Exploiting Mirrors for Laser Stripe 3D Scanning

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Abstract

This paper proposes and evaluates the use of a mirror for improving the scanning process when using laser-stripe acquisition devices. We propose to exploit mirrors for two different purposes: automatizing the 3D acquisition process and allowing the scanning of hard-to-reach parts. The combined use of a flat mirror and a rotary table allows to scan, in a completely automatic and unattended manner, small complex objects with an high level of completeness. Moreover we show how the use of a small hand-held mirror can to be effective for scanning parts that are difficult to be reached or scanned because the physical dimension of the scanner device.

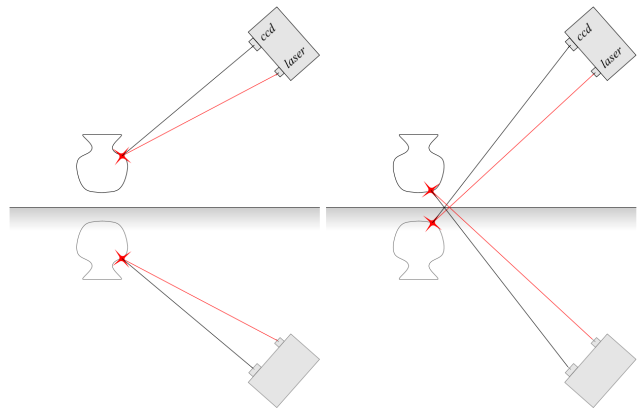

Figure 1. Acquiring a object with a laser stripe scanner in a mirrored environment can help to recover a larger part of the surface with a single scan.

1. Introduction

Nowadays scanning technologies are becoming very common in many different contexts and with various objectives and purposes (e.g. reverse engineering, inspection, documentation). An interesting domain of application of these technologies is the cultural heritage field where 3d scanning has proven as a very accurate medium for the truthful documentation of the shape and status of three dimensional artifacts like sculptures or other works of art. Notable examples in this field of application of 3d scanning technologies where, just to cite some, the Digital Michelangelo project [8], the acquisition of the Michelangelo's Florentine Pietà [1] and the monitoring of the restoration of the Minerva of Arezzo [12]; all these projects succeeded to provide exceptionally accurate three-dimensional models of famous statues ; for a specific choice the final models were not totally complete and exhibited holes in parts difficult to be reached by the scanner.

In fact, in the cultural heritage field, the use of 3D scanning technologies for documentation purposes introduces a peculiar requirement: the result of the scanning campaign should be constituted only by acquired data. Common actions like filling of holes or the reconstruction of missing parts with automatic or manual editing system should be not admitted. This requirement can be motivated by the will to document only the real status of an artifact without including any possible subjective intervention, like the ones that can happens when reconstructing missing parts. For this reason most of the models resulting from these acquisition campaigns are, willingly, incomplete; they exhibit a lot of holes and missing parts [6]. These deficiencies are mainly due to complex geometric situations which make difficult, or even impossible, to place the scanner in a position where it can acquire the missing portion of the surface. A typical example of this situation was the chin of the Michelangelo's David (Figure 2) that could be acquired in a complete manner only placing the scanner (and the supporting numerically controlled scaffolding) against the chest of the statue. This kind of problems is quite frequent in the context of scanning cultural heritage objects where, often, we are not allowed to freely move, or even touch, the artifacts to be scanned. A common wording in this field reports that to scan a complex object you get 90% of the surface in the first 10% of the time and use the other 90% trying to scan the last 10% of the surface.

