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Automatic Registration and Calibration for Efficient Surface Light Field Acquisition

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Abstract

This paper presents a novel protocol for the acquisition of surface light fields which is designed to deal with delicate objects that might not be touched or moved. This constraint is particularly important when art pieces are involved. Our protocol enables the automatic reconstruction of a model from many range images and the automatic registration of many pictures with the acquired geometry. A structured light pattern is first used to project a parameterization over the analyzed surface. Each surface point hit by this parameterization is uniquely identified, independently of the chosen viewpoint, and the problem of finding point-point and point-pixel correspondences is then immediately solved. These correspondences are finally used to perform the registrations and camera calibrations that provide the data to be used by a surface light field renderer.

1. Introduction

In the research field of computer graphics and visualization, a part of the scientific community is attempting, for many years, to take account of reality to increase the visual quality of synthetic images. The appearance and the development of digitization tools have widely promoted this kind of approach, allowing numerical measurements of complex real data. Unfortunately, although these tools are greatly used nowadays, they are often subject to high constraints and such measurements are not always easy.

The task is even more difficult when additional constraints arise from the objects to be measured. This is the case of our work which is a part of a national project done in conjunction with the ministry of culture and with museums. One aim of this project is the archiving of art pieces by the establishment of a numerical imprint, including geometrical and photometrical information. We are then interested in capturing the shape and the appearance of fragile models that might not be touched or moved too often.

Concerning the geometry, current devices are not able to immediately acquire the whole surface of an object. Range scanners, for example, can only view one side of the object at a time, and a complete digitization requires several acquisitions by placing the scanner at different locations to cover its surface as best as possible. All measured surface parts must be post processed during a reconstruction step. As each scan is defined in the scanner local frame, the first problem addressed by reconstruction is to express all scans in a common global frame. This problem, called *registration*, can be

Figure 1: Left*: a picture of the Greek vase model.* Middle*: a model reconstructed from several range images.* Right*: a synthetic view generated from the surface light field captured with our method. All acquired range images and pictures are registered in a fully automatic manner.*

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easily solved by systems such as robotic arms, able to accurately localize the scanner with respect to its target. All motions are recorded, and the transformation associated to each scan is immediately known. In spite of their convenience, such devices are expensive or are not always designed to be displaced. If the motion of the scanner with respect to the object is not recorded, it must be estimated. The crucial point to solve for an efficient registration solution is then to be able to accurately determine some correspondences between geometric points of the different scans.

Another important part of the digitization of real surfaces is concerned with the acquisition of materials. Indeed, as illustrated in figure 1, the only shape is not sufficient to represent the digital copy of an object in a realistic manner. Emerging in parallel to digitization tools, dedicated rendering techniques have been developed. Among these, the surface light fields attempt to represent the appearance of an object within a fixed lighting environment and from an arbitrary viewpoint. In order to synthesize images from real data, the radiance emitted by the considered object has to be measured beforehand for many viewpoints. This information is commonly captured by taking several pictures from different viewpoints. To correctly interpret this captured appearance, the viewing direction associated to each picture must be known. It can be determined by solving a well known problem of camera calibration, where intrinsic (optical parameters) and extrinsic (camera pose) parameters are estimated. As this estimation is computed from the image space projections of many scene points, the efficiency of the calibration procedure, once again, depends on the ability to accurately establish some correspondences between two data sets: the geometric points and their matching camera pixels.

This paper proposes a new protocol for the acquisition of geometry and radiance specifically designed to deal with delicate models. Neither contact nor displacement of the measured object is involved and all the registration procedures are fully automatic. Concerning the remainder of the paper, the related scientific context is first explored in section 2. An overview is presented in section 3 and the technical points are then explained in sections 4 and 5, respectively describing our extraction of correspondences and its use for the acquisition of surface light fields. Results and studies are presented in section 6, followed by conclusions in section 7.

