ENERGY EFFICIENCY RETROFIT APPLICATIONS

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Thermal efficiency of building is a fundamental aspect in different countries to reach energy consumption reduction. However, even if a great attention is paid to build new "zero-energy" buildings, low attention is paid to retrofit existing ones. A fast analysis of existing buildings with Infrared Thermography (IRT) has proved to be an adequate and efficient technique. Indeed, IRT can be used to determine energy efficiency and to detect defects like thermal bridges and heat losses. However, both surface temperature and geometry are needed for a reliable evaluation of thermal efficiency, where spatial relationships are important to localize thermal defects and quantify the affected surfaces. For this reason, integration between Building Information Models (BIMs) and Infrared Thermography (IRT) can be a powerful tool to combine geometric information with thermal data in the same model. In this paper a methodology for automated generation of 3D model of buildings from laser data and integration with thermal images is presented. The developed methodology allows also fusion of thermal data acquired from different cameras and platforms. In particular, this paper will focus on thermal images acquired by an Unmanned Aerial Vehicle (UAV). The proposed methodology is suitable for fast building inspections aimed at detecting the thermal anomalies in a construction. Its applicability was tested on different buildings demonstrating the performance of the procedure and its valid support in thermal surveys.

Key words: Building models, infrared imaging, image processing, laser scanning, retrofitting

1 Introduction

In many countries all over the word reduction of energy consumption and increase of efficiency in exploiting natural energy sources is playing an important role in national authority legislation (for example, the European Union fixed ambitious climate and energy targets for 2020). These targets, known as the "20-20-20" targets, are:

- a 20% reduction in EU greenhouse gas emissions from 1990 levels;
- raising the share of EU energy consumption produced from renewable resources to 20%;
- a 20% improvement in the EU's energy efficiency.

To meet these targets a significant role is played by energy efficient buildings. A building (either a new or a retrofitted one) can be defined as energy efficient if it is designed to provide a significant reduction of the energy needed for heating and cooling. In particular, energetic qualification of building, based on energy consumption as described in directives such as 2010/31/CE [1] for the European Union, become a standard to identify thermal efficiency.

Even if a great attention is paid to build new "zero-energy" buildings [2] also the retrofitting of existing buildings plays a fundamental role to reach the EU's target. For this reason the development of methodologies for a fast evaluation of thermal efficiency of existing buildings and technologies for their retrofit are increasing in interest [3], [4]. In particular, infrared thermography has proved to be an adequate technique for detection of thermal defects (air leaks, heat losses, and even structural defects such as cracks) [5]. The main advantage of thermography with respect to other surveying techniques is that the surface measurement is carried out in a continuous way, avoiding the need of measuring hundreds of points with a contact or infrared thermometer, and consequently reducing working time. However, even if a simple thermographic survey can give some information about thermal bridges, thermography alone does not allow the quantification of heat losses. The energy loss evaluation requires knowledge of both surface temperature and geometric data, i.e. the integration of thermal information with geometry is of primary importance. Building thermography is generally performed from the ground, but the development of micro Unmanned Aerial Vehicles (UAVs) in the last years opened new possibilities to IRT analysis [6], [7]. Indeed, UAVs allow exploring areas inaccessible from the ground like roofs. In addition the possibility to reduce the camera-object distance allows one to enhance the ground sampling distance (GSD). This effect is particularly evident in the case of tall buildings. In these cases images acquired from the ground may present a GSD of several centimetres at top floors, while the use of an UAV gives the chance to obtain a GSD uniform all over the building. Generally, UAVs are also equipped with a low cost GPS and an inertial system giving a coarse camera orientation that can be used for fast image processing or added as pseudo-observation in bundle adjustment.

Geometric models of building are generally derived either from construction drawings, in the case they are available and reliable, or starting from an ad-hoc survey. In recent years, terrestrial laser scanning (TLS) technology became popular not only in heritage applications [8] (where surfaces are complex and irregular) but also in civil engineering for producing as-built models of large structures. The popularity gained by TLS is related to the fact that a laser scanning instrument can acquire a high number of measurements of the building surfaces that is represented in a point cloud form. However, even if point clouds can be adequate for a rapid and general visualization, these raw data are generally not directly used for practical applications. This is due to the nature of point clouds, which is not associated with any topological relations and presents a very low level of abstraction for exhaustive analysis (for example area measurement). In addition, further problems arise due to the huge size of data to be managed. For these reasons the point cloud is generally vectorized.

In particular, nowadays great attention is paid to Building Information Models (BIMs) generation from laser scanning data. According to [9] a "Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition." As can be clearly seen from this definition (in contrast to traditional building design approaches) a BIM model is much more than a simple geometrical model. A BIM Model manages not only graphics, but also information that allows the automatic generation of drawings and reports, design analysis, schedule simulation, facilities management, and more. Last but not least it enables the building team to make better-informed decisions. In particular, the BIM logic is based not only on a 3D building geometry but also on semantic and descriptive information. Therefore, BIM models covers more than just building geometry [10]; they are a combination of objects, relations and attributes. Finally, the use of BIMs goes beyond the planning and design phase of the project, extending throughout the building life cycle of the building (design/build/operations).

This paper presents a methodology for the combination of thermal images and building models by generating a thermographic textured 3D BIM model of a building for supporting its energetic efficiency evaluation. In particular, thermal images used to generate the textured model will be acquired both from the ground and from a UAV platform.

In Section 2 an overview of the developed methodology is presented. Then in Section 3 the procedure for thermal image acquisition from UAV, IR camera intrinsic calibration and thermal image orientation are discussed. Section 4 describes the procedure for automatic generation of 3D semantic building models. Section 5 presents two practical applications showing the effective usefulness of the entire workflow.