To face these problems we have found that mirrors can

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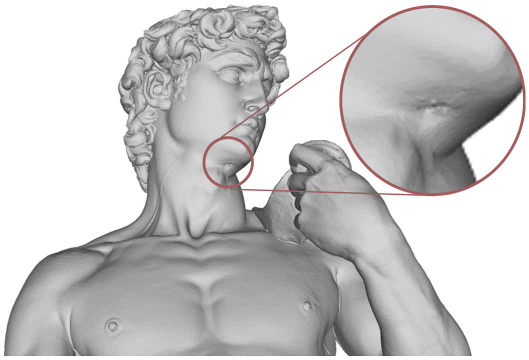

Figure 2. Many statues present some parts that are quite difficult, or even impossible to be directly acquired. The lower part of the David's chin presents some holes whose filling caused the noise visible in the circled area.

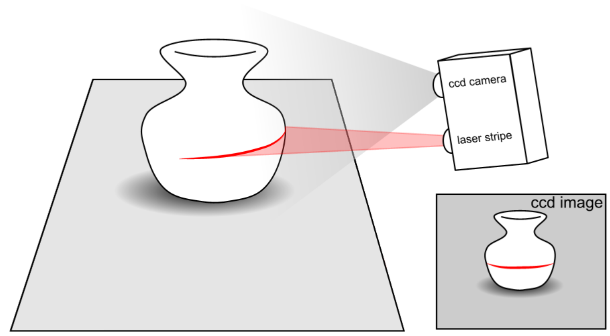

Figure 3. Acquiring a object with a laser stripe scanner. The 3D shape of the scanned object is recovered by the distorted shape of the laser stripe over the object.

greatly help to laser-scan, in a much easier way, parts that are hard to be directly reached. In this way the efforts usually required to trying to cover the final 10% of the surface are reduced. Given the promising results that we have obtained by simply using a small hand held mirror we have also applied this approach to improve the automatized scanning of small objects placing the a large mirror over a rotary table.

In section 2 we report some previous uses of mirrors in the 3D scanning field while in section 3 we give the main details on our approach describing the issues related with the placement of a mirror in a scanning environment and explaining the nature of error and noise resulting in the generated surfaces. Sections 4 and 5 describe the two proposed applications of mirror-enhanced scanning: acquiring hard to be reached parts and improving the completeness of automatic unattended 3d scanning.

2. Related Works

Range scanning technology has evolved in a considerable manner in the last few years. An overview of the field, covering both hardware and software issues, is available in a couple of recent papers [4, 2]. Many different systems have been proposed; a common characterization subdivides them into contact and non-contact devices. An important subclass of the latter is the one based on the adoption of optical technology, and it can be further subdivided into active and passive approaches. We give in the following a brief characterization of optical devices based on the active approach.

Active optical devices are based on an emitter, which produces some sort of structured illumination on the object to be scanned, and a sensor, which is typically a CCD camera and acquires images of the distorted pattern reflected by the object surface. In most cases the depth information is reconstructed by triangulation, given the known relative positions of the emitter-sensor pair. The emitter can produce coherent light (e.g. a laser beam or stripe) or incoherent light; in both cases, a given light pattern (point-wise, stripe-wise or a more complex pattern) is projected on the object surface. Different technologies have been adopted to produce the structured light pattern: laser emitters, custom white light projectors, low cost photographic slide projectors and finally digital video projectors.

In this paper we focus on the use of optical active 3D scanning devices, and in particular, on scanning devices based on the automatic sweep of a laser stripe over an object. This approach represent one of the well established scanning technologies and various commercial products, exploiting this technologies, are present on the market like, just to cite a few, Cyberware, Minolta, etc. In our experiment we used a Minolta Vivid 900.

The idea of exploiting mirrors for improving the 3d scanning process is not completely new: it has been already used but, to our knowledge, only in the field of passive systems. In [9] the authors use two mirrors placed vertically nearby a talking human face to improve the tracking of markers placed on head; in this way they can correctly estimate, with a single camera (simulating three stereo camera), the 3D position of the markers. Previously, but still regarding passive shape acquisition, Huynh [7] work focused on the problem of solving of 3D position estimation in the situation of a symmetry plane and discussed the advantage of non-linear computation that can be exploited when the image to be processed contains a mirrored image of the shape that we want to detect.

