# AUTOMATED 3D LASER SCANNING FOR BIOMEDICAL APPLICATIONS

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**Abstract: In this work, we present the prototype of an automatic and programmable laser projection system for 3-D surface scanning and for the generation of laser point patterns. Our specific intent was to investigate the combined use of laser scanning techniques and optoelectronic devices for patient positioning control in radiotherapy. The system was tested to verify the predefined technical requirements. Then, a simulated clinical scenario was reproduced in our laboratory in order to test the surface scanning features and the projection of laser points on a phantom model. Results proved the good performances of the realized system: accuracy and repeatability of the projected laser spots have been verified experimentally and assessed to be lower than 0.3 mm. Moreover they highlighted a great versatility that makes it possible to use the device for other biomedical applications.**

## Introduction

In recent years, 3D surface imaging has become an increasingly important technique in different biomedical areas. In the orthopaedic field, for example, laser scanning systems are used to realize adequately customized orthosis [1]; other applications comprise maxillo-facial [2, 3] and breast [4] reconstructive surgery, in order to perform accurate intervention planning and execution.

Similar methods are applicable in radiotherapy as well [5], aiming at optimised precision and reliability of the clinical procedures, and at maximizing, at the same time, the safety for the patient with minimal invasiveness. In fact, one of the weak points for radiation therapy success is to reproduce, during each treatment session, the planned geometrical set-up for target irradiation.

Recently, techniques based on surface detection and registration, by using optoelectronic localizer and laser spots projected on patient's skin, were proposed [6, 7]. Differently from the methods based on the exclusive use of passive control points, these new methodologies have the advantage of reducing both time issues and the errors due to the replacements of fiducials and easily provide the real-time monitoring of a greater number of points. For this aim, we realized a prototype of an automatic and programmable laser projection system for 3-D surface detection and for the generation of pre-defined laser patterns. The realized device can be programmed by means of a dedicate software and it was combined with an optoelectronic localizer, yielding the 3D acquisition of the projected laser points. The principal features of the entire system consist of:

- projecting a pre-defined pattern of laser spots at regular intervals, with high accuracy and repeatability, thus giving the opportunity to realize a personal configuration for each patient;
- storing the defined configuration in order to replicate it at each session;
- scanning the entire surface rapidly.

The technical requirements of the device were stated in terms of range of motion, accuracy, repeatability and flicker effects of the laser beam.

Two types of experimental tests were carried out in our laboratory in order to verify the laser projector performances and to assess its applicability in simulated conditions, reproducing the clinical set-up in a radiotherapy bunker.

## Materials and Methods

The work was carried out in cooperation with *Gruppo Cignoli s.r.l.* (Milano, ITALY). The system was designed in its essential electronic and mechanical components. A rotating motorized platform (see Figure 1) was realized to move a laser diode emitter (670 *nm* wavelength, output power ≤ 0.8 *mW*) that projected a spot measuring 5 mm in diameter: two brushless motors were employed and they were controlled by a PLC (Simatic S7-300) that was interfaced with a computer through a communication module.

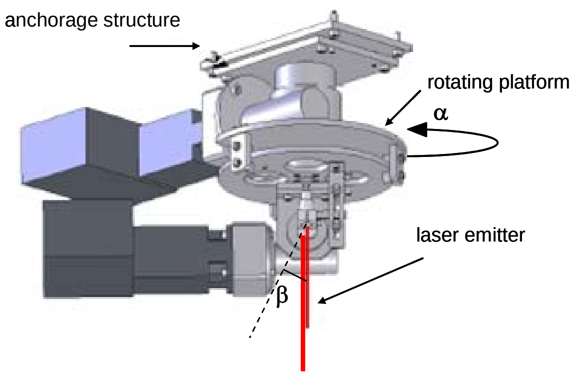


Figure 1: Laser projector device

An anchorage structure was designed to fix the system at the ceiling of the room.


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A dedicated graphic interface was developed for system control, data management and storage (see Figure 2). Through this panel, it was possible to direct the laser pointer both manually (incrementing its displacement step by step) and automatically (setting the reaching point), stating the scanning area and the motors speed. The laser beam movement was expressed in terms of two plane angles (α, β - degrees) virtually traced by the laser emitter around its axial and transversal axis (see Figure 1).

