

# Laying Out Tile Vaults with Local Positioning Systems

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## 1.-Introduction

Today, it appears odd to use sophisticated calculation programs to design masonry vaults but continue to work with traditional installation and setting out methods -in those buildings which we still cover with vaults and domes. This is even odder if we consider the current omnipresence of topographical machines: it is hard to find a building constructed without total stations or laser levels. However, masonry vaults, for all their sophistication, are still being set out with small falseworks, string gauges and complex formwork. When it comes to tile vaults, we can say we continue to build them without formwork, almost with the same laying out techniques that were used 400 years ago.

It is evident that the cause of this lack of progress is due to the fact that very few vaults are built today, and the few that are constructed don't justify a specific topographical device. However, in the current context of the recovery of the tile vault, and given the facilities that digital means offer to create new setting out tools, we believe that it makes sense to design a specific setting out system to aid the construction of vaults without formwork. Above all this could be used to build complex geometries which, as we will see later, are for various reasons increasingly more common.

It is important to emphasise the point made above -a topographical system to set out tiled vaults only makes sense if the object is to build complex structures. The simple forms are easy to transfer from a plan into the real world, without the need for any apparatus. A hemisphere, for example, can be built without difficulty, using a simple piece of string tied to the wrist, and a domical vault with a straight generatrix (traditionally the most common) is easily constructed using straight reference wires or strings (Truñó 2004 or García 2007). The traditional systems are very efficient for these forms, but to build complex irregular structures, generally based on inverted catenaries, it is necessary to elaborate formwork adapted to the desired shape. The more complex the form to be built is, the

more abundant the formwork needs to be. This is contradictory to the spirit of the system since a tiled vault should be erected, as far as possible, with little or no formwork.

### The problem of construction without formwork

A laying out tool that allows for the construction of vaults without formwork should be designed to construct with hardly any references. This implies resolving two problems. The first one is a question of compatibility between the virtual and the real: how do we turn any virtual surface (logically today, a digital model) into a real one, avoiding any physical reference? The second is a problem of the order of construction: how do we communicate the location of the structure to the bricklayer so that he can easily place each piece in the correct position?

Topographical apparatus already exist to deal with similar problems, although its application to vault construction is not immediate, and neither is it practical. Amongst the means available in the market today some can be used to register the position of a point in space. These include those based on GPS positioning or on traditional laser distance measurements. These systems offer general information (the location in relation to a plan or coordinates with respect to some prefixed axis) but they are not designed to make this information directly comparable with the area of a form which has been previously created. Besides, the precision they offer is inadequate for the construction of vaults since the taking of points is not agile or immediate. Furthermore the systems generally need expensive and delicate equipment, which makes them incompatible for direct use in bricklaying works.

The solution we put forward consists of the use of a positioning system based on the reconstruction of the optical relationship that exists between a camera and a series of predetermined objects, which are recognised

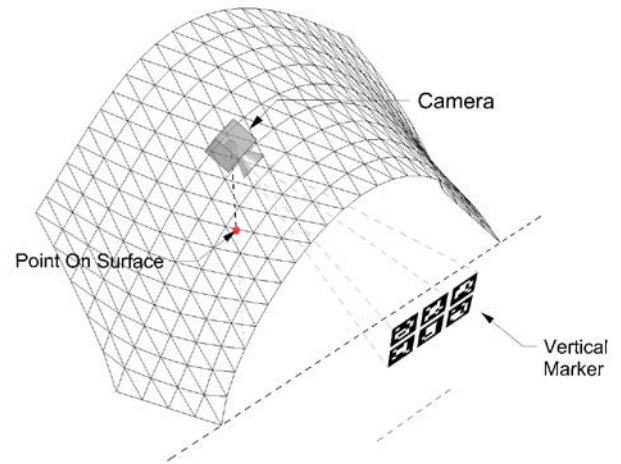
by means of artificial vision techniques undertaken by a computer.