2 Workflow of the presented methodology

As previously anticipated the integration between thermal data and geometry of the building is obtained by mapping thermal images on the 3D semantically enriched model of the building. In particular, the procedure can be divided into two main parts: thermographic image processing and automatic façade model generation (Fig. 1).

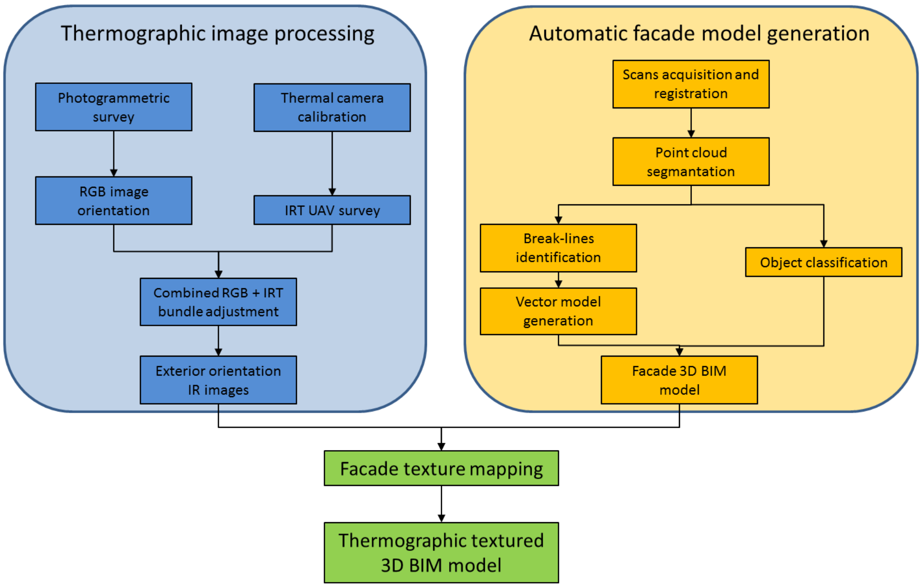


Figure 1 Workflow of the proposed methodology for the generation of a thermographic textured 3D as-built BIM model.

The thermographic image processing phase starts from thermal image acquisition (with the UAV) up to thermal image orientation. Indeed, although UAV platforms are generally equipped with on-board GNSS and IMU sensors they are usually not accurate enough for direct geo-referencing of acquired images. For this reason, to obtain the co-registration of thermogrphies with the 3D building model, thermal images are processed with some RGB images into a combined bundle adjustment. Indeed, this combined adjustment proved being more robust with respect to the simple adjustment of thermal images only. However, an image orientation strategies based on a photogrammetric bundle adjustment presents several challenges due to some peculiarity of thermal images: (i) the low resolution of thermal cameras, (ii) the need of an adequate internal camera calibration, and (iii) the limited local contrast of thermal images. All these issues are discussed in Section 3.

The generation of the building model is performed in an automated way by using an ad-hoc developed strategy [11]. Firstly, the entire point cloud of the building façade acquired by a TLS is segmented into planar patches. Then starting from this subdivision façade break-lines are automatically extracted by using the detected patches and enforcing some priors about architectural scenes (like the prevalence of straight lines and orthogonal intersection between surfaces). Finally, in a further classification the detected elements are classified into façade features (walls, doors, windows, etc.) and a final semantic 3D building model of the facade is generated in .ifc and .gml format.

Once these two parallel processing are completed integration between the two data is performed by texturing the building model with thermal image obtaining in this way a thermal textured 3D model of the building in a BIM format.

3 Thermographic image processing

This section presents the procedure developed to register thermal images acquired from a UAV with a 3D façade model. The developed procedure include IR image acquisition, IR camera intrinsic calibration and image orientation.

3.1 UAV thermal images acquisition

The thermographic survey of façade buildings is carried out with the UAV platform AscTec Falcon 8 (Fig. 2).

	FLIR Tau 640
Information	TIR
Focal length	19 mm
Resolution (pix)	640 x 512 pixel
Pixel size	17 µm

Table 1 Characteristics of the thermal camera FLIR Tau 640 used.

The Falcon 8 (70 cm x 60 cm, weight 2 kg) is equipped with 8 motors and is able to fly up to 20 minutes with a single battery. The system presents an actively stabilized camera systems that allows mounting different payloads. In particular, in our tests we used a RGB camera Sony NEX-

5N photogrammetrically calibrated and a thermal camera a FLIR Tau 640 (Table 1), equipped with a 19 mm lens system. The camera sensor is a vanadium oxide microbolometer sensitive to wavelengths in the range 7.5 - 13.5 µm.

Figure 2 The ASCTEC Falcon 8 equipped with a FLIR Tau 640 thermal camera.

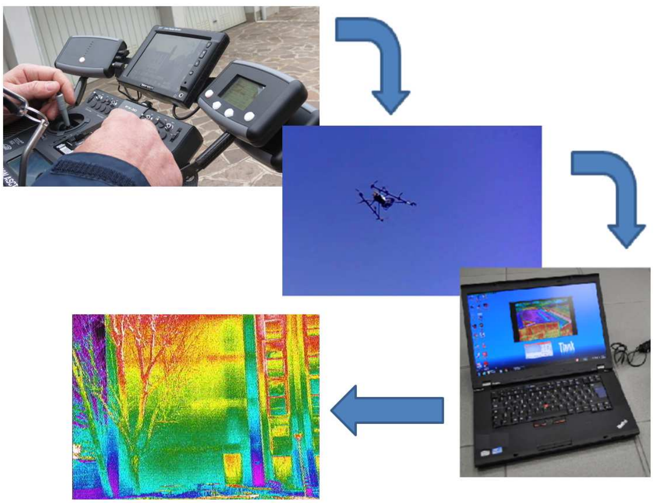


Figure 3 The thermal image acquisition procedure with the Falcon 8 system.