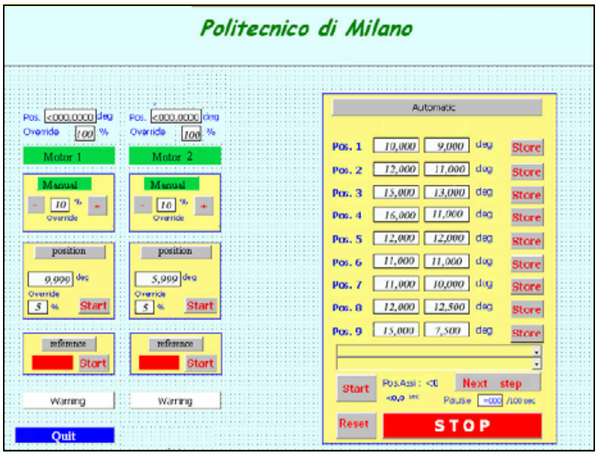


Figure 2: Graphic user interface for the laser projector control

Data acquisition was realized by using an opto-electronic localizer [8] (EL.I.TE.™ S.p.A., BTS, Milan, Italy) in two TV cameras configuration. This system ensured a localization accuracy, on each laser spot, lower than 0.4 mm and its acquisition frequency was 50 Hz.

The spatial coordinates of the laser points, acquired by the EL.I.TE. ™ system, were expressed in an absolute frame (X, Y, Z) defined through an adequate calibration procedure [9], so that α and β were the angles around Y and X axis respectively. For α=0° β=0° (zero-position) the 3-D coordinates of the laser spot corresponded to X=0, Y=0, Z=D (see Figure 3).

A previous set of experimental investigations was planned in order to check out the projector technical requirements, summarized in the table below. Measurements were performed projecting and acquiring different laser patterns on a plane surface, identified by X and Y directions, 3,280 meters far from the laser pointer (see Figure 3).

Table 1: System technical requirements: linear values were calculated considering D=3,280 m as laser pointer-surface distance.

| | | | | |
|---|---|---|---|---|
| LASER PROJECTOR RANGE OF MOTION | α | 12° | X | ~ 697 mm |
| | β | 8° | Y | ~ 461 mm |
| ACCURACY | α,β | 0,047° | X,Y | 2.691mm |
| REPEATABILITY | α,β | 0,007° | X,Y | 0.401mm |
| FLICKER | α,β | ±0,01° | X,Y | ±0.572 mm |

All collected data were analysed through dedicated procedures implemented in Matlab® enviroment (MatLab® version 6.5, The MathWorks, Natick, MA).

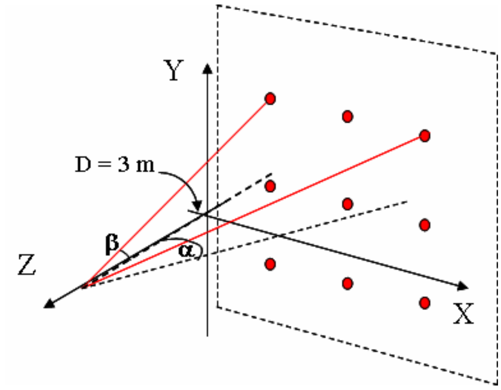


Figure 3: Geometrical set-up for system testing

First of all, the projector was manually moved to assess its range of motion.

Then, accuracy tests were realized directing the laser beam to a pre-defined location starting from the zero-position. The experimental protocol consisted of the following steps:

- set, on the control panel, the $\alpha_i$ and $\beta_i$ values;
- start the automatic laser beam positioning;
- acquire the new $X_m$, $Y_m$, $Z_m$ coordinates of the projected laser spot through the optoelectronic localizer (the average value of all frame acquired was computed);
- calculate the desired $X_d$, $Y_d$ coordinates through the following formula

$$X_d = D \cdot tan(\alpha_i) \quad (1)$$

$$Y_d = D \cdot tan(\beta_i) \quad (2)$$

- compute the desired and the real displacement of laser beam from zero-position as

$$S_d = \sqrt{X_d^2 + Y_d^2} \quad (3)$$

$$S_m = \sqrt{X_m^2 + Y_m^2} \quad (4)$$

- re-set the laser emitter to the zero position.

This procedure was iterated six times (i=1,..,6).

Repeatability was evaluated by projecting a 3x3 laser point grid, as it is illustrated in Figure 3. For each $i^{th}$ point (i=1,…,9) the standard deviation was computed, on a set of 4 grid plotting. Moreover, this investigation was executed in different system working conditions, by changing the motor speed from 100% of the maximum rate to 10%.

Data acquired in this section were analyzed to estimate the flicker of projected points: since each laser spot was plotted for 2-3 seconds (i.d. 100-150 frames for X, Y), the standard deviation of collected frames was determined.