With respect to the first issue above, the one that concerns the translation of any structure to reality, the relationship of the camera configuration and markers considerably simplifies the system necessary to transfer the location of a point in reality to a virtual environment and vice versa. It is sufficient to have control over the marker series in the chosen area by allowing the camera to “see” something of these in order to recognise the relationship of the positions between both. The equipment doesn’t necessarily need to be of a high level of sophistication. It is possible to use webcam type cameras or those installed in most mobile telephones while keeping levels of accuracy compatible with the construction system of tile vaults. On the other hand the markers, which the system should recognise, can be as simple as printed geometric patterns on supporting plans. The use of standard devices – camera, markers and computer – reduces the cost from the start compared to other systems.

With respect to the second issue, related to communicating the bricklayer where the structure has to be, we agree that the most comfortable and operative way would involve him taking the camera with him, and that it would operate wirelessly with respect to the rest of the system. Thus, just by moving the camera until one of the markers enters its field of vision the bricklayer could know the position of the camera in space. By contrasting these coordinates automatically with those of the surface area we wish to construct, we would know if this point pertains to it or not. More importantly, by moving the reader as we do with a conventional laser level we will know the distance we are from the surface to be built, which means how much below or above we are from it. Following this procedure, similar to that with a laser level for curved areas, the bricklayer could easily obtain as many points as necessary and could have references in space of each new row and also, if needed, each new piece.

## 2.-Positioning System

In general terms, the system is based on obtaining the position of a camera with respect to a scene known by means of optical recognition of a series of markers located in predetermined positions. It involves the correlation of the position with a virtual reference module, which contains the ideal geometry of the vault to be built, including the distance from the camera to its vertical projection over the ideal surface.



**Figure 1.** Schematic positioning system, including the camera, a panel of markers and the designed surface.



**Figure 2.** Implementation of the system, with a webcam, a marker board upright and the use of a dead load to precisely locate the reference point.

What follows are the technical characteristics and operation of the proposed positioning system in relation with the two building experiences conducted.

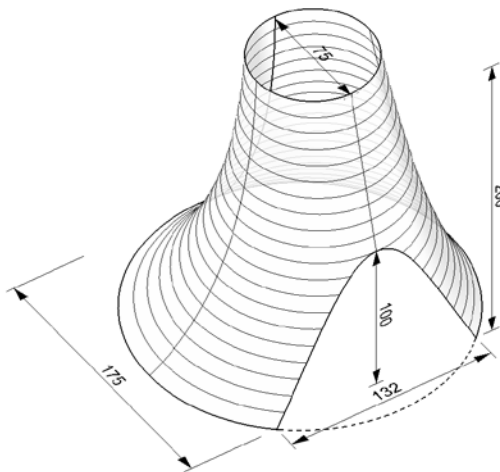
### Reference model

The first element necessary to layout and build a tile vault is of course a reference model. The model may have been designed in various ways, considering its projection in two-dimensional documents, via a reduced physical model or, more conveniently, in the form of a digital model.

Obviously, the positioning system that we are proposing requires access to the digital model to determine the relative position of each piece to the ideal shape, so we chose to directly generate digital vaults, using commercial software for modelling surfaces. Since the aim of this article is to validate building counterintuitive forms, we tried that our reference models did present some geometric complexity while maintaining static properties and construction to ensure their stability and feasibility.

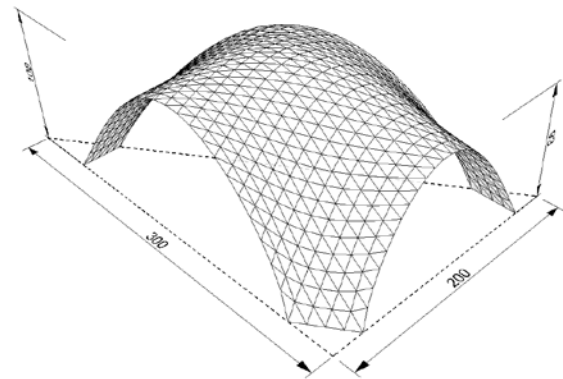
We chose to use Rhinoceros as modelling software because of its proper treatment of continuous surfaces and polygon meshes. It also allowed us to incorporate routines and functions for formal and constructive analysis of these geometries.