The electronic equipment of the Falcon 8 includes a GPS antenna and a system of accelerometers determining the system roll, pitch and yaw. The communication system allows the ground station to receive telemetry data and video signals from the on-board sensors. During the survey the UAV can be remotely controlled by a human operator while thermal images were acquired by using a laptop to record the video signal from the thermal camera (Fig. 3).

The GSD (i.e. the pixel size reprojected on the façade) was about 2.0 cm, i.e. sufficient to obtain a 1:100 orthophoto. Additional thermal images were also acquired from the ground to obtain more data and strengthen block geometry.

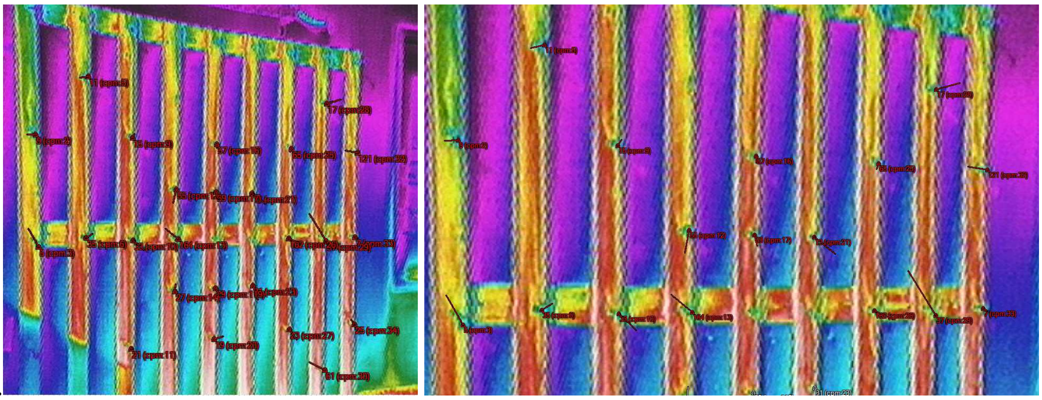
3.2 Thermal camera calibration

The intrinsic calibration of the camera used to acquire thermal images has to be determined in order to orient images by using a bundle block adjustment. This means that interior orientation parameters and additional parameters must be estimated to compensate for the effect of lens geometric distortion. In the case of IRT sensors, the *pinhole camera* model can be used and the calibration procedure follows the 8 parameter model [12] (principal distance, principal point coordinates, 3 coefficients for radial distortion compensation, and 2 parameters for decentering distortion). However, calibration of IRT cameras has several issues:

- geometric lens distortion is generally large, especially at the borders of the images;
- terrestrial thermals sensors generally have larger pixel size (one order of magnitude larger) then low-cost RGB cameras;
- in terrestrial applications the IR image resolution is generally less than 1 megapixel (e.g. 640x512 pix or even lower, except in some expensive sensors;
- the limited field of view (FoV) makes difficult to carry out a calibration project.

A further problem is connected to the difficulty in defining a calibration polygon clearly visible in the IR spectrum [13]. All these aspects should to be taken into account when performing a calibration of a thermal camera. To partially cope with these problems we used a calibration polygon made up of a wood frame, with a surface of about 2x4 m, with 40 nails. These nails have different lengths forming in this way a 3D calibration polygon (Fig. 4a). We used iron nails because they cool and heat faster than the supporting wood allowing a clear identification of the center of the nail heads. The calibration was then carried out by running a photogrammetric calibration project, where all calibration parameters are added as additional unknowns in bundle adjustment.

As shown in [14], the configuration of the block geometry has to follow particular requirements in terms of image overlap, camera orientation and position. In particular cameras should present a convergent geometry and a series of rolled images (i.e., in portrait position, being the others in landscape orientation) have to be added in the block to reduce correlation between calibration parameters. However, due to the characteristics of thermal camera and in particular to its limited field of view, a well convergent set of images is quite hard to be obtained resulting in lower calibration accuracy (Fig. 4.b).

a. 

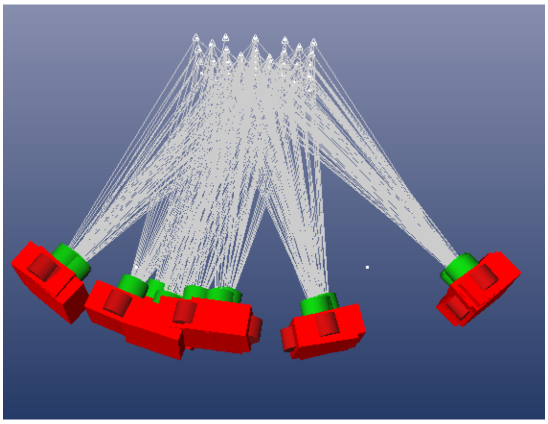
b. 

Figure 4 The calibration polygon used: red lines are a graphical representation of the residuals after calibration through bundle adjustment (a magnification factor 50 is applied) (top); camera stations for the calibration of the FLIR Tau 640 camera (bottom) and intersection in space of 3D rays.

3.3 Thermal image orientation

In the last step of the implemented pipeline thermal images are mapped on the 3D building model automatically derived from point cloud processing. The main issue for an accurate integration of these two different data is the co-registration of building model and thermal images. This task can be accomplished in different ways depending on the object geometry and the image acquisition scheme.