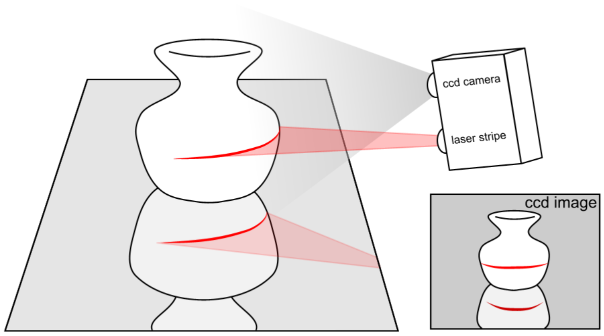

Figure 4. Acquiring a object with a laser stripe scanner in a mirrored enviroment: the ccd can see two different laser stripes projected onto the object.

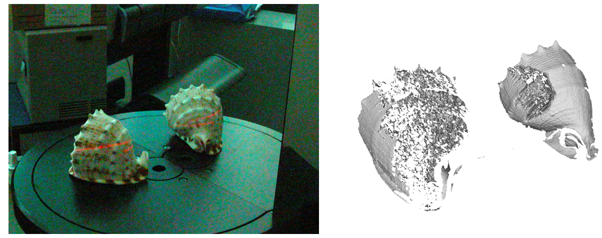

Figure 5. A double laser stripe onto the object caused by the mirrored laser emitter. On the right the resulting noisy wrong surface that is generated by the scanner.

In some cases mirrors are used just in place of placing multiple cameras or, alternatively, multiple active emitters (lasers or projectors), with the objective of saving space, costs and obtaining a surely good synchronization between duplicated devices.

In our approach we could say that we are using mirrors to completely duplicate both the object and the scanning device (Fig. 1) with the aim of acquiring the object and its mirrored image in a single range map at the same time. As shown in Fig. 1 we try to reach in this way also parts of the object that are not directly visible by the scanner. The main problems that we have to face are: understanding the location of the duplicated geometry and coping with the errors due to the mutual interaction of two scanning device (a real and a virtual one) scanning the same object at the same time.

3. Active Optical Scanning with a Mirror

As stated in the introduction, our objective is to exploit mirror reflections to help the scanning of difficult parts. Given that a naive straight use of a mirror in a scanning environment causes a lot of noise, errors and scanning failures, we need to understand their nature and how to avoid or minimize them. For a better understanding of the advantages and the problems caused by the simultaneous use of a laser stripe scanning device and a mirror it is useful to recall the basic principle about this kind of technology. As shown in Fig. 3 the laser projects a horizontal line onto the object and the camera ccd, placed above the laser emitter, captures the distorted shape of the line onto the surface of the object. Knowing the relative positions of the laser and the camera, the 3d position of each point of the laser stripe can be recovered by triangulation. The geometric configuration of laser stripe and ccd allows to be sure that for each vertical line in the acquired image there should be only one bright laser spot. Usually it is easy to detect it by searching the brightest point on each vertical line. Filtering the ccd according to the laser wavelength ensures that the maximum intensity point of each ccd column is easily detectable.

When adding a mirror to the scene we virtually duplicate the whole scanning environment, both the scanned object and the scanning device as shown in figure 1. As previously cited, mirrors are quite useful when using passive scanning technologies because they allow to acquire different parts of the same object in a single shot, exactly like when we add another camera to the scene. On the other hand using active optical technologies this approach is not straightforward because also the optically active emitting part of the scanner is virtually duplicated by the mirror and the projected patterns can appear twice onto the object surface. This is a quite hard problem when we use structured light approaches [10, 14, 11] where usually each pixel of the projected pattern bring information, allowing to recover accurate depth information using a number of images that is roughly logarithmic with the horizontal resolution of the projector. On the other hand, laser stripe scanners rely on a much more redundant approach since an image is taken for every position of laser stripe; for each column of the image there is only one *informative* spot that has to be detected.