The model of the first experiment was prepared using double curvature continuous surfaces, resulting in a completely hyperbolic geometry with a configuration that ensured stability during its construction. [Figure 1] For the second model we chose to generate the form by means of following a dynamic relaxation process of a polygon mesh under the action of parallel and vertical forces on its vertices. Thus the antifunicular surface created ensures, with an appropriate level of confidence, the fact that the whole vault will work on compression once completed. [Figure 2]



**Figure 3.** Geometric model of the first vault experience described in this article.

The simplicity of the base layout was an important fact taken into account in the design and preparation of reference models. The geometry of the support of the first model consisted of a circle of known radius, easy to trace in the floor, and the second is inscribed in a triangle of predetermined dimensions and equally easy to trace.

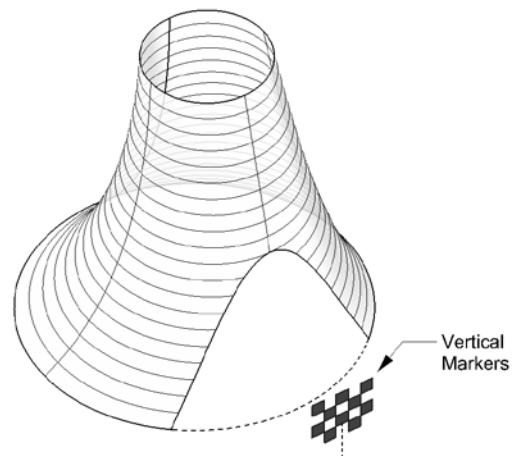


**Figure 4.** Geometric model of the second vault experience described in this article.

### Scene set-up

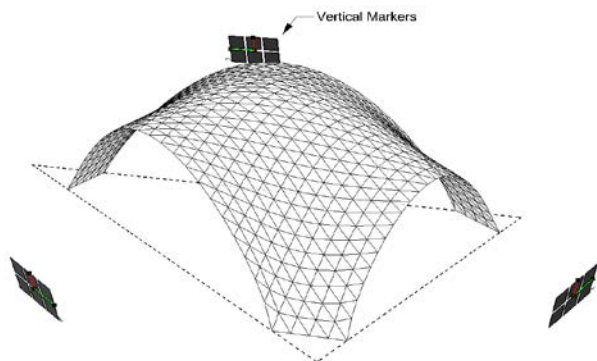
Having decided the shape and dimensions of the vaults to raise, the physical environment in which they will build has to be prepared. In addition to determining the bearing zones of the vaults in the ground, markers as reference objects must be placed, and its position must be transferred to the virtual environment model. The relationship between markers and digital reference models is used to validate the same relationship between markers and vaults in the, so to speak, real world.

In the first experiment we used a single marker, whose position was determined relative to the floor and the circle where the vault started. That same position was introduced in the digital model and was used as a reference for the determination of the position of the camera relative to the virtual model. [Fig 5]



**Figure 5.** Relative position of the markers on the first geometric model

In the second dome, with a geometry that was larger and more complex, three different boards with markers were used, whose positions relative to each other and to the boot triangle in the soil were determined once fixed on stable supports. The markers were then introduced in the virtual model as reference elements for determining the position of the camera relative to the virtual model. [Fig 6]



**Figure 6.** Relative position of the markers on the second geometric model.

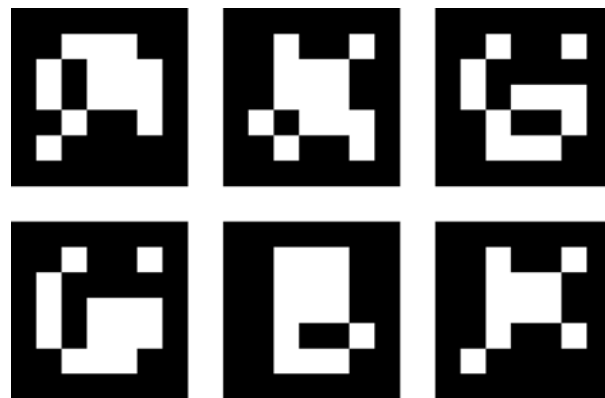
### The markers detection system

As mentioned in the previous section, we worked with tools affordable and accessible to most users: a webcam and a PC, as hardware elements, and a combination of free and open-source tools for the process of recognition of markers and positioning.

