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Active Infrared Imaging For 3D Control of Multi-Layer Transparent Objects

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Abstract

Three-dimensional (3D) digitization of manufactured objects has been investigated for several years and consequently, many techniques have been proposed. Even if some techniques have been successfully commercialized, most of them assume a diffuse or near diffuse reflectance of the object's surface, and difficulties remain for the acquisition of "optically non cooperative" surfaces, such as transparent or specular ones. To address such surfaces, we propose a non-conventional technique, called "Scanning from Heating" (SfH). In contrast to classical active triangulation techniques that acquire the reflection of visible light, we measure the thermal emission of the heated surface. The aim of this paper is to demonstrate, by using the experimental setup designed for specular (transparent or not) objects, how this method allows reconstruction both of internal and external surfaces of glass objects from a unique measure.

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1. Introduction

While machine vision capabilities were improving, the need to control the 3D aspects of complex objects followed the same trend. The field of application is broad: industry, medicine, robotics, and video games... Consequently, 3D scanning has been investigated for several years and the literature on the subject is usually divided into active and passive techniques [1]. Passives systems do not use additional light and consequently their efficiency depends on ambient light [2], it include stereovision, shape from focus, shape from motion; however, active techniques such as laser triangulation or time-of-light require some controlled light. Specular reflection or refraction of light contradicts the operation of conventional 3D scanners, based on the acquisition of diffuse components of reflection. One way to circumvent these issues is to change the original surface into a diffuse one by surface treatment [3] or by the deposit of a thin layer of powder. To avoid this troublesome step, a wide range of non-conventional methods has been experimented. These techniques present common interests for *computer graphics* and *computer vision* communities and are recently reviewed by Ihrke et al [4]. 3D acquisition of transparent and specular objects has received a lot of attention in the recent years and the state-of-the art methods include: multi-wavelength range sensing [5], shape from distortion [6], multipeak range imaging [7], shape from polarization [8] [9], light path triangulation [10], shape from induced fluorescence [11]...

Nevertheless, these techniques are not yet ready to be implemented in industry. Moreover, most of them are efficient for only one type of surface. The results that we present in this paper are provided by a versatile technique, whose efficiency has yet been demonstrated for both specular and transparent surfaces acquisition. For the case of multi-layer surface reconstruction, a recent paper [12] describes how to calibrate a single camera to estimate the orientation and the thickness of refractive layers. The authors validate their theory by presenting real experiments using a water tank. However, they assume that all layers are flat and parallel to each other, considering only planar refraction. Anyway, a noncontact acquisition technique has not yet been developed for the 3D digitization of unknown refractive surfaces.

We will first present the working principle of the technique SfH [13], and we will expound the implemented experimental setups and the related 3D reconstruction results. Then, we will explain how to extract both 3D internal and external shapes of several glass objects by means of one of the scanning prototypes previously presented and in a single stage. Some preliminary results on three glass objects will illustrate this idea, and some possible applications will be discussed. Finally, we will give some perspective work to improve our results.

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2. Scanning from Heating

The principle of this technique is different from standard active triangulation technique in the sense that we measure the thermal radiation emitted from a heated point instead of acquiring the reflection of a visible light pattern on the surface. Assuming that infrared emission distribution is omnidirectional for most materials, we can address 3D digitization of specular or even refractive surfaces, regardless of the scanner position. A laser source is geometrically describes how to calibrate a single camera to estimate the orientation and the thickness of calibrated with a thermal sensor to extract a cloud of 3D points from infrared images. If the wavelength of the laser source is correctly selected, the technique can be applied either on transparent surfaces or on specular surfaces.

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Considering the thermophysical properties, we have built a theoretical model of heat exchanges induced by the technique [14]. The energy balance is evaluated for the three exchange modes that are: conduction, convection and radiation (illustrated in figure 1). We finally obtain partial differential equations that are solved in 3D using a finite element numerical solver. The simulation results help to validate the feasibility of the technique on dielectric or metallic materials and to predict the best settings of the system (incident power, pulse time) for a given surface.