The main problem when using a laser stripe scanner with a mirror in the scene it can happen that the ccd see two different laser stripes: the real one and the one generated by the mirror. Figure 4 shows an example where the mirror is placed under the object and the scanner sees two distinct laser stripes; this double line usually causes a failure of the surface recovering algorithm. A typical situation is depicted in Fig. 5, where a mirror is vertically placed near to an object (a seashell); the mirror reflect the laser stripe onto the right part of the object causing a double line.

Since the scanner ccd is expecting a single spot for each vertical line, the reconstruction software driving the scanner

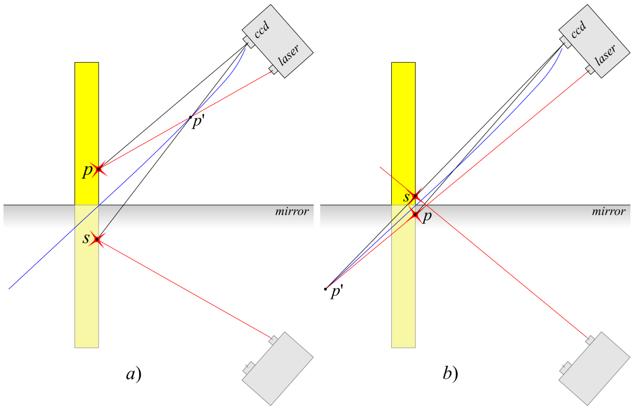

Figure 6. A double laser stripe onto the object caused by the mirrored laser emitter.

can handle these situations basically in two different ways:

- if two spots are quite near the ccd will probably merge them and consider its average as the resulting spot;
- if the two spots are far enough the scanner driver will choose one of the two arbitrarily and it will reconstruct a wrong surface.

It can be noted that a double laser stripe appears every time the same portion of the surface is visible twice[1]: directly and mirrored. There are various solutions to this problem. The simpler one is to try to place the mirror in a place that it captures only unseen parts, for example by placing the mirror behind the object with respect to the scanner. Another possible solution exploited in subsection 3.2 is to try to understand how the presence of a double laser line in the ccd wrongly affects the determination of the object surface. We will exploit this approach in section 4 to help the scanning hard to reach parts.

3.1. The mirrors

We performed the scans using two different sized front-surface mirrors, one of 400x400mm and a smaller one of 250x100mm. A front-surface mirror has the specularly reflective layer on its front side. Front-surface mirrors represent a fundamental element in order to achieve a good mirrored scan. Infact, our very first experiments done with standard (or back-surface) mirrors showed clearly that these mirrors produce too much noise and errors: the laser beam emitted by the scanner must travel two times through a thick glass layer before hitting the reflective (back) surface and bouncing out. This behavior introduces many artifacts in the final mesh obtained.

[1] from both the ccd and the laser emitter

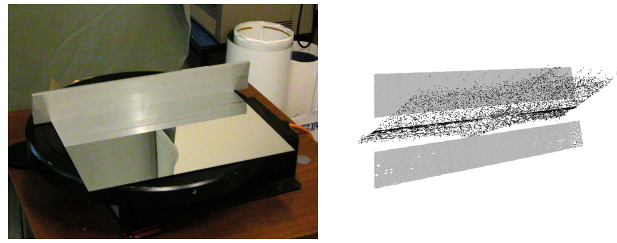

Figure 7. The wrong sample points generated when scanning an object in a configuration similar to the one in Figure6.