For the positioning system we have developed a console application -without graphic interface- in which we employ OpenCV as an artificial vision library, and Aruco as a library to facilitate detection of the markers and to estimate the position of the camera.

OpenCV (Bradsky 2000) is a library for image processing, initially developed by Intel, focused especially on real-time processing of images for developing applications for machine vision and facial recognition.

Aruco (Muñoz-Salinas 2012) meanwhile, is an open-source library built on top of OpenCV to recognize optical patterns that can be generated with the library itself. Aruco helps us to identify these patterns and, most importantly, to give the relative position of the observer (our camera in this case) on these patterns. Optical patterns generated by Aruco consist of one or several markers. When a pattern combines multiple markers a board is generated. Using a panel of several markers increases accuracy and minimizes the chances of references not being recognized. In our experiments we used 2x3 boards markers, such as the one in [Fig 7]



**Figure 7.** Example of a marker board. Each board is unique and therefore several can be used for the same layout, increasing the comfort and precision of the system.

Each marker contains an encoded number with 25 bits, 15 of which are used for error corrections. With the remaining 10 bits it is possible to use a total of 1024 markers simultaneously in the same system, grouped as boards or separated. It is important to note that although Aruco can recognize a single marker without any previous data, to recognize a board (that is, a combination of markers) it will need the identifiers of the markers and their position on the board. Similarly, it is essential to know the size of the markers, and the separation between them, in arbitrary units (eg pixels), and also the size of the marker in meters, so we can afterwards obtain the relative position of the camera marker.

For more information about the detection process see Aruco's reference page.

### Reconstruction of the pose

To describe how our application determines the position of the camera relative to the marker board, it is important to remark that the camera model that we have considered is the one known as pinhole, where the relationship between the coordinates of a point in the real space of the scene  $X_e$  and the coordinates of that point in the plane of image  $X_c$  have the following projective relation:

$$X_c = I \cdot E \cdot X_e$$

Where:

$X_c$  is a vector of coordinates in the image plane of the form  $[u, v, 1]$

$I$  is the 3x3 matrix of intrinsic parameters of the camera' –the one which expresses its projective properties.

$E$  is the 4x3 matrix of extrinsic parameters of the camera –the one which relates the reference system of the camera with the reference system of the scene.

$X_e$  is a vector of coordinates in the space of the scene form  $[x, y, z, 1]$

When the positioning system is running, the application attempts to analyze and process as many frames per second as possible. For each frame analyzed, the process obtains the extrinsic parameter matrix  $E$  (4x3 elements) of each board detected, with a rotation matrix  $R$  (3x3 elements) and a translation vector  $T$  (3x1 elements):

$$E = R \cdot T$$

$R$  and  $T$  provide the position of a coordinate system  $M$  centred on each board.  $M$  is detected taking as origin of coordinates of the centre plane of the camera sensor  $C$ . The marker board position, relative to the camera  $C$ , in a matrix of coordinates  $M_c$  is:

$$M_c = E = R \cdot T$$

However, the proposed system seeks to know the position of the camera relative to the reference board markers. To perform this calculation, we use the modelview matrix, taking the rotation submatrix  $R$ , and the translation vector  $T$ . The position of the camera relative to the board of markers is a coordinate matrix  $C_m$ :

$$C_m = -R^{-1} \cdot T$$

And as  $R$  is a rotation matrix:

$$C_m = -R^T \cdot T$$

## Coordinate comparison

In the above equation  $C_m$  are coordinates of the camera that the application determines relative to the marker. Given that the positions of the markers are known as coordinates in the scene, once the camera focuses on one of the boards, it is possible to know the position of the camera in relation to the scene  $C_e$ :