2. Related Work

A light field is an approximation of the plenoptic function [AB91] which describes for all points in space the incident light incoming from the whole scene. The first approaches proposed to represent this function were purely image based renderings [LH96,GGSC96], able to generate new views from a set of acquired pictures. Later, the *surface light fields* [MRP98, CBCG02] propose to store the light field directly over the surface of an object, leading to some interesting simplifications. In first, only the relevant information is kept, avoiding all background data. Next, as the information is stored on the surface, texture mapping can be exploited to speedup the rendering. Unfortunately, as a surface light field requires a geometric support, both the radiance and the shape must be acquired while dealing with real data. Hence, the registration problem is of great importance and is present at two different levels: many range images must be merged to produce a single consistent model and many pictures which sample the radiance must be registered with the acquired geometry to determine the data of the surface light field.

Concerning the geometry, many works have investigated the problem of reconstructing a single model from many range data. When an initial coarse alignment is known, iterative methods are able to progressively refine the solution [BM92,TL94,BS99,GGT00,GG01]. But if a fully automatic procedure is preferred, such a prior knowledge is not always available and some correspondences must then be found to compute a transformation between different data sets. Based on the idea that the scanner pose is never arbitrarily chosen, a knowledge about the adopted scanning strategy [PFC*05] enables to predict the overlaping relationships between scans, reducing the search of matching elements to small subsets. Sometimes, features may be extracted when data arises from specific scenes or situations. Urban scenes [ZSHQ04], for examples, present many apparent and organized edges that can be identified. In the case of a real time acquisition pipeline [RHHL02], the temporal coherence between successive frames can be exploited. But even if feature extraction has the advantage of avoiding the requirement of a prior knowledge, it is generally designed for scene dedicated methods and not for general approaches. Based on the same idea, other works attempt to extract invariant characteristics which does not rely on any assumption about the scene [JH97, CHC98, ZH99]. These methods, even if working on arbitrary data sets, are often based on exhaustive searches and are then computationnaly expensive. All the aforementioned techniques are focused on pair-wise registration, only able to deal with two data sets. Generally, a complete digitization requires many more than two acquisitions and global registration methods have been proposed to take into account all of the resulting range images at the same time [Pul99,HH01,NI02,ZSHQ04]. Unfortunately, many of them require an initial alignment to prove practicable or efficient.

Beyond the shape, a surface light field acquisition protocol has to be able to register a set of pictures with the geometry. The most common way to achieve this is to use targets [CBCG02]. The problem is that targets must be seen by the acquisition devices and this is not an obvious task. In cultural heritage, for example, scanning art pieces forbids to put targets directly over the object. In its neighborhood, some occlusion problems may be introduced. Moreover, depending on lighting conditions, an automatic image segmentation may fail to localize the targets. Methods based on silhouette matching [MK99] might not be robust enough

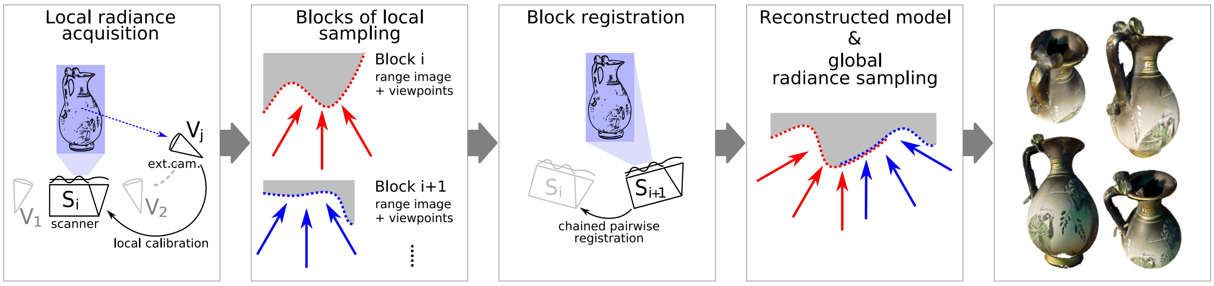

Figure 2: *Our acquisition protocol. A local radiance sampling is first acquired by registering several pictures with respect to the current range image. The resulting* blocks of local sampling *are then merged together in a common global frame by a chained procedure that register each block with respect to the previous one. The registration transformations are applied to the range images and to their associated sets of pictures, leading to a consistent model and a global radiance sampling.*