3.2. Noise Geometry

It is interesting to note that, once we have chosen a particular scanner/mirror configuration, we can, in some measure, predict the noise and errors due to the fact that the camera ccd sees the laser stripe twice. For sake of simplicity we assume that we are scanning a vertical surface placed orthogonally onto an horizontal mirror. In Figure 6 we show this error-generating configuration, where the ccd sees exactly twice each point of the surface. In this situation the laser stripe (shown in Fig. 6 as a red star-shaped dot) is seen twice: as a point p onto the real object and as a point s on the mirrored object. If the reconstruction software chooses the wrong point s the reconstructed surface will pass through a point p' that is wrongly placed; in fact the fake point p', will be placed on the intersection between the laser line and the line connecting the center of projection of the camera with the wrong spot s. In practice there are two possible cases:

- the laser is directed straightly on the object (Fig. 6.a): the fake laser spot s is below the real one, so the fake point p' is much nearer than the real one.
- the laser hit the object after a single bounce on the mirror (Fig. 6.b): the fake laser spot s is above the real one, the fake point p' is placed on the laser line of sight but much farther than the real one;

Within the assumption that the object and mirror are laid accordingly to the configuration shown in figure 6 we can analytically calculate the locus of the points where the fake surface can be created; this locus is shown as the blue curved line that crosses the contact point between the mirror and the object (where the real and mirrored laser spot coincide). It has to be noted that the fake point p' falls near to the original one only when the two laser spots are very near (e.g. near the mirror surface), and in most cases the fake point p' is so far (or so near) that it is immediately detected by the scanner software itself as an outlier. Therefore it is important to set up mirror, object and scanners so that the portion of surface where there can appear a double laser line is min-

Figure 8. The small mirror used to acquire hard to be reached parts.

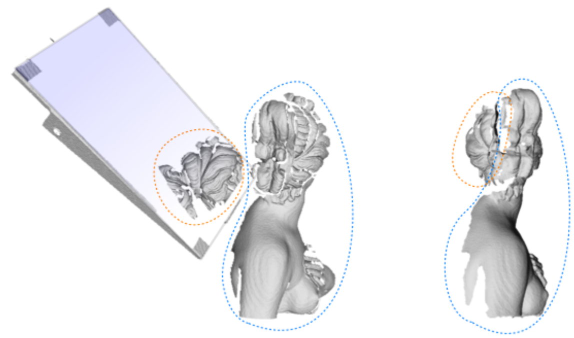

Figure 9. Recovering the lower part of hair of a statue. On the left the result of the scanning before the processing, on the right the result obtained after the mirror plane detection and geometry reflection and merging.

imal, this is roughly equivalent to trying to minimize the portion of surface that is seen twice directly and reflected.

We have found that we can greatly reduce the presence of wrong sample points when scanning an object placed over a mirror by simply placing the object to be scanned over a black pedestal that keeps it away from the mirror surface. This technique can be recommended for at least three reasons: lifting the object allows to see better under the object; the errors are more frequent in the part of the object near the mirror where it is highly probable that the real and mirrored laser stripe fall nearby; you preserve the surface of the mirror from scratch and various kind of damages.

It should be noted that if we could know with great precision the position of the mirror and the center of projection of the scanner laser and camera we could correct the fake samples by placing them again in the correct position. After some experiment we have found that this is not practical because of the numerical instability of the problem: a small variation in the mirror position cause a visible, non linear, error on the recovered surface. This numerical instability is not a problem when we have to reverse the whole mirrored geometry, as explained in Sec. 4, because any error in the mirror placement has the effect of just a rigid movement that we can easily cut off by running a Iterated Closed Point algorithm [3] to precisely correct the placement of the mirrored geometry.

4. Hand held mirror

The most interesting use of mirror is to help the scanning of hard to be reached parts. As explained in the introduction, for many different reasons it is very difficult to scan the whole surface of a complex artifacts. With the purpose of helping the scan process we have adopted a small mirror of 100x250 mm that can be either placed by hand or mounted on a photographic tripod support for a more stable, but less flexible, setup. Fig. 8 shows our hand held mirror fixed to the tripod. We have found that some experience is needed in order to place mirror and scanner in the best way. The following hints summarize the acquired experience and should be considered when using mirror to reach hidden parts:

- try to keep the mirror as stable as possible;
- place the mirror as parallel as possible with respect to the laser stripe;
- place the mirror as distant as possible from the hidden surface that must be acquired;

4.1. Locating the mirror and flipping the geometry

Clearly, to exploit the added geometry that is acquired through the mirror, we need to know the mirror position with respect to the scanner. For this purpose we have placed six optical markers near to the edges of the mirror. The markers are drawn in colors that are easily scannable by the 3d scanner, white and red (Fig. 8). The position in image space of the markers is detected by analyzing the color ccd image returned by the Minolta 900 scanner. Then we can easily find on the scanned geometry the position of the markers and therefore recovering the position of the mirror. Once you have located the mirror you have to identify the mirrored geometry and flip it with respect to the mirror. To identify the mirrored geometry it is sufficient to intersect the whole scanned geometry with, in sequence, the frustum pyramid defined by the center of projection of the camera

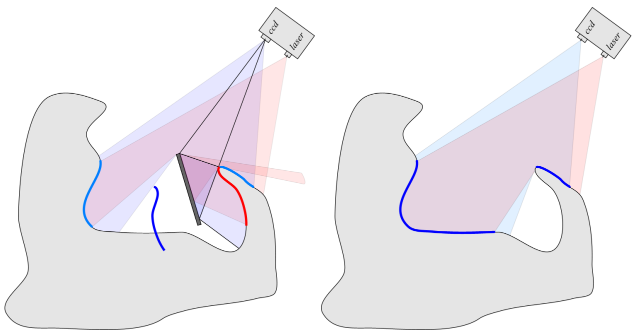

Figure 10. When scanning hidden parts with a small mirror part of the scanned geometry (in blue) has to be clipped and flipped in the correct position.

Figure 11. Scanning a constrained object, a small statue fixed on a pedestal (right). Left and center image show, respectively, the results of the acquisition without and with the help of a small mirror.

and the border of the mirror, the frustum pyramid defined by the laser emitter and the mirror border and then the half plane behind the mirror. Fig. 10 illustrates this configuration in 2D. On the left a concave object that cannot be entirely scanned, the acquired geometry is shown as a thick blue line. On the right the insertion of a mirror (the black thick line) allows the acquisition of a newer portion that appears behind the mirror (in blue). Once clipped against the camera and laser frustum and flipped with respect to the mirror plane it is placed in the correct position (in red).

Results To evaluate the gain that can be obtained by exploiting mirrors during scanning we acquired the same object with and without the help of a small mirror allowing to acquire as much range maps as needed without moving the object. The object was a small gargoyle that was blocked onto a small flat pedestal (200x250mm) in order to introduce a small constrain in the scanning process. When scanning real cultural heritage artifacts in a museum the usual constraints are much more harder (objects are usually near to a wall and you cannot move them). Figure 13 shows the result of this experiments, on the left the result of the scanning without the mirror; many small parts of the statue where impossible to be scanned without removing it from the pedestal. In the center while, with the help of a small mirror, almost the whole surface was recovered, yielding a approximative gain in the acquired surface of 3%.

5. Rotary platform

The use of a rotary platform together with a 3D scanner it is a common technique to automatize as much as possible the acquisition of simple small, medium sized objects. Usually, after a calibration step which allows to reconstruct the relative position of the turntable with respect to the scanner, a set of 8-16 range maps are automatically taken with the object rotated in different positions. A subsequent high quality alignment done using ICP [3, 13] is usually done to take off possible turntable calibration errors. The well registered range maps are then merged together in a single mesh using, in our case, a volumetric approach [5]

While this approach works well for some kind of object, like for example human heads that have a roughly cylindrical shape, only objects with a very simple shape can be completely acquired with just a single scanning turn. For most real object it is necessary to complete the scanning process by adding some range maps or by placing the object in a different position onto the rotary table and then aligning and merging by hand the acquired meshes.