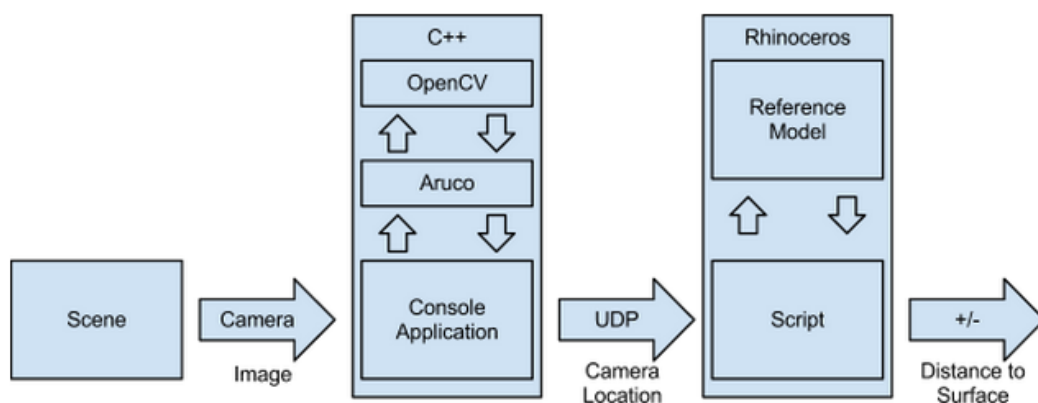
$$C_e = C_m \cdot M_e$$

Where  $M_e$  is known, as it is the matrix of transformation between the coordinate system of the scene and the detected marker board.

In the two experiences we did to prepare this article, the final calculation of the position of the camera was calculated within the same application that contains the virtual model, Rhinoceros in our case. This was done this way to have more flexibility in locating and adjusting the scene and the relative position of the markers. Once the application recognizes the markers and determines the position of the camera relative to them, it sends to Rhinoceros, via a network connection using the UDP protocol, the coordinate matrix  $[C_m]$  of the camera and the reference board used. A simple Rhinoceros programmed routine finally locates the point in the scene.

The proposed system does not seek to know the position of a particular point of the virtual model in real space, but rather to advise the bricklayer on the suitability of the real space point he chooses, as it informs about the distance from that point to the hypothetical ideal surface.

The routine within Rhinoceros vertically projects the point on the reference model and calculates the distance between the camera and the projection. This information is shown to the bricklayer in the display, who this way knows if he should move up or down his position. **Figure 8** summarizes the described process:



### 3.-Placing the Tiles

Now that the process of the positioning system has been described, we move on to describe its handling and application based on the tests undertaken.

#### Construction and structural design

As mentioned previously, a tiled vault is above all a structure, and as such it should be safe, which in terms of masonry work can be translated as “stable for a range of given actions”. It is known that this stability is achieved simply by designing a correct form, usually anti-funicular, which guarantees that all of the pieces of the structure work by compression within certain safety margins (Heyman 1997). This stability is only achieved when the shape is completely closed, and the intermediate states of the structure may not be stable. For this reason, some formwork is used at times, not only as a setting out element, but also as provisional support points to the structure.

In the tests undertaken by us we wanted to know the limit of the possibilities of setting out through local positioning and we have worked radically, without physical guides, formworks or props. To achieve stable levels of construction in the intermediate phases we have used (also in accordance with the tradition of vault construction of this type) provisional hollow flat tiles, held together with plaster, which support the layers of the vault until the rows begin to close. The main advantage of this system is that, once the first layer is finished, these provisionally used hollow flat tiles can be removed and used as regular pieces in subsequent layers.

#### Construction and intuition

Leading on from the above, the construction of the vault is undertaken in a conventional way, with the only exception of using the positioning system. The procedure is simple: the bricklayer places the dry hollow tiles in plaster each time that a new reference is needed, he does not need to tense the string as is done traditionally, but instead he places the camera on a point somewhat ahead of the last piece laid. In this way he knows where the new piece should be placed and more generally where the curvature is to be modified in this area so that he can continue placing tiles over the space.

In the tests undertaken we consciously used forms which were not very intuitive and which included significant changes in the curves. This was done to increase the need of the bricklayer for more constant references than is normal. Despite this, it proved to be

sufficient to take a reference from each four to five pieces on average. However, in the more delicate areas (the start or the joints between spandrels) reference was taken of all pieces, simply in order not to accumulate errors.