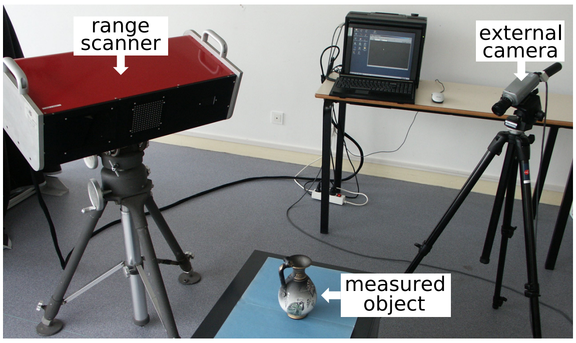

Figure 3: *Our digitization bench to capture whole surface light fields. Only a lightweight device is involved: a structured light range scanner and an external camera.*

(with surfaces of revolution or symmetrical objects, for example). Most recently, a system has been proposed to infer new image-to-geometry correspondences from a set of known ones [FDG*05]. But the user interventions, even if greatly reduced, are not totally avoided as the initial set of correspondences must be specified manually.

3. Method Overview

We are interested in capturing the appearance of delicate objects, such as art pieces, that cannot be touched or moved. At the end of the acquisition step, we recover all the data required by a surface light field rendering method, that is a fully reconstructed model and a set of pictures, to sample the radiance, whose viewpoints are known. To achieve this goal, we propose an acquisition protocol which performs the model reconstruction and the viewpoint determination in a fully automatic manner without any contact or displacement of the measured object. Moreover, to agree with a mobility constraint, only a lightweight hardware is involved: we just need a range scanner based on structured light and an external digital camera, as shown in figure 3.

Our protocol, summarized in figure 2, works as follows: an acquisition procedure enables to automatically register many pictures with respect to a single range image. This step is iterated as mush as needed to cover all the object surface, resulting in many separate blocks made of a range image and its associated set of pictures. All blocks are then registered by a chained procedure that register each new acquired block with respect to the previous one. The transformations required to align the scans are automatically computed and are applied not only to the range images but also to the associated sets of calibrated pictures. Thus, both the geometry and the pictures used to sample the radiance are expressed in a common global frame.

The two tasks of registering a picture with a known geometry and registering a piece of surface with another one consist in computing a transformation between two data sets from a list of correspondences which must be determined. The major benefit of this work is the solution proposed to solve this relationship problem. We use a structured light pattern to project a 2D parameterization onto the considered object. Consequently, all the surface points covered by this parameterization are identified by a unique couple of coordinates. The search of correspondences then reduces to find points in the different data sets whose parameterization coordinates are equal. The picture's viewpoints and the range image's alignments are then computed from these correspondences by some well known and experienced algorithms (see sections 5.1 and 5.2).

As our goal is the acquisition and not the visualization, we are using a basic surface light field renderer to provide some examples to rely on for analysis and validation.

4. Extraction of Correspondences

In this section, we first discuss the interesting properties of the structured light model we use and how we extend it

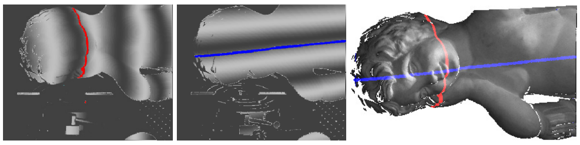

Figure 4: *The phase is strictly increasing orthogonally to the stripes orientation, producing some iso-phase lines over the measured surface. Given two different stripes orientations, each surface point is associated to the intersection of two iso-phase lines and is then uniquely identified.*

to produce a spatial parameterization of the measured surface. This parameterization defines a unique identifier at each point and is used to establish a set of correspondences between different data sets. As some errors are necessarily introduced while measuring, some of the correspondences which have been found are erroneous and it is of great importance to estimate the accuracy of the acquired data. We therefore introduce an error metric based on our parameterization to easily and efficiently classify the possible outliers.