According to the theoretical background, two different experimental setups have been designed. Radiative behaviour of glass objects tends to be similar to opaque ones if the incident wavelength is above 10 µm (no transmission). Consequently, a CO_2 laser (emitting at 10.6 µm) has been chosen to design a SfH-based scanner prototype in order to acquire 3D shape of glass objects. As shown in figure 2-(a), the X-Y translation scanning is realized with a moving platform. The spectral band of sensitivity of the IR camera should not include the laser wavelength so that neither direct laser radiation nor reflection can be detected. The used detector is sensible to the interval [3-5] um (MW band). The figure 2-b gives some 3D reconstructions of glass objects obtained with this system.

For specular metallic objects, a new scanner prototype has been implemented (see figure 3-(a)). Since the radiative behaviour of metallic objects is completely different from the one of the dielectric materials, incident radiation should be modified. According to the optical constants given by the databases in the literature and according to our theoretical model, the chosen laser is made of ytterbium fibber pumped by diodes, which delivers a 1.07µm laser beam. Indeed, in the near infrared spectral band, losses by reflection are lower thermal emission can occur after the radiation absorption. Compared to the previous system, we have improved the scanning speed and accuracy and reduced the size of the system by inserting a galvanometer scan head. A bolometer camera, sensible to [8-13] µm (LW band) is used to perform the thermal measurement. An adjustable power ranging from 0 to 50W allows the system to be versatile and efficient on different materials with various thermo-physical properties. Some examples of 3D coordinate computation results are given in figure 3-(b). Moreover, a comparative study was led on metallic objects to prove that the technique is robust against roughness variations [14] .

In both cases, we compute a cloud of 3D points of the external surface from the 2D-3D correspondences given by a previous geometrical calibration. Each 2D point projected in the image results from a local heated zone on the object, emitting infrared radiation. In other words, we only consider the energy that is absorbed by the external surface.

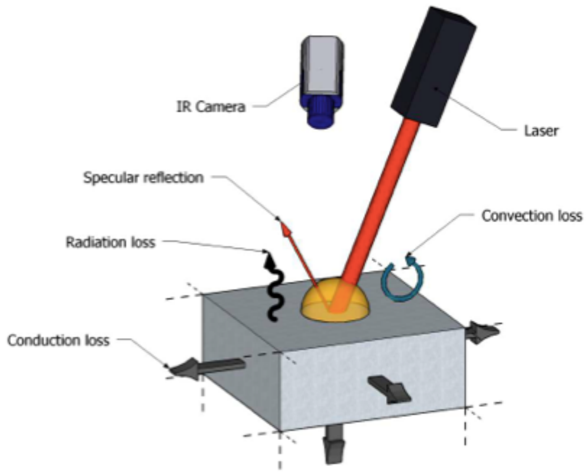

Figure 1 : Heat transfer exchanges for SfH

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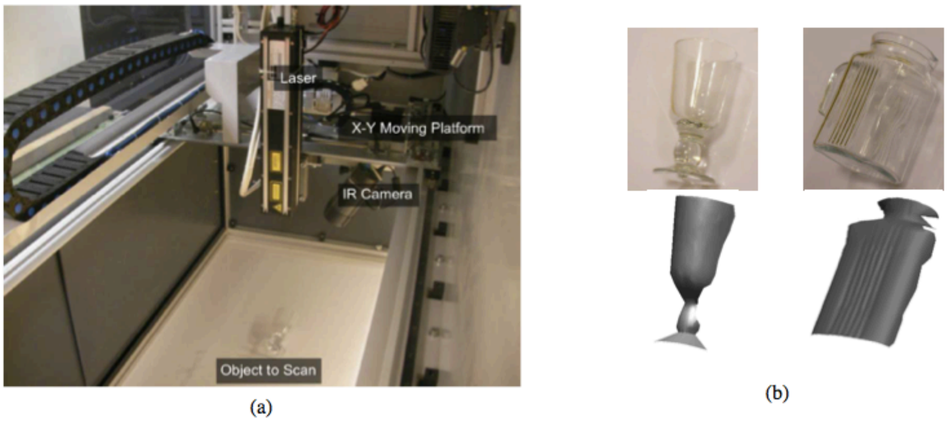