*Figure 9. Resulting vault after two layers of tiles.*

### 4.-Problems and possible solutions

#### Precision of the System

When dealing with a local positioning system for building hollow tile vaults, it is necessary to incorporate sufficient precision within the parameters which would be characteristic of the artisanal construction approach. Therefore, for our tests we established an indicative deviation value in the region of + or - 30mm. We can confirm that although this precision is acceptable in the majority of cases, in determined situations it may not be acceptable, for at least an order of magnitude. In these cases the coordinates translate as substantial variations in angles such as in the starts of the vaults. This makes much more precision necessary in order not to accumulate errors which would be incompatible with the construction system. In the case of the start, we believe that the solution involves setting out the first pieces to be placed with the help of some type of angle conveying template.

It must be born in mind, at all times, that the error is the total accumulated and it is not possible to have an error of continuity. That is to say, it is not an error that

could arise between two continuous points, but rather the total deformation – in reality the distortion – of the structure in the most unfavourable area.

Regardless of the above, if we suppose that the thickness of the average tile vault of three layers is  $3 \times 50 = 150\text{mm}$ , the  $\pm 30\text{mm}$  precision estimate is sufficient to believe that we will always keep reasonably close to the safe central third of the vault's thickness. As will be seen later, the error that which was estimated for the tests undertaken, can be reduced in different ways, some of which are as simple as increasing the size of the markers.

It should be kept in mind, that for vaulted forms, an accumulated total error of this magnitude is completely negligible from the point of view of structural safety. This type of error is, in essence, a homothetic distortion of the original surface area with respect to the orthogonal axis and centre of the marker. The resulting area of whatever homothetic distortion (in a range of  $\pm 30\text{mm}$ , mentioned for a realistic scale) in a secure form gives result to another equally secure form, as can be imagined in a simple case. For example, that of a hemispheric dome set out with a single marker in the centre of the floor as the axis of distortion. The result, a half orange somewhat curved or flattened, is undoubtedly a safe structure.

During the preparation of the system and its use in the tests we found multiple sections and functions which considerably affect the precision of the system and which could have made it insufficient, by exceeding the established value of  $\pm 30\text{mm}$ . We would comment on the points in which the precision of the system might present inconveniences.

If we remember the fundamental equation which determines the position of a point of the image, we see that **I** should be determined a priori so that **E** can be calculated and therefore the position of the camera with respect to the boards obtained.

$$\mathbf{Xc} = \mathbf{I} \cdot \mathbf{E} \cdot \mathbf{Xe}$$

**I** represents the matrix of intrinsic camera parameters and collects the projective model of the same, and contains the focal distance, the image format and the principle point of the same, and includes the effects of distortions inherent in the camera lenses. In order to know **I** it is necessary to calibrate the device. Calibration is a key step since the proposed system works with low cost cameras, designed for restitution exercises and about which we do not exactly know the intrinsic parameters.

OpenCV includes calibration routines through the capture of known patterns (chessboards or meshes of points). Once the calibration process has been undertaken, unique parameters are obtained for each camera, which help to correct the lens and sensor defects. Due to the discrete nature of digital images and due to the low quality of the components used in the cameras, the calibration process is far from perfect, which makes it necessary to effect it various times in order to obtain average values and in this way know the possible error. A small variation in the intrinsic parameters of the camera will lead to considerable variations in the matrices of the positions calculated by our application, which makes this step so crucial. For the calibration process we follow the habitual steps (which can be found in the documentation of the OpenCV online tutorials) using the asymmetric circles pattern provided in the same tutorial.

The maximum resolution, which the web camera can provide, is also an important factor for two distinct reasons. A higher resolution will give more definition and therefore more precision at the moment of ascertaining the camera position. However, a higher resolution implies that the processing of each image will take longer (going from a resolution of  $640 \times 480$  to  $1920 \times 1080$  implies a sevenfold increase in processing time per image). Due to this, fewer frames per second can be processed, and therefore the data of the camera position can fluctuate considerably. During our tests we agreed to work with a resolution of  $1280 \times 720$ , which supposes an acceptable equilibrium between precision, oscillation and user experience.

The configuration of the scene and location of the markers is another critical point with respect to precision. Given that all of the camera positions are determined by function of these references, the errors made at the time of positioning the markers within the digital model will have repercussions at the time of knowing the real position of the camera. In our experience this is the most critical factor in determining the points in a consistent manner. Without painstaking measurement of the relative positions of the panels, the same point measured from distinct markers will result in distinct locations among them which amount to more than the desired precision for the entire system. A simple and practical solution to this point would be to work with only one panel, although this is not always possible or recommendable due to the inherent complexity of the scene, the visual obstructions that can arise and the working comfort of the bricklayer.

