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# ITR: an AM laser range finding system for 3D imaging and multi-sensor data integration

M. Ferri De Collibus, G. Fornetti, M. Guarneri, E. Paglia, C. Poggi, R. Ricci
ENEA FIS-LAS,
Via E. Fermi, 45 I-00044 Frascati, Italy,
roberto.ricci@frascati.enea.it

## Abstract

The ITR (Imaging Topological Radar) is a prototypal amplitude-modulated laser range finding system designed and realised in the ENEA "Artificial Vision" laboratory in Frascati (Italy). It can be used to produce faithful 3D digital models of real targets, either single objects or complex scenes, in a wide range of environmental conditions. The AM range finding technique enables to produce in a single step an accurate range image and a shade-free, high resolution, photographic-like intensity image of the target. Thanks to the pixel-by-pixel correspondence of the two images, intensity data can be exploited in 3D rendering as grey-scale vertex colour information, resulting in highly realistic models. The accuracy of range measures can be made to depend mainly on the laser modulation frequency, provided that the power of the backscattered light reaching the detector is at least a few nW. The best performances obtained so far are ~100 µm. In order to take advantage of system peculiarities, specific software tools have been developed for system control, data pre-processing and 3D rendering, as well as to perform precise matching of geometric information with data acquired independently with different sensors (LIF laser sensors, metric cameras, thermographic cameras, etc.). The system has been applied in various fields, ranging from industrial machining to medical diagnostics, vision in hostile environments and cultural heritage conservation. The relevance of this technology in cultural heritage applications is discussed in special detail, by providing results obtained in recent campaigns with an emphasis on the system's multi-sensor data integration capabilities.

**Keywords**: Laser range finder, laser scanning, 3D imaging, cultural heritage applications, multi-sensor data integration

## 1 Introduction

Active optical scanning technology [1] is currently used for 3D digitization in a wide range of industrial, scientific and cultural applications. In particular, these techniques can be very profitably applied to the cultural heritage domain [2][3][4], where they provide a powerful yet versatile means to reproduce faithful computer models of rare – sometimes unique - delicate objects, that can then be used for cataloguing and computer-aided restoration purposes. The increasing accessibility of 3D models of both single art works (statues, pottery, jewelry etc.) and entire scenes of cultural or archaeological interest (building façades and interiors, archaeological sites etc.) poses new challenges in terms of the possibility to integrate geometric models with information obtained by using other diagnostic techniques (laser induced fluorescence, thermography etc.) [5]. The possibility to use a single tool for combined 3D inspection and diagnostics is expected to bring enormous benefits to current cultural heritage conservation and restoration processes and pave the way for unprecedented applications.

We present here some of the most relevant results obtained in this field by the "Artificial Vision" group of the ENEA National Research Laboratories in Frascati (Italy). These results have been achieved by using the ITR (Imaging Topological Radar), an advanced laser scanner entirely designed and realised in ENEA and aimed at applications that require enhanced viewing capabilities combined with accurate distance measurements. In particular, we report about some promising examples of multi-sensor data integration, that have been obtained by combining the geometrical information provided by the ITR with data acquired by other distinct sensors – namely, a LIF (Laser Induced Fluorescence) scanner system and a high-resolution digital metric camera.

Several ITR prototypes have been realised in the ENEA "Artificial Vision" laboratory during the last years, as a result of an adaptation process of the general AM range finding scheme to the requirements of the specific application at hand. Beside metrological and viewing applications in manufacture and nuclear research [6], ITR systems have proved to be very well suited to accurate 3D digitization of valuable and/or hardly accessible objects [7]. Due to the unique features of the information produced by the system, data processing is conveniently and effectively performed by using internally developed software tools, tailored onto the specific system characteristics and continuously updated to reflect hardware improvements and enlarge the ITR application domain.