In many applications carried out in standard thermal surveys of buildings, registration is carried out by using homographic transformations independently estimated one for the different images [15]. Homography estimation requires the identification of at least four corresponding control points (CPs) on both image and object surface. However, this method is rigorous only in the case of planar façades. A more comprehensive approach for image registration is based on collinearity equations which are normally used in photogrammetry to describe the perspective transformation process behind image formation. In this case there are two opportunities: methods based on space resection techniques and methods based on bundle adjustment [16]. The former is more popular in most commercial software for texture mapping. In this case the registration of each image can be directly performed by using collinearity equations and by knowing coordinates of at least 3 GCPs (e.g., by using a theodolite or directly from the point cloud derived from TLS). Coordinates of GCPs have to be measured on the images as well to obtain an estimate of camera parameters (position and attitude). However, images are processed independently increasing the number of points to be measured on the images and determining some problems in overlapping areas between consecutive images.

In photogrammetry, a bundle adjustment approach is used to partially overcome these problems. Several images are registered in a common reference system through the solution of a linearized system of collinearity equations. The unknowns of the system are the six Exterior Orientation (EO) parameters of the images, while the intrinsic calibration parameters are usually considered as fixed after their estimate with a calibration project. Additional GCPs are used to control the solution and setup the reference system.

However, as thermographic cameras have intrinsic parameters similar to a telephoto lens (narrow FoV and long focal lens) it is rather difficult to obtain a block of thermal images suitable for a stable adjustment. Indeed, because of the limited field of view thermal image blocks generally present a low ratio between image baselines and camera-object distance. For this reason a simple bundle adjustment of thermal images could provide unreliable results. In this paper a different approach is used in order to avoid instability problems and increase precision of camera pose estimation. It relies on the combined use of thermal image and standard RGB data [17]. This solution allows a better control on the quality of results and reduces the number of points to be measured with respect to other traditional approaches based on space resection.

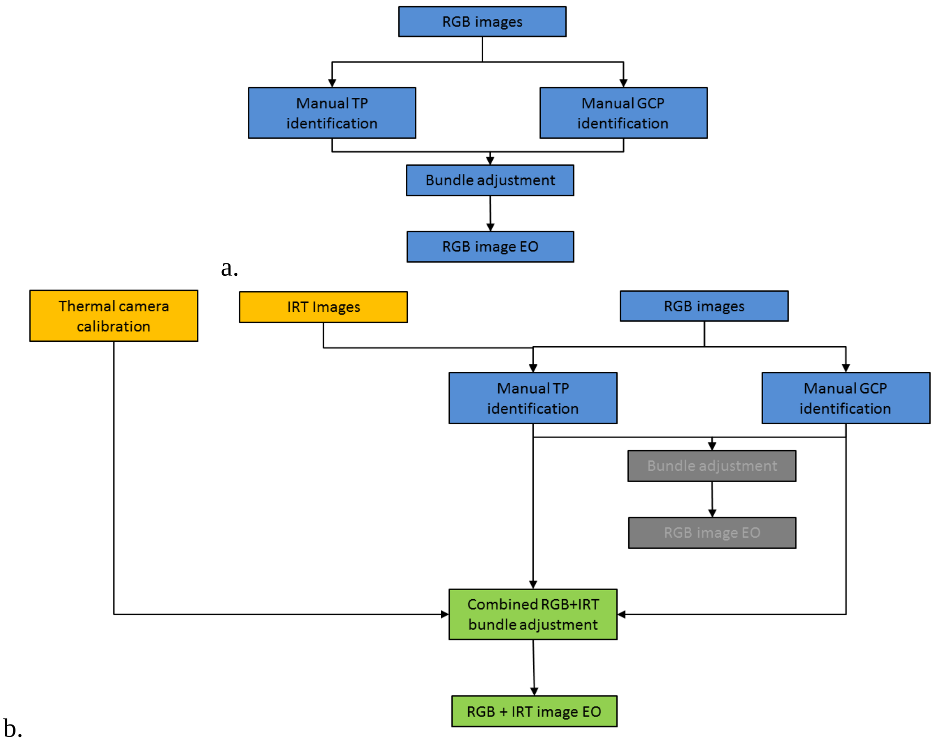


Figure 5 The first step of image orientation: only RGB images are processed (a); second step of image orientation: IRT images are added and a combined bundle adjustment is performed.

The procedure starts with the acquisition of an adequate set of RGB images with a calibrated camera. This means that the image block should satisfy the standard requirements of a close-range survey in terms of image overlap, baseline between consecutive images, and image resolution [18]. Then, RGB images are oriented within a standard photogrammetric bundle adjustment, which is based on a set of Tie Points (TPs) measured on the images, and some GCPs that are used to register the project in the reference system of the laser scans (Fig. 5a). An important consideration deserves to be mentioned: TPs individuated in this first step will be used for the registration of IR images. For this reason TPs should be preferably measured in correspondence of elements that are clearly visible in both RGB and IR images (e.g., windows and door corners).

After the registration of all RGB images IR images can be added to the block by measuring some tie points between RGB-to-thermal and thermal-to-thermal points. A final combined bundle adjustment including all images is finally carried out to obtain the EO parameters of all images simultaneously (Fig. 5b). This allows the creation of a more robust image block made up of both images, where RGB images strengthen the bundle adjustment solution and allow the estimation of reliable EO also for thermal images.

4 Automatic façade modelling

For the modelling of the façade a new automated procedure was specifically developed. This procedure uses as input an unorganized point cloud coming from TLS survey of an urban building façade. In particular, we focused on modern residential buildings which represent the majority of buildings to be retrofitted in Europe. This building type presents a dominant planar structure, characterized by a flat dominant surface and with other façade components having off-plane depth variations with respect to this plane, either positive (outwards) and negative (onwards). The automated façade modelling is performed by using the approach presented in [11]. Here only some aspects mainly related to thermal data integration are briefly described.