4.1. Structured light model properties

The structured light model we use is based on the phase shifting principle. A set of grayscale stripes whose intensity's variation follows a sinusoidal is projected and an image analysis enables to determine, for a pixel p of a sensor camera, the value of the phase $\phi(p)$ corresponding to the observed surface point. Many shape measurement methods, as [HZ05] for example, are based on a phase shifting principle to compute a depth information by optical triangulation. We recommend the reader to take a look at these works for more precise informations.

An interesting property is that such structured light models induce a 1D parameterization of the measured surface. Indeed, the phase information is monotonically increasing and is continuously defined over the whole projection domain, orthogonally to the stripe direction. Each stripe is then clearly identified by a unique phase value, producing some iso-phase lines over the object. A second property is that the computed phase is independent of the viewpoint chosen to capture it. If the projector remains static with respect to the measured surface, the phase values computed at a given surface point from different viewpoints are identical, whatever the camera settings are.

4.2. Extension to a surface parameterization

The 1D parameterization induced by this structured light model can be easily extended to a 2D parameterization. By projecting the same stripe pattern along two orthogonal orientations, a couple $\Phi(p) = (\phi_1(p), \phi_2(p))$ of phase values is defined at each surface point p. As the two functions $\phi_1(p)$ and $\phi_2(p)$ are monotonically increasing over their own domains and then do not have the same value twice, the couple $\Phi(p)$ represents a unique identifier for the point p, as illustrated in figure 4. In the remainder of this paper, we call this 2D parameterization the Φ-*parameterization*.

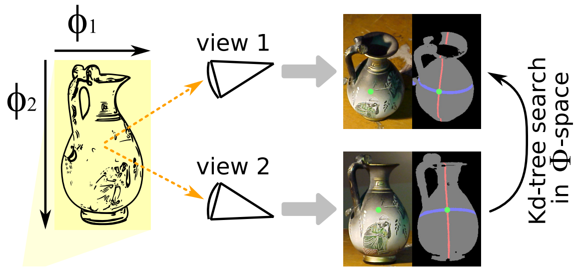

Figure 5: *The same Φ-parameterization is captured (the projector and the object remain static) from two different viewpoints to define correspondences. An element in the first view is paired with the element whose couple of phases is the nearest in the second view.*

By considering the properties of the structured light model presented beforehand, as long as the scanner and the considered object remain static, the Φ-parameterization remains the same and is completely independent of the viewpoint chosen for its acquisition. As a consequence, while the parameterization does not change, two pixels p and q coming from two distinct viewpoints and having their coordinates $\Phi(p)$ and $\Phi(q)$ identical are necessarily focused on the same surface point.

4.3. Selection of correspondences

This identification of some surface points is used in order to solve the problem of finding correspondences between different data sets. Unfortunately, practical problems arise as digitization tools are subject to many error sources ([RHHL02]). The most stringent one is the CCD discretization: as the acquisition camera is not able to capture a continuous domain, two pixels taken from different viewpoints never see exactly the same surface region, involving dissimilarities between their respective Φ coordinates. The search of correspondences is then no longer an equality test but should be replaced by a nearest neighbor search.

We use the squared Euclidean distance between the couples of phases as an accuracy criterion. Given two points x and y coming from different viewpoints but captured with the same Φ-parameterization and their respective couples of phases $\Phi(x) = (\phi_1(x), \phi_2(x))$ and $\Phi(y) = (\phi_1(y), \phi_2(y))$, the distance between x and y is denoted $\varepsilon(x, y)$ and is defined by equation 1:

$$\varepsilon(x,y) = (\phi_1(x) - \phi_1(y))^2 + (\phi_2(x) - \phi_2(y))^2 \qquad (1)$$

As shown in figure 5, given two data sets identified by

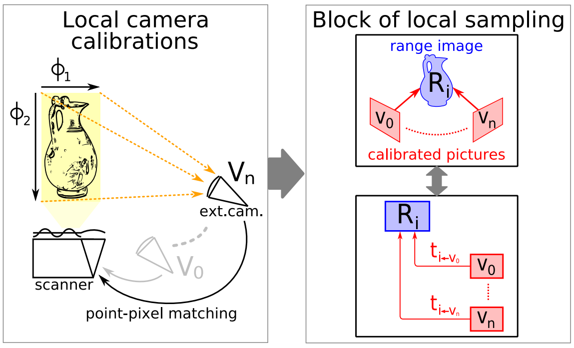

Figure 6: *The acquisition of a* block of local sampling. *The block is made of the range image and all the pictures that have been calibrated with respect to it.*

the same Φ-parameterization, the correspondences are then found by parsing all elements of the first set and searching the nearest element with respect to the ε-distance in the second one. This search is efficiently implemented by using Kd-trees. As we are exploring the space of the Φ-parameterization, trees of dimension two are used.