## 2 The ITR

### 2.1 Functioning principle

The ITR can be categorised among amplitude-modulated laser rangefinders. Its functioning principle is based on the indirect determination of the round trip time delay of the AM sounding beam through the measurement of the phase delay $\Delta\varphi$ of the signal photocurrent with respect to a reference signal. Distance is simply determined by the formula:

$$d = \frac{c}{n}\frac{\Delta\varphi}{4\pi\nu_m} \qquad (1)$$

where $\nu_m$ is the modulation frequency, $c$ the velocity of light in vacuum and $n$ the refraction index of the transmitting medium. For laser optical powers such that the signal shot-noise dominates over all other noise sources in the detection process, the accuracy of measurements can be showed to increase with the modulation frequency $\nu_m$, according to the formula [8]:

$$\sigma_R \propto \frac{1}{m\nu_m (SNR)_i} \qquad (SNR)_i = \sqrt{\frac{P_S \eta\tau}{(h\nu)\Gamma}} \qquad (2)$$

where $\sigma_R$ is the "intrinsic" error (i.e. the minimum attainable error in optimal experimental conditions), $m$ is the modulation depth and $(SNR)_i$ is the current signal-to-noise ratio - depending on the laser frequency $\nu$ and collected power $P_S$, the integration time $\tau$, the detector's quantum efficiency $\eta$ and the overall optics merit factor $\Gamma$. All measured distances are relative to the sensor's position – specifically, to the center of the scanning mirror.

AM range finding techniques are generally affected by the so-called "folding" ambiguity. In fact, using a single modulation frequency only enables to perform univocal distance measurements within a well-determined range window, equal to half the value of the corresponding modulation wavelength $\lambda_m$ (e.g. ~15 m at 10 MHz). The position of points located in the scene out of this range is erroneously "folded", i.e. reported as if it was falling within the range. This is due to the periodicity of the modulation signal, which only permits the determination of distances up to multiples of $\lambda_m/2$. In order to overcome this problem, we normally use two modulation frequencies (double-mode ITR), whose values are usually chosen far apart from each other. In double-mode ITR configuration, the low-frequency measurement range is large enough to encompass the whole scene of interest. Low-frequency – unambiguous, yet less accurate – measurements are then used to remove the "folding" ambiguity that affects the corresponding high-frequency - more accurate – measurements. This technique - enabling to measure distances at the level of accuracy permitted by the high-frequency mode but well beyond its intrinsic range – can profitably be used to digitize large scenes such as building façades or interiors, vaults etc.

The simpler single-mode technique (single-mode ITR) can also be successfully applied whenever the target is completely contained within the range corresponding to the chosen operating modulation frequency. The single-mode technique is particularly well suited to the digitization of small-size objects, since a relatively high frequency can be chosen in this case without incurring in folding ambiguities.

### 2.2 The real system

The ITR is actually composed of two separate parts: an active module, including the laser source and the detector, and a passive module, which only contains the transmitting and receiving optics. The two subsystems are optically coupled trough optimized optical fibre connections. This modular setup enables to place the passive module in the position that is more convenient for the measure, without compromising the overall functioning of the system even in extreme or hostile conditions, such as at high or low temperature, and in presence of intense ionizing radiation background. A detail of the ITR optical head is shown in figure 1.

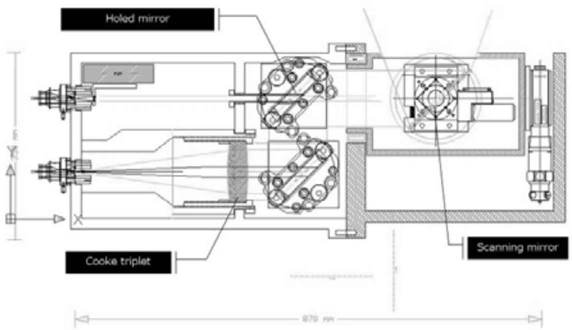


**Figure 1:** Scheme of ITR optical head.

### 2.3 3D model reconstruction: the "Isis" software package

Before actual 3D rendering, "raw" information contained in the pair of range and intensity 2D maps is pre-preprocessed in order to:

- convert range data values into Cartesian coordinates expressed in physical units and rearrange the geometrical information contained therein so as to get rid of the apparent distortions introduced by the viewing frustum of the scanning system (since the frustum is shaped like a spherical cap in the ITR case, we refer to the rearrangement procedure as "polar reformatting");

- remove extraneous elements such as background points, outliers, fake points that happen to be erroneously recorded by the sensor in correspondence with abrupt depth discontinuities.