In the second part of the experiments we tried to reproduce, in our laboratory, the scenario of the therapy room of "*Istituto Europero di Oncologia*" (IEO, Milan) where we collaborate with clinical personnel for daily patient position optimization [6, 10].


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The two cameras were installed at the ceiling of the room and a female phantom was placed on a couch in supine position (see Figure 4).

Figure 4: Experimental set-up.

Breast surface was scanned and acquired in real time by the optoelectronic localizer. Scanning area was set by software choosing the beginning and the end points. The laser emitter was automatically moved at the 10% of the maximum rate. A point-based model was obtained and it was interpolated, by using dedicated MATLAB™ procedures, to obtain a surface model representation.

On the same phantom, a laser point grid was projected four times. Each laser line, covered by the cameras field of view, was acquired by moving a rigid panel from the surface to the emitter. Subsequently, through a minimization procedure, it was possible to estimate the director cosines of beams, respect to the absolute frame of the EL.I.TE system, and the resulting repeatability.

At last, human body segments were acquired in order to consider eventual artefact movements.

## Results

The range of motion of the laser projector resulted larger than the required one: the maximum values for $\alpha$ and $\beta$ were 360° and ± 50 ° respectively.

In table 3 the difference between the desired and measured values during the accuracy tests are shown: the total mean ± standard deviation measured 0.428 ± 0.885 mm.

Table 3: Results of the accuracy tests.

| Test | $S_d$ [mm] | $S_m$ [mm] | $S_d$-$S_m$ [mm] |
|---|---|---|---|
| 1 | 282.840 | 282.924 | -0.084 |
| 2 | 426.723 | 426.696 | 0.027 |
| 3 | 400.000 | 401.635 | -1.635 |
| 4 | 350.409 | 350.440 | -0.031 |
| 5 | 530.380 | 531.798 | -1.418 |
| 6 | 477.029 | 476.461 | 0.568 |

Results concerning repeatability and flicker are reported in Table 4. The mean value of standard deviation of the 9 points is shown for the five different motor speeds.

Table 4: Repeatability and flicker results

| | % rpm max | **X** (mean values) | **Y** (mean values) |
|---|---|---|---|
| **Repeatibility** | 100% | 0.308 mm | 0.356 mm |
| | 90% | 0.292 mm | 0.252 mm |
| | 80% | 0.197 mm | 0.270 mm |
| | 20% | 0.217 mm | 0.193 mm |
| | 10% | 0.282 mm | 0145 mm |
| **Flicker** | 100% | 0.188 mm | 0.190 mm |
| | 90% | 0.197 mm | 0.207 mm |
| | 80% | 0.188 mm | 0.190 mm |
| | 20% | 0.197 mm | 0.207 mm |

In Figure 5 (upper panel) the scanned phantom model is displayed. It consisted of approximately17000 points acquired in 5 minutes.

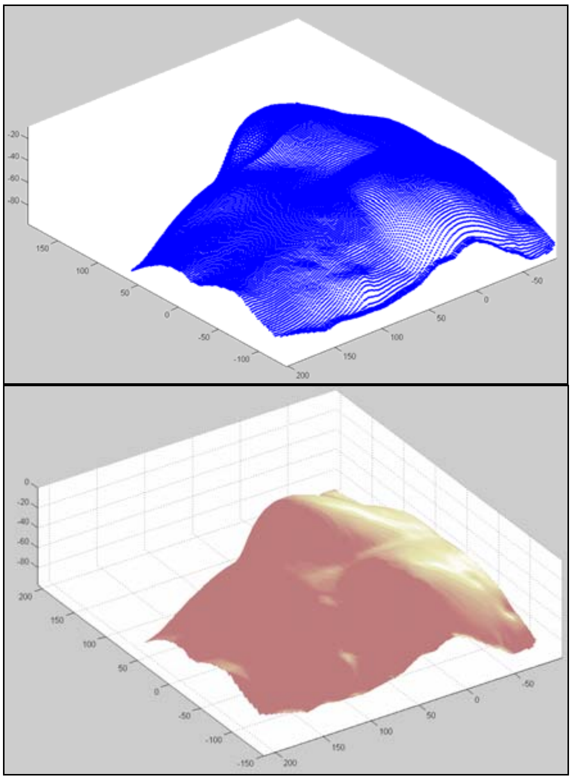

Figure 5: Breast phantom surface detected through the laser projector: point-based model (upper panel) and the resultant surface (lower panel).

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The interpolation among points provided the surface-plot illustrated in the lower panel of Figure 5.

Figure 6 shows the result of estimated laser line: four different colours were used to represent the outcome of each configuration projection. The respective director cosines are reported in table 5 as mean±standard deviation values on the four acquisitions.