4.4. Outlier classification

Among all the resulting pairs, some might not be valid. Indeed, even if the Kd-tree search leads to a result, the nearest element that has been found is not necessarily a good correspondence. We use the ε-distance to determine the validity of each association. If the ε-distance exceeds a given threshold S_ε, the two elements are considered as too distant and the association is discarded. More than rejecting outliers, this thresholding is a good way to retain only the most accurate correspondences by setting a low threshold. In our application, this threshold is data dependent and is defined as $S_\varepsilon = \lambda\, S$, where S is the average ε-distance between adjacent pixels of the considered viewpoint and λ is a factor depending on the desired quality of registration.

5. Surface Light Field Acquisition

As our acquisition protocol is based on the aforementioned principle, we have modified our range scanner to be able to get back the phase image before its transformation into a range image. A second modification enables to perform a phase acquisition with an external camera instead of only the one embedded in the scanner. The protocol is decomposed in two parts. In first, a local sampling of the radiance consisting in a set of calibrated pictures is linked to each acquired range image, resulting in what we call *local sampling blocks*. Next, all these blocks are merged together by a registration step that remaps all data (geometry and pictures) in a common global frame.

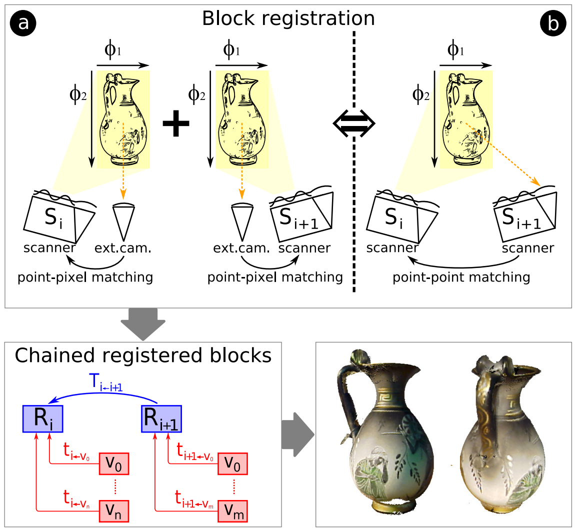

Figure 7: *A local sampling block is registered by a chained procedure with respect to the previously acquired one. The external camera is used as a fixed reference between the two scanner positions.*

5.1. Acquisition of a local sampling block

Considering a single range image R_i, the acquisition of the associated radiance information is easily made by using our structured light pattern, as illustrated by figure 6. After having performed the geometric acquisition, the scanner projects the Φ-parameterization onto the object and captures it. As the scanner as not been moved, there is a pixel-to-pixel matching between the phase image and the range image R_i, and many acquired surface points can then be uniquely identified, as explained in section 4.2. The radiance information is then captured by using the external camera. More than taking the picture v_j, this camera also captures the Φ-parameterization. Some correspondences can then be established between many pixels of v_j and the matching 3D points of R_i by using the search procedure of section 4.3. Tsai's calibration algorithm [Tsa92] finally estimates the scan-to-camera transformation $t_{i\leftarrow v_j}$ from these point-pixel correspondences and thus associates a viewing direction and a localization to the considered picture v_j.

This procedure is repeated for many camera positions to get a radiance information with a dense sampling of viewing directions. Obviously, the external camera needs to view the parameterization projected from the current scanner position. Thus, the captured set of pictures does not correspond to a whole radiance sampling but only to a part of it, defined around the current scanner viewpoint. We call *local sampling block* the set composed of the range image R_i and all the pictures $v_0,\ldots,v_n$ that are locally calibrated with respect to it.