In the rendering process intensity data are naturally used as vertex color information, resulting in an extremely realistic 3D model of the original object or scene. In cases when a series of linear scans are taken from different orientations, the corresponding partial range surfaces must be registered [9] in a single frame. The last step of the rendering process consists in merging the registered range surfaces into a single polygonal model, possibly taking advantage of data redundancy in overlapping regions. Many algorithmic procedures have been devised at this purpose, such as surface zippering [10] and volumetric methods [11].

Although many software products exist on the market that supply general purpose tools for the rendering of most commercial 3D scanner data, they are generally not versatile enough to cope with all the requirements of a laboratory instrument like the ITR. For this reason we started implementing from the outset custom versions of the advanced algorithms needed for the 3D rendering of the intensity and range map pairs produced by the ITR. These tools are bundled in the "Isis" software package, a Windows application written in Microsoft Visual C++ with OpenGL support that comprises a control and acquisition tool and an interactive 3D reconstruction and visualization tool (see figure 2).

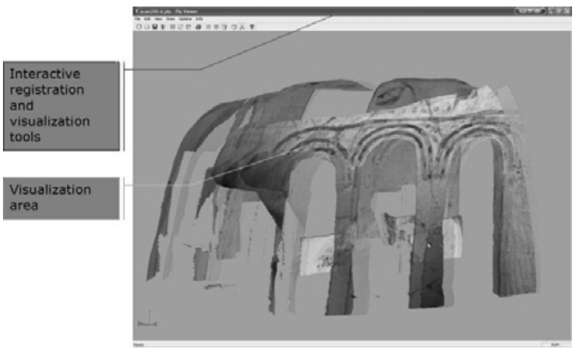


**Figure 2:** A screenshot of the Isis interactive 3D reconstruction and visualization tool.

The reconstructed models can be inspected at any angle by performing simple mouse-driven operations and exported in the most important 3D data formats. Current software development activities are aimed at implementing new advanced features, such as exploiting "colour" – i.e. intensity – information for enhancing the registration of multiple range surfaces. Colour-enhanced registration is expected to provide much better results in all situations where geometric features do not provide enough information to permit the convergence of the registration method (quasi-planar surfaces etc.). It is worth remarking that the simultaneous generation of distance and intensity information is a distinctive feature of AM range finders.

## 3 Applications of the ITR

### 3.1 Industrial and scientific applications

In recent years various ITR setups have been successfully utilized in numerous applications. A simple version of the instrument, configured to operate as a collision avoidance tool, was mounted on board of an ENEA self-operated vehicle for Antarctic exploration [12]. Other ITR prototypes have been integrated with industrial machinery (wood cutter) for quality control purposes or embedded in a nuclear fusion vessels for remote viewing in hostile environments (high-energy neutron and X-ray radiation). In fact, the necessity to comply with the demanding requirements of such extreme applications stimulated continuous improvements, such as: the inclusion of higher and higher modulation frequencies in order to enhance resolution; the realization of custom designed optics and electronics in order to achieve miniaturization and adapt to inhospitable environments; the adoption of a modular design to separate active and passive elements and make it possible to use the system in extremely adverse conditions.

### 3.2 Cultural heritage applications

The ITR accuracy, versatility and non-invasiveness has come out to be particularly advantageous in cultural heritage applications. The laser power required for ITR operation (a few mW) guarantees a negligible interaction between the laser radiation and the target surface material. This is to be compared, e.g., with time-of-flight laser range finding techniques, where high power and short pulses are required, that can easily induce surface ablation. The wide operational range – extending, in double-mode configuration, from ~1 m to ~50 m with no loss in accuracy – makes the ITR an extremely versatile 3D digitization device. It can very profitably be used in conditions where common laser triangulation techniques are either inapplicable or very demanding in terms of time and computer resources (scanning of very large statues, façades, building interiors, exploration of underground cavities in archaeological campaigns). Moreover, in all cases where metrological aspects are marginal for the application at hand, the system can be configured so as to give prominence to other performance parameters (higher scanning velocity, lower cost, higher viewing accuracy, etc.) or even adapted to different purposes (e.g. surface vibrometry, with vibration amplitude resolution of ~50 μm up to vibration frequencies of some hundreds Hz).