Apart from the above, we find ourselves affected by the size of these markers. In general, the bigger they are, the more simple and precise it results for the system to position the camera. Evidently, the size is dictated by the working restrictions and comfort of the bricklayer. In our second experiment we opted for three DIN-A3 sized panels.

Finally, we have to comment on the real camera position and physical point considered. The application calculates the camera position, on the basis that this position comprises the principal point of the camera. Given that this is located on the inside of the camera we can do no more than estimate it from the outside, and take an alternative reference point on the camera from which to take measurements. The available cameras do not have a format which allows us to maintain the main point located in a convenient way, so that it is necessary to add an accessory which serves as a constant reference for the bricklayer. The lack of precision deriving from this point can be considered fixed for any camera model and to correct it in our experiments we used a small plumb-bob and hung it at a known fixed distance from the main point of the camera.

The sum of all of these points can give rise to a combination of errors of considerable significance for which reason it is important to try to individually minimise them as much as possible. In the tests previous to the experiment, undertaken in a very controlled environment, we estimated a precision of  $\pm 15\text{mm}$ , whilst in working conditions, over the configuration of the scene, the values were in the region of  $\pm 30\text{mm}$ .

### **Correlation between virtual model and real context**

A potentially problematic aspect of the positioning system, and not necessarily exclusive to the proposed optical system, consist in the imperfectly determined relationship between the physical environment and the virtual reference model.

During the two trials, the vaults were directly erected above a flat floor, so that the real local conditions were easily translated to the virtual model. However, the construction of tile vaults usually takes place on the inside of buildings, within existing structures such as walls or beams that have fixed sizes and forms.

The error which can be generated upon translating the physical context at the time of modelling the reference area can initiate considerable deviations between what was planned and what is effectively built. In this sense

the dexterity of the bricklayer will be determinant, as will be the precise survey of the local conditions, which will help to minimise any imprecision.

### **Ease of use**

From the point of view of ease of use, the system is reasonably comfortable. We have only used trial versions until now, in which it was necessary to employ a camera connected to a computer, which made construction slower. However, at the moment the camera reader and the data process can be integrated into a single device (many existing mobile telephones can undertake these two tasks with the required precision) the ease of use will be equivalent to what the traditional systems make possible for the simple forms.

## **5.-Architectural applications**

Over the last decade we have witnessed a unique renaissance of the tile vault. A renaissance which is supported by the renewed confidence of architects and structural engineers in these structures, in their moderate economic cost and their ubiquitous nature - given the availability of the necessary materials to build them in almost any place in the world. However, there are two very important additional aspects for architecture today: their low energy cost and suitability for building complex geometries. The feasibility of the proposed laying out system is analysed in three areas as follows: new construction, building refurbishment and cooperative architecture.

### **New construction**

The tile vault has recently started to be used again to cover new buildings in very different regions of the world. A few excellent examples include the Mapungubwe Interpretation Centre in South Africa, Pines Calyx and the Zero Carbon House in Great Britain and the experiments of Block Research Group in Switzerland. All of these buildings are covered by tiled surfaces of a certain complexity and extol the low energy impact of this system in their programs compared with other structures with similar performance.

The complex geometries which cover these buildings are always, as previously stated, irregular surfaces based on inverted catenaries. These forms are designed to respond to compression under a specific load framework, or a range of them, so we can assume that they are optimum from a structural point of view. However, they are very anti-optimal from a construction viewpoint since their erection, by way of traditional setting out systems, can be extremely

complicated as they cannot be broken down into simple forms, of easy layout and immediate execution.

In view of the above, the system proposed here is ideal. Complex forms can be constructed through digital setting out avoiding costly (economically and energetically) falsework. Also, as in traditional tiled vault construction, even provisional elements (such as the support tiles providing temporary equilibrium described in the previous section for example) can end up forming part of the final structure.

## Refurbishment

As previously stated, traditional setting out fundamentally employed combinations of simple forms, which when reinforced in determined areas were undoubtedly safe and which could be visually attractive when combined. The setting out of these forms is very simple, only some marks on the floors and walls and some wires or strings are necessary.