The developed modelling methodology can be applied to unstructured point cloud of tens of millions points. This means that each point is parameterized by its spatial coordinates and may also features some attributes (e.g., intensity or colour), but does not share any topological relationships with the points in its nearby. The input point cloud can be generated by a single or multiple laser scan station(s). Indeed, after scan registration/geo-referencing, scans are merged without needing any reorganization into a specific data structure.

The overall procedure is presented in Fig.1. Once all scans are acquired and registered together, the main elements constituting the façade are firstly identified by means of a segmentation process based on a modified RANSAC implementation. In particular, the standard RANSAC approach for point cloud segmentation is modified by adding the topology in the process. This topological information between scan points and detected clusters is added in order to minimize problems connected to under- and over-segmentation, respectively. Once planar clusters constituting the façade are detected, façade breaklines are automatically derived. During this phase some constraints related to façade geometry, like the prevalence of straight lines and orthogonal intersections, are enforced to obtain a regularization effect. At the same time, a further classification is performed, on the basis of some priors on the façade structure organized in a classification tree. In this way objects are classified into façade elements (e.g. walls, windows, etc.). Finally, breaklines are used to obtain the 3D geometry of the façade while classification results are used to enrich geometrical data with semantics and to generate a 3D BIM model of the entire façade.

The output of the classification phase are clusters and their labelling (façade objects) allowing the generation of a semantic enriched model. File formats supporting for semantic definition are relatively few. The two most prominent standards are Industry Foundation Classes (IFC) and City Geography Markup Language (CityGML) [19], [20]. In this paper we mostly focused on CityGML, which defines classes and relations for the most relevant objects in cities with respect to their geometrical, topological and semantic properties.

5 Data integration

The integration between thermograpic data and building geometry is performed by applying the thermographic images as a texture to the 3D model of the façade. This process is called *texture mapping*. In particular, once thermal images and 3D façade model are registered the correspondence between image pixels and the façade surface elements can be easily estimated by means of collinearity equations. Although some commercial software packages accomplish texture mapping (e.g., 3D Studio Max®, Geomagic® Studio, PhotoModeler® Scanner, ShapeTexture®, etc.) the process in many cases loses the advantages previously described for an image orientation phase based on a combined bundle adjustment. For this reason, an ad-hoc algorithm was implemented using as input the exterior orientation parameters of thermal cameras and the automatically generated façade model [21]. The implemented procedure can be split into two steps. Firstly, a visibility analysis for each image is performed, and then the proper texture is assigned to each visible surface.

The aim of the visibility analysis (step 1) is to detect occluded areas in the images. The basic idea of this analysis is to check if a surface can be seen from a viewpoint (defined by EO of thermal images). This check is performed to prevent erroneous texture assignments because of occluded areas. The main idea is simple: if an object surface is not visible from the defined viewpoint there will be at least another triangle of the mesh that gives the occlusion. This has a direct impact in the image space because it reflects the intersection between two back-projected surfaces. The distance of the surfaces and the viewpoint is used to distinguish between the occluded surface and the occluding one. In particular, the farther surface is occluded whereas the closer is the occluding one. After the assignment of the visible triangles from each camera position, the best texture for each surface is determined. Two quality parameters are considered for this choice: the resolution of the image in the object space and the camera viewing direction. The image whose quality parameters reach the maximum is used as texture. Finally, the texture coordinates for the triangle are calculated by back-projecting the triangle coordinates in the object space on the selected image by using collinearity equations.

6 Applications

In this section two complete case studies are presented to show the entire process demonstrating its technical applicability in thermal surveys. The case studies presented are buildings of the Politecnico di Milano university. The first one is termed “D’Oggiono Building” and is located in Lecco (Italy), while the second one is called “Edificio 21” and is located in the main campus in Milan.

6.1 D'Oggiono Building

The aim of this case study is the evaluation of the thermal efficiency of the building and the detection of potential thermal bridges. The laser scanning survey consisted in 2 scans of the building façade acquired by a FARO – CAM2 FOCUS 3D laser scanner. Each scan is made up of 44 million points with an average ground sampling distance of about 2 mm. Scan registration was performed by using as ground control points 14 checkerboard targets surveyed by a first order theodolite LeicaTS30 and by means of 6 sphere targets used to strengthen the relative referencing of the scans. The average referencing precision, evaluated observing residuals on the target measurements, is about 2.5 mm.

Scan processing was carried out by using the procedure presented in Section 3. In particular, 79 planar clusters were detected in the D'Oggiono building façade during the segmentation phase (Fig. 6).

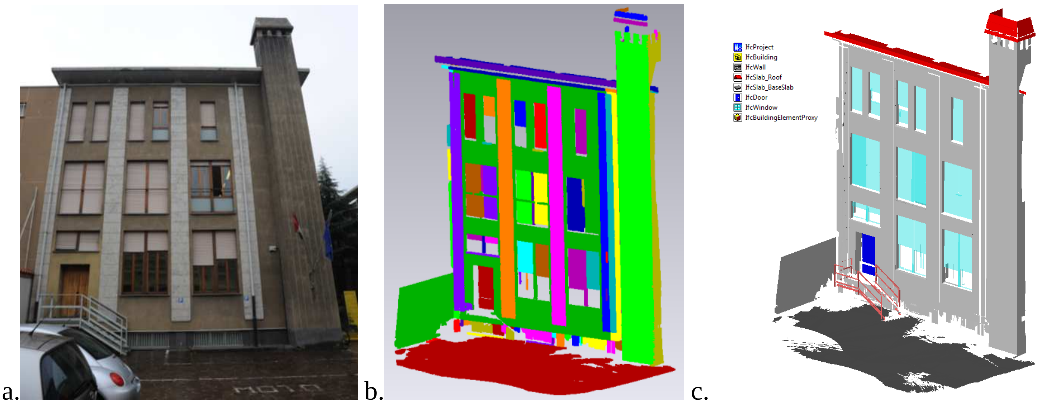


Figure 6 The D'Oggiono Building (a); segmented façade (b) and semantically enriched BIM model in .gml format (c).