5.2. Block registration

Each block represents an isolated part of the final surface light field, disconnected from the others. All blocks must then be merged together by a registration process. This registration does more than just aligning the geometry data sets: a rigid transformation is computed from the geometric data and is applied to the whole local sampling block, that is to say to the range image and to its set of locally calibrated pictures. All geometry parts are then merged in a common global frame, as well as all calibrated pictures.

Each time a new block is to be acquired, the scanner is moved to a new position. However, there is no explicit common reference between the frames of the different blocks. We are then using the external camera as a fixed reference between two successive block acquisitions, as illustrated by figure 7. Standing at a given position, the external camera captures the two parameterizations projected from the previous and the current scanner positions. As previously discussed, correspondences are extracted between some pixels of the external camera and some points of both range images R_i and R_{i+1}. The pixels that are linked to the both range images provide the geometric correspondences needed for the block registration. The rigid transformation $T_{i \leftarrow i+1}$ to remap R_{i+1} in the frame of R_i is finally computed from these correspondences using a quaternion-based method [BM92]. Once the registration transformation is known, we apply it not only to the range image but also to the viewpoints of the associated set of pictures. For the i-th block composed of the range image R_i and the viewpoints $v_0, \ldots, v_n$, the transformation T_i to remap R_i to the global frame is the composition of all the previous registration transformations $T_i = T_{1 \leftarrow 2} \times \ldots \times T_{i-1 \leftarrow i}$ and the transformation t_j that projects the global frame to the image space of the viewpoint v_j is defined as $t_j = t_{i \leftarrow v_j} \times T_i^{-1}$. Thus, each block is registered with respect to the previous one by a chained procedure. The final geometry reconstruction is performed by the VRIP algorithm [CL96].

If two range scanners are available, a more immediate solution is clearly possible. The second scanner can act as the external camera: it captures the parameterization projected by the first scanner, as shown is figure 7*b*. The phase based search then results in a direct mapping between the two scanner frames. It is obvious that using an intermediate device instead of two scanners clearly induces a loss of accuracy. This point is discussed in the result section. Nevertheless, it is important to note that the examples provided in this paper have been produced with the method involving only one scanner. Usage and measurements have shown that this first solution is accurate enough to be used.

6. Results

To visualize the data provided by our method, we have developed a basic rendering algorithm which computes the color of a geometric primitive for a given viewing direction by the interpolation of the three closest radiance samples. Figures 1 and 8 have been generated by this renderer. These surface light fields have been reconstructed from 5 range images and 27 viewpoints for the Greek vase model, and from 6 range images and 42 viewpoints for the African wood statue.

Figure 8: Left*: the mesh of the Venus at Bath reconstructed from 23 range images registered with our method.* Right*: a picture of the African statue and two synthetic views generated from the surface light field acquired with our protocol.*

Set	ICP		Φ-param.	
	mean	*std. dev.*	*mean*	*std. dev.*
Angel	0.270	0.235	0.328	0.235
Greek1	0.234	0.360	0.292	0.371
Greek2	–	–	0.234	0.336
African	0.248	0.265	0.250	0.262

Table 1: *Comparison of ICP against our method. The given values correspond to the average distance (in mm) between nearest neighbors in the overlapping region of the two scans. Empty cells correspond to a case where ICP has failed to perform the registration.*

Concerning the calibration process, the main advantage of our method against the use of standard targets resides in the number of available calibration points. While the number of targets in the scene is necessarily limited, the number of available point-pixel correspondences is generally not exceeding a few tens. In our application, the number of calibration points used in the Tsai's algorithm is of many thousands. Moreover, as we use a projected parameterization, the occlusion problems that can be encountered with targets are avoided. Concerning the registration, table 1 compares ICP to our method in terms of accuracy. As can be seen, ICP remains more accurate, certainly due to its iterative nature. But it is important to recall that ICP requires an initial coarse alignment whereas our registration if fully automatic. Moreover, ICP may fall into a local minimum if the two surfaces