Figure 2 – Scanner prototype designed for transparent objects (a) and 3D clouds of points obtained (b)

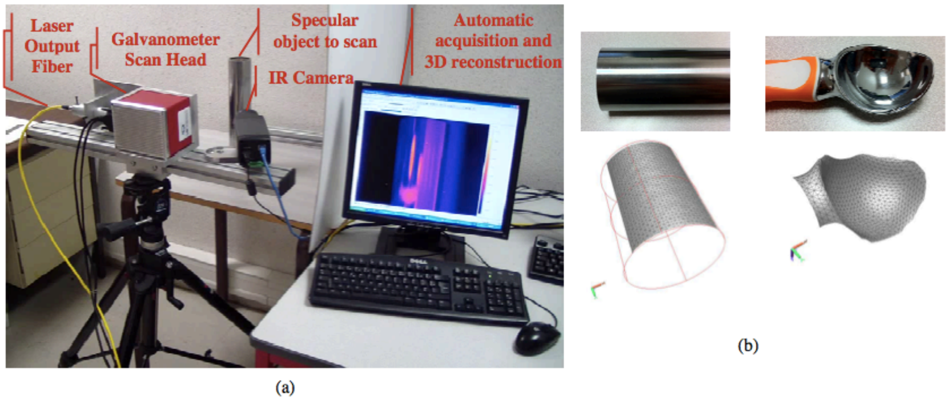

Figure 3 – Scanner prototype designed for specular objects (a) and 3D clouds of points obtained (b)

3. Experimental

For the following experiment, we use the prototype that was built for 3D digitization of specular surfaces. When exposing a glass bottle (see object in figure 5-(c)) to the laser radiation, we can observe that at least two points are emitting some thermal radiation that is detectable by the sensor. One point is more intense than the second one and if the incidence angle increases, a third point appears (see figure 4). The most intense thermal region occurs commonly when performing SfH process, and is due to the heat that is generated on the first surface impacted by the laser beam. Concerning the second point, some experiments show that some heat is generated again on the external surface after that the radiation was reflected by the internal surface. This optical phenomenon is observable with this laser source because a significant part of incident energy (at 1.07 µm) is transmitted through the first interface and a fraction of this radiation is reflected by the second one. This observation could not have been highlighted with the prototype presented in figure 2. The two advantages of this system are that glass objects are not completely opaque to the laser wavelength and the incident energy can reach a high value so that the amount of absorbed energy remains significant.

According to the Fresnel equations, the reflected part of the energy increases with the incidence angle on each interface (the internal and the external surface). The acquired images shown in figure 4 confirm this theory: the second imaged point tends to be brighter while the first one is less intense. Moreover, for the glass/air interface (the internal surface of the bottle), the critical angle can be reached such as all the energy is reflected. This phenomenon occurs when passing from glass to air, when the incidence angle is around 42°. Consequently, more than two points are heated and the differences between intensities are less significant, which explains the observations of the right image of the figure 4. In this extreme case, the material behaves like a waveguide.

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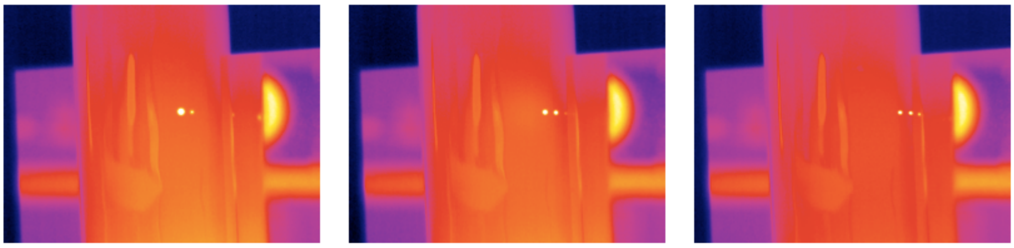