The ITR has been used with success in various measurement campaigns aimed at the conservation and valorisation of cultural heritage sites, singled out for their relevance and peculiarity in the context of both national (Italian) and European Union initiatives. In most cases, the ITR micrometric resolution capabilities have enabled to reconstruct extremely detailed models of artworks and entire sites of archaeological or historical interest. One remarkable result is shown in figure 3.

**Figure 3:** View of S. Maria Antiqua (Roman Forum , Rome, Italy) presbytery and 3D reconstruction of the palimpsest wall.

### 3.2.1 Multi-sensor data integration

In the context of cultural heritage applications, an emergent research field, suitable to further enlarge the applicability domains of the ITR, is the integration of the geometric information provided by the rangefinder with data collected using various other diagnostic tools and techniques. Multi-sensor data integration is particularly important for cultural heritage conservation, since it enables conservators engaged in the restoration of an artwork to reference diagnostic information directly onto the 3D model of the object to be restored, thus making it possible to adjust potentially invasive interventions and limit possible damages. In order to be able to reference any external data directly onto the 3D models produced by the ITR, the system used to collect the external data - simply referred to as SSS (second sensing system) in the following - must obviously provide some minimum amount of metric information.

We describe here a technique that has permitted to achieve good results [13][14] in integrating geometric information with laser induced fluorescence (LIF) data. LIF data was acquired by supplementing the LIF sensor with a scanning system similar to the one used in the ITR (a rotating mirror moved by means of high-precision stepping motors). This permitted to record, for each sampled point, the scanning angles as measured in the LIF system reference frame, whose origin was conveniently located in the system "nodal point", i.e. the center of the scanning mirror. This technique – possibly with some modifications, described later in this section - is suitable to be applied to sensing systems with different characteristic, provided the same minimum metric information is supplied - that is the angles under which each data pixel is seen in a reference frame joint with the sensing system and centered in the system nodal point.

The general idea underlying the integration method is to try to determine the linear transformation (rototranslation) that relates the ITR and the SSS local reference frames. Once this transformation is known, it can be used to refer to the ITR frame the view line under which each data pixel is measured by the SSS. This in turn enables to determine, for each view line of the SSS, the closest vertex in the geometrical model and to associate the corresponding information to that vertex. In all cases where the SSS nodal point is directly accessible to the ITR – the LIF system just described fell in this category - the overall procedure can be schematically summarised as follows:

1. identify at least three reference points on the target scene;
2. use the ITR to determine the vector lying between the two systems' nodal points;
3. for each reference point, measure corresponding angles in the second reference frame;
4. for each reference point, measure corresponding vectors (angles and distances) in the ITR frame;
5. use the data collected in steps 2 to 4 to calculate the distances of the reference points from the origin of the second frame;
6. use the data obtained in steps 2 to 5 to calculate the rototranslation transformation that links the two reference frames [15].

Alternatively, distances of reference points in the second frame - needed to calculate the rototranslation transformation - can be evaluated without measuring the vector between the nodal points, but using instead the relative distances between the reference points themselves, which can be easily calculated in the ITR frame. The problem of determining the distances of n points from a fixed "centre", given the relative distances of the n points between each other and the angles formed by the line segments connecting the