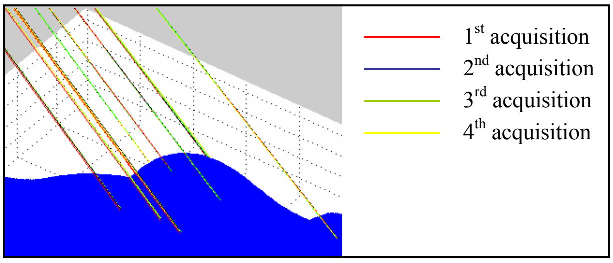


Figure 6: Laser beams estimated by acquiring laser spot on a moving plane

Table 5: Director Cosines of the estimated laser beams

| Line | $C_x$ [mm] | $C_y$ [mm] | $C_z$ [mm] |
|---|---|---|---|
| 1 | 1.023±0.079 | -43.039±0.145 | -37.807±0.163 |
| 2 | 0.643±0.041 | 43.441±0.097 | 37.353±0.113 |
| 3 | 1.387±0.034 | 43.180±0.070 | 37.634±0.082 |
| 4 | 1.404±0.040 | 43.032±0.094 | 37.802±0.107 |
| 5 | 0.685±0.068 | 43.076±0.122 | 37.773±0.141 |
| 6 | 0.497±0.099 | -42.473±0.217 | -38.451±0.238 |
| 7 | 0.440±0.017 | 42.601±0.039 | 38.312±0.044 |
| 8 | 0.757±0.071 | 42.601±0.081 | 38.307±0.092 |
| 9 | 1.420±0.047 | 42.653±0-056 | 38.230±0065 |

In the figure below the 3D scanning of a human face is depicted: acquisition time was about 3 minutes and the step between contiguous points was 2 mm along the linear directions X and Y.

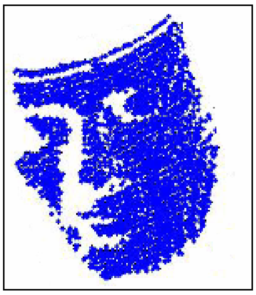

Figure 7: Acquisition of a human face.

## Discussion

In this paper, we illustrated the use of a laser projection system for the three-dimensional scanning of anatomical human districts and laser points configuration plotting. Our principal goal was to verify if the device could be considered an important, useful, additional component for the patient position verification in the radiotherapy field, through the application of surface registration algorithms and by using laser spots as fiducial points.

For this reason, the main features of the system were designed to be adequate with the ordinary clinical radiotherapy practice: the laser projector works in cooperation with an opto-electronic localizer, commonly employed to monitor the location of passive markers used as control points on patients surface; the measure of the laser emitter-surface distance, for system testing, was chosen to be compatible with a possible installation in the therapy bunker.

Technical requirements, in terms of accuracy, repeatability and flicker, were assessed to be comparable with the error introduced by the optoelectronic system. In particular, repeatability on single point measured in average 0.251 mm: this result reveals that the device is able to cyclically project pre-fixed configurations of laser spots, with high precision.

Consequently the newest methodologies, based on use of non-deterministic algorithms for the anatomical surface registration through the real-time localization of a pattern of laser spots, could take great advantage by this automatic projection system.

Results regarding anatomical surface scan give evidence of the high performance of the methodology to obtain extremely detailed point-based models in a very few time and with minimal invasiveness. Moreover, the detected data can be easily manipulated by using different tools in order to remove system noise and movement artefacts and to improve shape definition in a 3-D view.

The speed of the automatic scan was limited to 10% of the maximum rate because of the optoelectronic system sampling frequency: all new optoelectronic system could guarantee 100 Hz as acquisition frequency at least; so it is possible to increase scan velocity to obtain the same data in half time.

The unique limit of the entire methodology was due to visibility problems: in the case of face acquisition, for example, some portion was obscured by other anatomical parts. However the problem can be easily resolved adding one or more cameras according to the utilization requirements.

Since we realized only a functional prototype of the presented system for pre-clinical investigations, we did not take in account the overall size: different and smaller motors can be utilized in relation to economic availabilities.

## Conclusions

Results confirmed general good performance of the realized system that should be considered a suitable device for pre and intra-clinical investigations. Its great flexibility to acquire and manage data allows us to use it for different other biomedical applications.

On the base of our long experience matured in quality control of radiotherapy treatments, our future step will be:

- to implement a software package for the automatic detection and correction of patient set-up errors


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through the real-time localization of a set of laser spot;

- to plan a specific trial to test off line the quality treatment improvement in the clinical practise of breast cancer radiotherapy.

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