In the area of historical refurbishment, vaults are rarely of a straight generatrix, and the domes never ended up as hemispheres. A 400 year old building, however solid it may be, settles, changes shape, moulds itself to the movement of the land, to climatic changes and to small works. This is even truer for masonry, whose essence is precisely in its capacity to adjust.

It is not possible to build by traditional methods a dome which is not deformed, when the base upon which it is built is not truly circular. The wire cannot function here, which is why it is necessary to balance by some method the start, even forcing this element to be truly circular. Of course, this regularisation is possible, but it can affect other elements of value (pendentives, round niches, etc) which it may be appropriate to preserve.

Due to the above, we understand that the proposed solution to laying out is also ideal in these cases, since it permits erection in a form which respects the original start however irregular it is. This permits a new dome to slowly take the shape of the old as it grows (always assuming, of course, that the deformations are not such that the new construction is unstable or anti aesthetic). In determined cases this solution can prove to be the most respectful possible in relation to the original construction.

## Architectural aid

The last field in which we believe that this setting out system could be of interest is in that of architectural aid. We believe that the tiled construction technique is

ideal for this type of building, due to its ubiquitous nature and moderate economic and energetic costs. The proposed setting out process could also be of interest for this architectural construction sector.

Recently we have undertaken construction trials of vaults without formwork for housing in development aid and we have come across some problems. The most difficult issue has been the lack of formal precision in the construction of the vaults, although for the most part they were simple structures and easy to set out in accordance with traditional methods. We believe that these problems were due to the inexperience of the bricklayers, as is logical, and also due to the difficulties of the technicians responsible for controlling the construction process. Use of a setting out system making use of local optical positioning tools would permit, in this case, closer control of the construction form during the process and therefore the ability to erect structures which are more accurate and safer. However simple the shape of the vaults and domes are, it is on occasion complicated to know during construction the formal precision of what has already been built.

## 6.-Conclusions

The laying out system proposed here, based on optical recognition, needs significant development. Progress to date allows us to affirm in any event that setting out without formwork is possible with the simple help of small cameras and markers. The problems of the optical recognition procedures for the traditional topographic setting out works (precision above all) are slowly but surely being diluted as more powerful commercial cameras appear and simpler software tools for processing information become available. This will permit, as demonstrated in this case, the design of personalised and increasingly tighter implementation at reasonably low cost.

Without doubt, the future involves the application of these technologies to a hardware that simplifies all of the problems previously discussed, making its use as accessible as that of a plumb bob. Mobile devices today are increasingly potent, and include photographic cameras with very precise sensors and higher resolution screens. These present themselves as the perfect tools for implementation of the system. Our current efforts are precisely focussed in this direction of adapting the system, and furthermore of harnessing the many other possibilities which mobile devices offer today, including accelerometers, gyroscopes, gravity, light, magnetic force, orientation, proximity, rotation, etc.

New tile vault construction can benefit from these advantages. This could be through the tool which we propose in this article or through whatever variation may be proposed of it -from surveying the local area and using it as a large marker to tracing, through a coordinated camera system, the position of a point (the piece to be placed) in space. It is our intention in the future to continue exploring this subject and other ways forward.

## 7.-References

BRADSKI, G. *The OpenCV Library*. Dr. Dobb's Journal of Software Tools, 2000.

GARCÍA, J. Y MARTÍN, C. *Una escalera tabicada al aire*. at Oppidum: cuadernos de investigación nº3. Universidad Internacional SEK. Segovia, 2007. ISSN 1885-6292, pags. 317-328.

HARTLEY, R. Y ZISSERMAN, A. *Multiple View Geometry in Computer Vision*. Cambridge University Press, 2004.

HEYMAN, J. *The Stone Skeleton: Structural Engineering of Masonry Architecture*. Cambridge University Press, 1997.

MUÑOZ-SALINAS, R. *ArUco: A minimal library for Augmented Reality applications based on OpenCV*. Universidad de Córdoba, 2012.

TRUÑO, A. *Construcción de bóvedas Tabicadas*. Instituto Juan de Herrera. Madrid, 2004.