ICP		Intermed. camera		Two scanners	
mean	*std. dev.*	*mean*	*std. dev.*	*mean*	*std. dev.*
0.270	0.235	0.328	0.235	0.303	0.239

Table 2: *Comparison of our two variants of registration. The given values correspond to the average distance (in mm) between nearest neighbors in the overlapping of two scans.*

Nb. points in the 1st scan	*Nb. points in the 2nd scan*	*Nb. corres. found*	*Registration time (ms)*
325K	331K	15K	629
331K	329K	2K	455
75K	76K	3K	419
215K	182K	10K	579
23K	20K	11K	250

Table 3: *Timings measured during some pairwise registrations. The registration time includes the search of correspondences and the computation of the rigid transformation.*

present the same global shape. We have experienced this problem with the Greek vase model, as shown in table 1. We have also compared the two variants of our protocol (with one scanner and a camera or with two scanners). Two scanners have performed a geometric acquisition and an external camera were placed between them during the phase acquisitions. The result, reported in table 2, shows a loss of accuracy induced by the use of the external camera instead of the two scanners. This loss was predictable but is not as significant as we expected.

In terms of performance, registration timings are given in table 3. These timings have been obtained with a processor AMD Athlon 3800+. The bulk of our technique consists in finding inside a range image the best approximation of a given point, based on its phase identifier. This search is done in the space of the Φ-parameterization and must be done only once, as opposed to the ICP algorithm where Kd-trees of dimension three must be recomputed for each iteration. Performance for the calibration has not been measured, as it only depends on the effectiveness of the Tsai's algorithm.

There are two drawbacks with our method. The main one is the cumulative nature of the error due to the chained pairwise registration. We have compared, in table 4, the average distance between the two scans of all the registered pairs and the distance between the first and the last scans of the whole chain of 23 range images of the Venus at Bath. In this example, the incidence of the accumulation remains neglectable as it does not induce any misalignment artefact during the reconstruction. This first drawback exists in all methods that are not designed in the purpose of a global registration. However, our results can be used as a good starting point for global registration methods where an initial alignment is needed. As shown in table 3, our registration is fast enough to be used as the initialization of another technique.

Avg. dist. for pairs: 0.243mm	*Last-to-first dist.:* 0.477mm

Table 4: *Error accumulation for the 23 acquisitions of the Venus at Bath.* Left*: average distance of all registered pairs.* Right: *distance between the first and the last range images.*

The second drawback is related to the capture of the radiance. Since the Φ-parameterization must be known for each viewpoint, the method does not allow the use of a hand held camera. Indeed, both the camera and the projector have to remain static since a picture and two phase acquisitions need to be taken with respect to the exact same viewpoint. The acquisition time of the radiance information may then be increased compared to the use of standard targets. Moreover, as the calibration process depends on the registration to establish a global radiance sampling, the cumulative error described beforehand may have an incidence on the accuracy of the viewpoint localization.

7. Conclusions & Future Work

We have presented a new protocol for the acquisition of surface light fields from real objects. This protocol is designed to perform some measurements on delicate objects, such as art pieces in a context of cultural heritage, that cannot be touched or moved. We are using a structured light pattern to project a parameterization over the analyzed surface which enables to uniquely identify many scene points. This identification is used to deduce the viewing directions of a set of pictures that captures the radiance of the scene, but also to perform a chained pairwise registration to reconstruct a consistent model from many range images.

Due to the use of a spatial parameterization, a quasi immediate mapping is established between the different data sets. The search of correspondences and so the registration are then fast comparing to iterative methods, even if the result is not as accurate. To increase accuracy, our solution could be used as a good starting point for a global registration method to avoid the cumulative nature of the error.

Concerning the material acquisition, we work on extending our protocol to enable the digitization of models with their complete bidirectional information. We are particularly interested in the simplification of the digitization process as it is always, nowadays, a really tedious task due to the requirement of an exhaustive sampling of the lighting. Indeed, capturing a bidirectional information means to control the lighting environment. The ability to precisely localize a light source in order to deduce the incident light directions is then another goal to achieve.

8. Acknowledgement

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