The thermographic survey was carried out in December 2012 with a temperature of 2°C. 4 RGB and 3 thermal images were recorded from the UAV while 3 RGB and 1 addition thermal image were acquired from the ground. The checkerboard targets used for scans registration were also added as GCPs during bundle adjustment for RGB image only. In addition, 20 tie points in correspondence of window and door corners were manually measured on both RGB and thermal images to run the final bundle adjustment and obtain the EO parameters of all images. Statistics of the combined bundle adjustment show a final sigma-naught of about 0.9 pixels while accuracy of check points is about 1 mm in the façade plane and 3 mm in the perpendicular direction.

After the registration of thermal images the integration with the facade model is performed by means of the texture mapping algorithm described in Section 4. The final result is textured 3D BIM model. Finally, starting from the textured digital model an orthophoto (pixel size 2 cm) was obtained by projecting the model texture on a projection plane parallel to the main plane of the façade.

a. b. c.

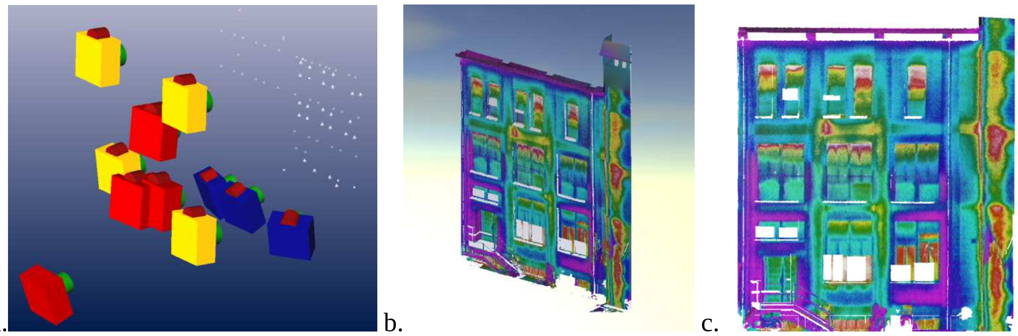


Figure 7 The "D'Oggiono Building" camera poses (thermal images in red), RGB acquired from the UAV (yellow) and RGB acquired from the ground (blue) (a); textured 3D façade model (b) and thermal orthophoto of the façade (c).

6.2. Edificio 21

The second test was carried out on a façade of the seven storey building named "Edificio 21" located at the Polimi Campus in Via Golgi 39, Milan. The chosen test façade presents existing precast panels at the two top floors, while the remaining part has a mortar finishing. An important issue related to the thermographic survey is the presences of a large tree just in front the façade, determining in this way large occlusions during thermal image acquisition (Fig. 8).

Data were registered in a common reference system by using 7 retro-reflective targets in the nearby of the building. Scans were registered with 8 checkerboard targets measured with a theodolite Leica TS30. The same points were also used for the RGB images, along with some additional natural points (e.g. windows and doors corners) measured also in IR images. The network scheme is presented in Fig. 9a. After network adjustment the estimated accuracy in retro reflective target measurements is 0.5 mm while checkerboard accuracy is about 2.0 mm.

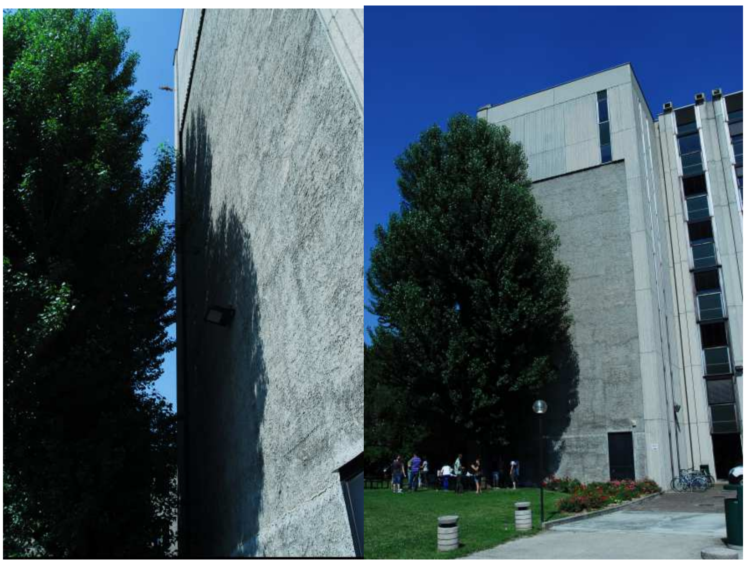


Figure 8 The Edificio 21 test façade.

The laser scanning survey consists in 3 scans (Fig. 9b) acquired from different standpoints in order to survey the entire western facades of the building. The GSD ranges from 1.5 mm in the lower part of the façade up to 3.5 – 4 mm in the upper part. As mentioned, scan referencing was performed by using as ground control points the checkerboard targets surveyed by theodolite and by means of 5 sphere targets used to strengthen the relative referencing of the scans. The mean referencing precision, evaluated observing the residuals on target measurements, is about 3 mm.