Figure 4 – Infrared images acquired while augmenting the incident angle (from left to right)

The immediate application of this experiment is the ability to extract separated 3D shapes of both internal and external surfaces, what is done with our scanner prototype. Three different glass objects have been reconstructed and the meshed surfaces computed from both interfaces are given in figure 5. To estimate the accuracy of the 3D acquisition, we have computed the average deviation between the measured points and a perfect plane for each surface of the flat object (figure 5-(a)) and we obtain respectively: 164 μm and 147 μm.

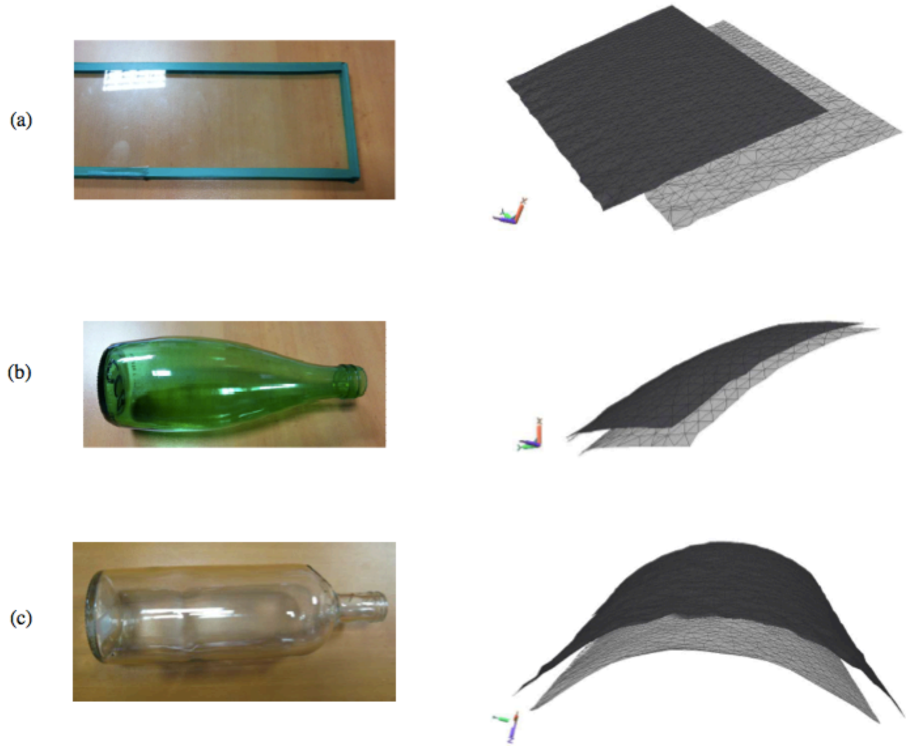

Figure 5 – 3D meshed surfaces measured from internal and external surfaces of three glass objects

Nevertheless, these preliminary results are calculated from a unique calibration method based on active triangulation. As a consequence, the relative position of the second surface is distorted. This constraint is illustrated in figure 6: the first object point that is impacted by the laser is correctly computed by triangulation but the second one is estimated at a wrong position. These coordinates result from the intersection of the known incident ray and the line described by the central point of the camera and the 2D point that is projected in the image frame. The direct measurement of local thickness ε_{meas} is different from the real value ε and depends on the refractive indice of the medium, on the orientation of the surface and on the relative pose of the second one. Its accurate determination would require some *a priori* information or at least assumptions about refractive indice and orientation of each surface.