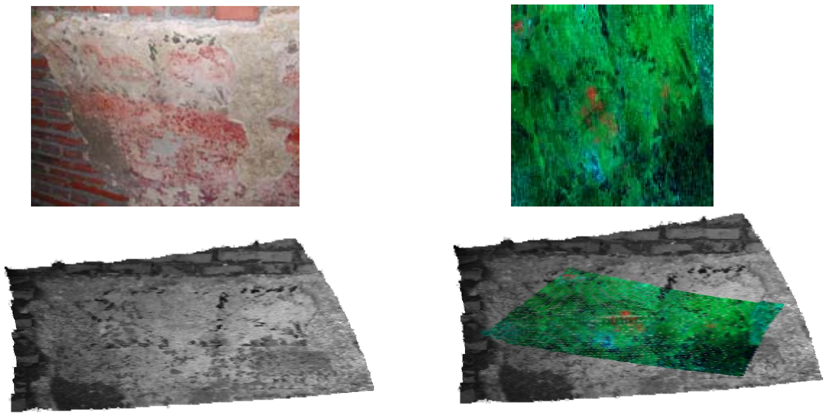

**Figure 4:** An example of multi-sensor data integration. Top left: photograph of the target – a wall in a Byzantine crypt in Constanta (Romania). Top right: LIF data, providing combined information about the fluorescence intensity on three channels at 580 nm (R), 532 nm (G) and 450 nm (B). Bottom left: 3D model. Bottom right: LIF data superimposed onto the 3D model.

points with the centre, is conceptually equivalent to the so called "PnP" problem, well-known in photogrammetry and completely solved [16], at least in the case of three points (P3P).

This variant of the method has some obvious advantages, namely:

- the nodal point of the second system must not be accessible to the ITR;
- it is not necessary for the two systems to coexist at the same time in the same place: measurements can be performed at different times with no particular positioning constraints for the second system.

On the other hand, the determination of distances in the second method is mostly based on calculations, with possible round-off effects also due to the complexity of the P3P problem, that demands for a numerical approach. The first of the two methods just outlined has been successfully applied to integrate ITR and LIF data, that were acquired sequentially during a single measurement session in Constanta (see figure 4).

A completely different, much simpler technique, based on the so called "Direct Linear Transformation" widely used in photogrammetric applications, can be used for the superposition of data acquired with non-scanning sensors, such as high-resolution digital metric cameras or thermocameras. This technique has effectively been applied during a 2005 campaign - carried out in the Roman Forum on the ruins of Santa Maria Antiqua, the most ancient Christian church in Rome - to match colour pictures of the church, obtained with a metric camera, onto a high-resolution 3D model of the church itself. Results, though impressive, cannot be adequately reported in this article, because of the constraint to include only BW pictures.

## 4 Current work and future developments

Present research activities and future plans are mainly focused on both enhancing current ITR performances and enlarging the range of application of range finding techniques by designing and realizing new ITR prototypes.

We have recently realized some new optical heads including a launching autofocus system - to improve spatial resolution at any distance from the target - and larger collecting optics - to decrease SNR at larger distances. The first laboratory tests performed with the new heads have evidenced that the system is quite close to reach diffraction-limited spot dimensions on the target. This is expected to produce a considerable improvement in terms of scanned surface "continuity", but also poses some problems related to the presence of a noticeable noise contribution due to speckles, that spoils the quality of distance measurements. Investigations are ongoing on how to get rid of this hardly tractable noise component – e.g. by reducing the beam time coherence without compromising spatial coherence.

Another activity in advanced development stage concerns the design and realization of a prototype underwater ITR. The development of laser scanning systems for underwater imaging is a subject of remarkable interest in view of their potential applications in several fields ranging from exploration of submarine archaeological sites to background inspection for industrial and scientific purposes. Nevertheless, the task is challenging because light absorption and scattering, in undersea applications, cooperate to degrade image quality [17]. Very promising results of underwater imaging have recently been obtained by our group [18] with an AM single-mode laser beam combined with a miniaturized piezoelectric-actuator-based scanning system. The basic elements of the system are a diode laser source at 405nm with digital amplitude modulation and a micro-scanning system realized with a small aperture aspheric lens mounted on a pair of piezo-translators driven linear stages. The system has been designed to be a low weight and rugged imaging device suitable to operate at medium range (~10m) in clear seawater, as also demonstrated by computer simulation of layout performances. In controlled laboratory conditions sub-millimetric range accuracy has been obtained at a laser amplitude modulation frequency of 36.7 MHz.

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