The photogrammetric survey, designed for a 1:50 scale, consists in 18 images acquired with a Nikon D700 camera equipped with a 35 mm lens. Image orientation was performed with Photo-Modeler 2012 and its aerial triangulation routine termed SmartMatch. Image orientation was firstly performed with a free-network adjustment by using more than 57,000 tie points identified by SIFT operator. Then, the exterior orientation parameters were computed using 10 natural points (e.g. windows and doors corners) measured with a theodolite Leica TS30 as GCPs. Sigma-naught of image block orientation is about 0.69 pixel (Fig. 10).

This test façade was used only to check the accuracy of extracted breaklines and segmentation procedure. The accuracy of laser scanning extracted breaklines and manual extracted ones showed mean discrepancies in the order of 3 mm, i.e. similar to the sampling resolution of the scanning survey.

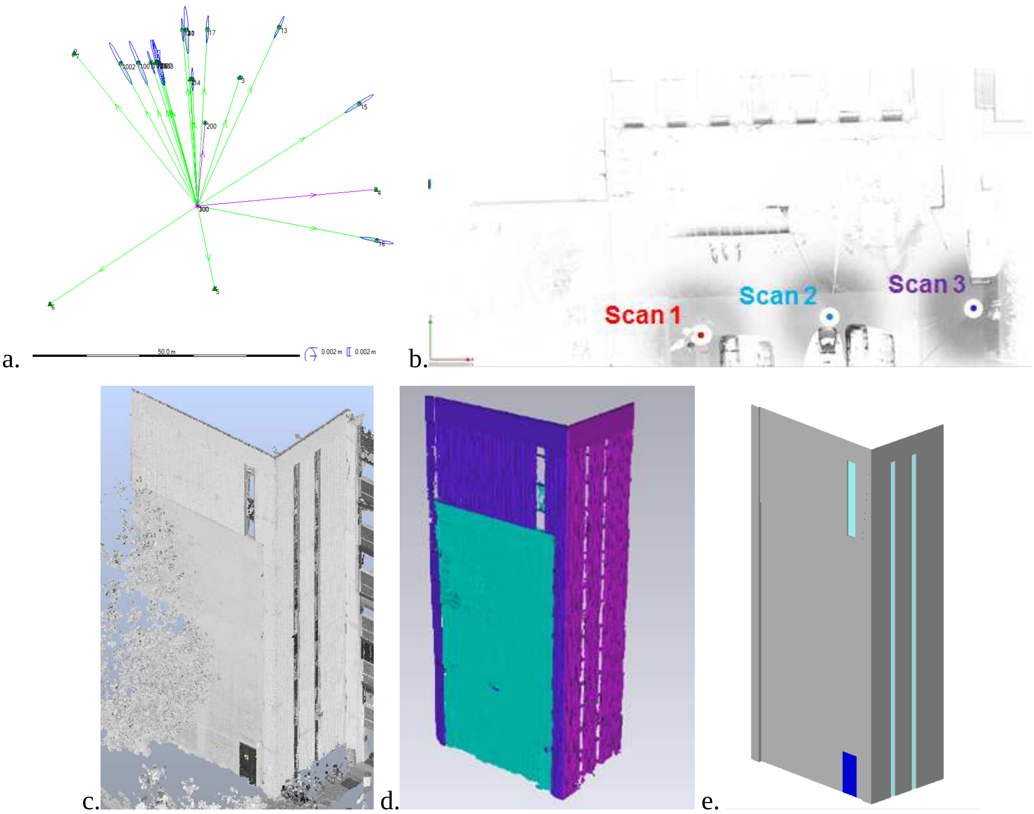


Figure 9 The geodetic network scheme with error ellipses (a); the scan position scheme (b); point cloud of the building façade (c); segmentation results (d) and semantically enriched model (e).

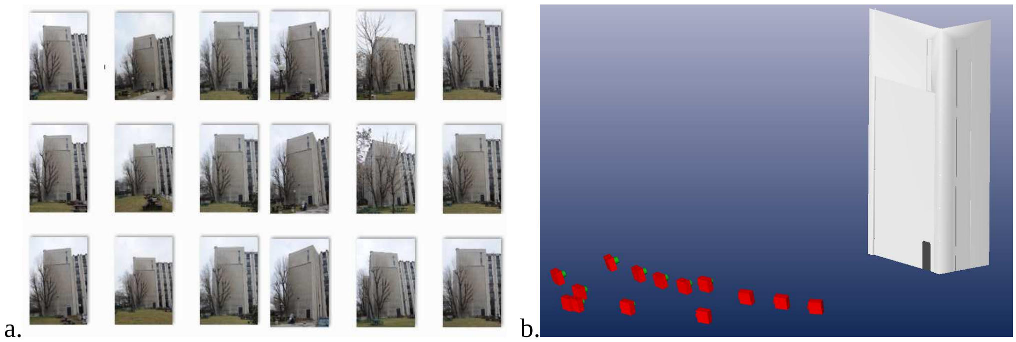


Figure 10 Images acquired for the Photogrammetric survey of the facade (a) and their poses after image orientation (b).