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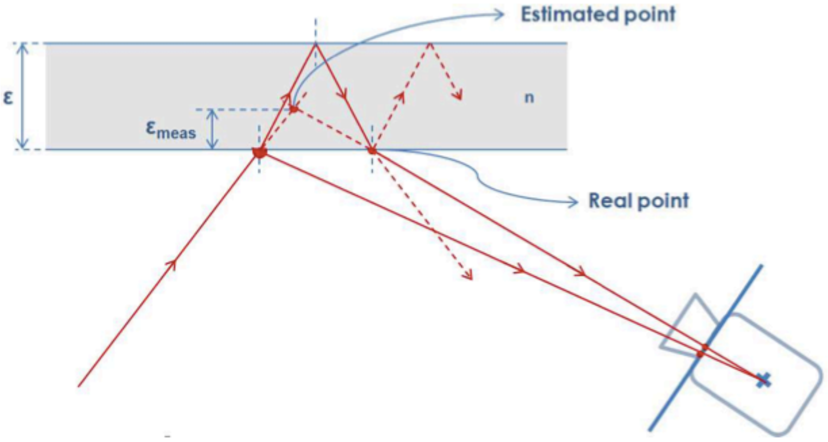

Figure 6 – Principle of triangulation method in our configuration

However, since the estimated points of the second surface are still linked to its real pose, it is possible to perform defect detection on it. If the curvature of the first surface is constant, we can highlight a local slope variation on the second one. This is precisely the case of the glass bottle (see figure 5-(c)). The figure 7 shows the color-coded deviation maps between both acquired interfaces and cylinders that are fitted to each cloud of points. The results are displayed with the same colour scale and show that we can identify a defect that is really located on the whole periphery of the internal surface.

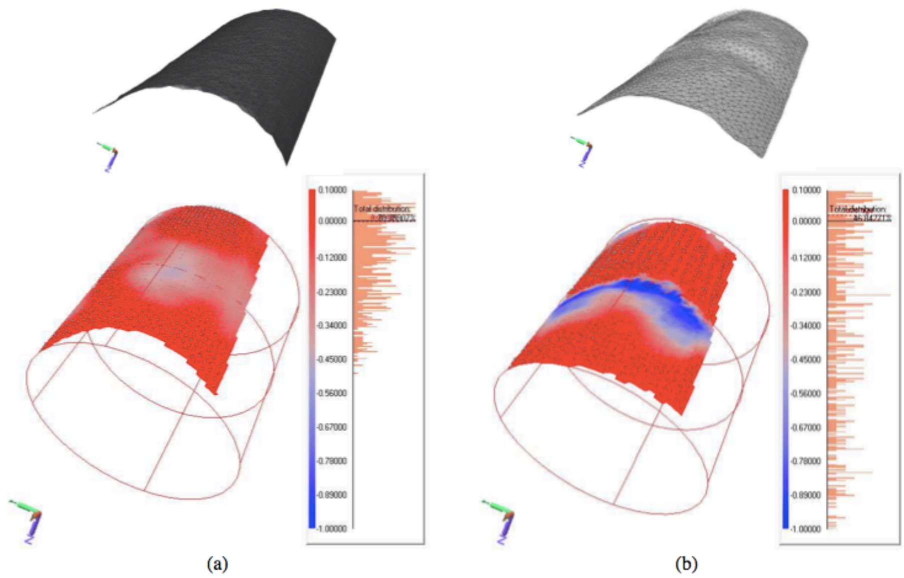

Figure 7 – Deviation maps between 3D clouds of points of external (a) and internal surface (b) of the glass bottle and their corresponding fitted cylinders

4. Future Works

The future work concerns the 3D modelling of the problem in order to solve the ambiguity between the depth of the internal surface and the orientation of both surfaces. Different cases will be identified and some solutions can be proposed by making some assumptions on the object geometry, for instance if the interfaces are parallel. This ability would enlarge the range of application of Scanning from Heating and would allow computing dense thickness measurements on transparent objects.

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Another perspective to investigate to improve the reconstruction accuracy of the internal surface could be the use of multispectral method: at least two wavelengths from the same optical path will lead to different refractive rays and an additional imaged point would help to improve our preliminary results.

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