For this reason we have found that a very interesting use of mirrored scanning is its combination with a rotary table in order to make the scanning process of small objects really a completely unattended and automatic process. For this purpose we have chosen to place the mirror under the object as shown in figure 12. Assuming that the rotary table has been calibrated, we know the position of the mirror plane so we can both reflect the geometry under the mirror plane in the correct position and, within a certain degree of accuracy, we can identify the fake surface points described in subsection 3.2(the ones created when the scanner ccd sees a double laser stripe). This approach allows to gather a much more complete representation of the scanned object.

In table 1 we show some numerical results on the use of the mirrored rotary table. The first column reports the

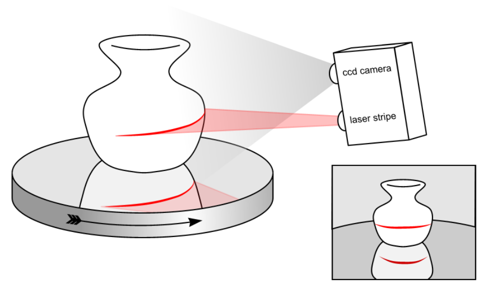

Figure 12. Placing a mirror over a rotary table allows to recover a more complete representation of a 3d object in a totally unattended and automatic manner.

	Angle	Upper	Lower	Merged	Perc.	Total
Head	30°	553.82	276.14	591.25	96.3%	613.35
	37°	538.41	314.74	588.63	95.9%	
	45°	512.25	416.40	592.16	96.5%	
	53°	471.57	109.59	555.90	90.6%	
Pig	30°	342.05	238.71	435.02	98.8%	440.09
	37°	328.15	294.83	438.05	99.5%	
	45°	310.61	267.49	434.89	98.8%	
	53°	291.14	226.09	422.65	96.0%	
Gargoyle	30°	324.90	214.43	394.05	90.7%	434.37
	37°	302.34	193.45	385.18	88.6%	
	45°	288.48	209.31	382.83	88.1%	
	53°	241.38	124.53	330.58	76.1%	

Table 1. Measures of the area of the surfaces that are acquired directly, through the mirror and the combination of both. Varying the incidence angle of the scanner affects the completeness of the final surface.

angle of inclination of the scanner (0 horizontal, 90 looking vertically down), the second and third column report, respectively, the area of the upper and lower surface that are recovered by the scanner; the upper part correspond to the portion of surface that is directly seen by the scanner, while the lower one is the one that is acquired exploiting the reflection on mirror. The third and fourth column reports the surface area (absolute and relative the complete object) that its obtained after the merging of both upper and lower parts, larger this number more complete is the object. The last column reports the total surface of the object resulting from a unconstrained fair scanning of the object obtained taking two or three turns of an object in different positions plus some range maps to cover some difficult parts. It can be observed that the incidence angle of the scanner affects the completeness of the surface, with lower angles we are able to see better under the object, so there are more hidden parts that are revealed by the mirror; on the other hand when looking at the object more horizontally you need a much larger mirror in order to avoid that some parts of the object fall outside of the mirror (like for example the top of the vase of Fig. 12). For this reason it is difficult to place the scanner with angles smaller than 30 degree except for very small objects. Moreover with smaller elevation it become more probable that the top of the object will be not completely covered.

6. Conclusion

We have presented and discussed the use of mirrors to improve the 3d scanning process when using a laser stripe scanning device. We have shown how the combined use of a mirror and a rotary table allows to make almost complete object reconstructions even for object with complex shapes, where the traditional single pass methods will surely fail. Moreover, we have investigated the use of freehand mirrors for the acquisition of hard to be reached parts showing how a well placed custom small front surface mirror can help a lot the scanning of some parts.

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Figure 13. Automatic, unattended scanning of the gargoyle and of the statue head with a rotary table and a mirror; columns from left to right: the upper part acquired directly by the scanner, the lower part, acquired through reflection and the merged meshes.

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