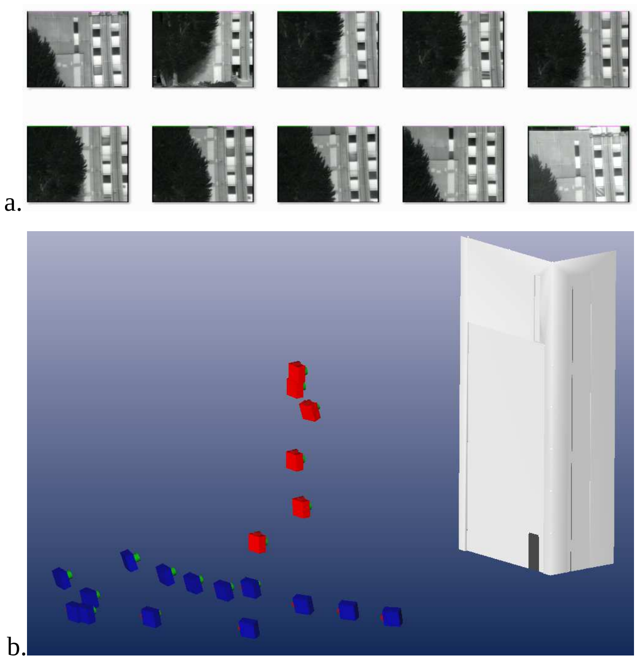


Figure 11 Thermal image processing: (a) the acquired thermal images, (b) camera poses: red cameras are IR images, whereas blue cameras represent RGB images.

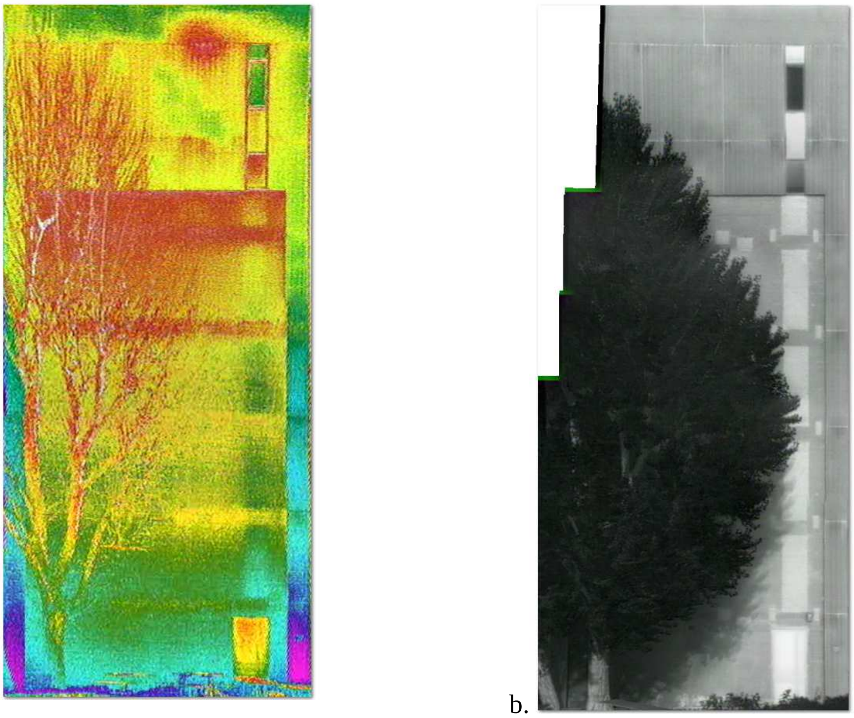
Two thermographic campaigns were performed, the first one in winter (March 16th, 2013), the second one in summer (July 9th, 2013). In both cases thermal images were acquired with the UAV following a vertical strip.

As described in Section 3 the orientation of these images were performed in two steps. Firstly, 14 RGB images acquired with a Nikon D700 were registered within a bundle adjustment. In this project 10 natural points (e.g. windows and doors corners) measured with a Leica TS30 were used as GCPs during bundle adjustment. Then, starting from using 30 TPs measured in the RGB images, 11 IR images were included in bundle adjustment. Statistics of the combined bundle adjustment show a final RMS of about 0.9 pixels (Fig. 11). This result can be considered as acceptable due to the low geometric resolution of IR images. In fact, the GSD of thermal images was about 2 cm while that of RGB images was 2 mm, highlighting one order of magnitude of difference.

An important remark concerns the identification of TPs on RGB and IR images. When IR images are used repeated elements, such as windows or doors, may determine some ambiguities in the identification of tie points.

After the registration of IR images in the same reference system of laser scanning point cloud, data can be mapped and mosaicked on the triangulated model of the façade, and then the final thermal orthoimages were derived by simply projecting the data on a plan parallel to the façade. Orthopotos shows the presence of some thermal anomalies on the façade. In particular, was put in evidence the presence of some closed doors and other objects that are not visible in standard RGB pictures (Fig. 12).

March 2013 July 2013



a. b.

Figure 12 Facade thermal orthophoto: March 2013 (a), July 2013 (b).

7 Conclusion

This paper presented an innovative procedure able to integrate IRT analysis from UAV platforms and façade models automatically derived from TLS point clouds. The final product is a thermal textured 3D BIM model of a building façade useful for energy efficiency retrofit purposes.

The digital model is obtained integrating different surveying techniques like photogrammetry, terrestrial laser scanning, and IR thermography, along with new designed methodologies and algorithms for data processing. Results demonstrated that the use of thermal images from UAV platforms is a powerful tool in the field of thermal building inspection as the building can be better analysed and effects in hidden parts can be revealed. Obviously, as the field and its applications are quite innovative new algorithms for data acquisition and processing have to be developed.

In our case studies the combined registration of thermal images and building model in a common reference system was carried out with a rigorous bundle adjustment that integrates both thermal and RGB images in order to improve numerical stability and robustness. Thermal camera calibration is performed beforehand by using a rigorous photogrammetric procedure.

In addition, a method able to derive 3D façade model of building façades from point clouds in an automatic way was also presented. The final output is a semantically enriched model of the façade in CityGML standard, where user's interaction is reduced to a minimum.

The final textured 3D BIM model with temperature information can be then explored ad analysed in order to combine geometry and radiometry into a single product. Starting from the global model other products can be derived, such as orthoimages or temperature profiles. This opens new possibilities in the field of infrared building inspection.

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