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VIRTUAL REALITY FOR ARCHAEOLOGICAL EXPLANATION BEYOND "PICTURESQUE" RECONSTRUCTION

1. The relevance of visual models

A *system* is a part of some aspect of reality where we are concerned with space-time effects and causal relationships among parts of the system. A *model* is a description of this system intended to predict what happens if certain actions are taken. To learn about the system we must first build a model and make it run. That means, that to understand reality and all of its complexity, we must build artificial objects and dynamically act out roles with them. If we drive the model with known inputs, and observe whether the corresponding outputs fit what we previously knew, we create a *simulation*. Simulation is an applied methodology in that we describe the behaviour of complex systems using models, and it embodies the principle "learning by doing".

A computer simulation, on the other hand is a simulation where the model is a computer program. Models must be converted to algorithms to run on a digital computer, and then to be able to reproduce the system dynamics. Verification is the process of making sure that the written computer program corresponds precisely to the model. Validation, the next step, is the process of making sure that the model's output accurately reflects the behavioural relationships present within the original real system data.

There are hundreds of possible models, depending on the specific knowledge structures we need to understand reality, and depending on the language used to write the model roles. Among them, *visual models* are those that use graphical means for creating and editing the model, to obtain values for its parameters, and to understand its behaviour and structure. Visual models are the result of a transformation of input data, into a geometric explanation of the input. Geometry is used as a visual language to represent a theoretical model of the pattern of contrast and luminance, which is the strict equivalent of perceptual models of sensory input in the human brain. The idea is the mapping of abstract inputs into graphical representations as an aid in the understanding of complex, often massive numerical inputs of scientific concepts or results (McCormick *et al.* 1987; Bryson 1994; Colonna 1994; Fishwick 1995; Miller, Richards 1995; Goldstein 1996).

The main reasons for visual models is to help to see what the data seem to say and to test what you think you see. They are used to *visualize* data obtained through numerical simulations describing phenomena, that is, converting data (usually numerical) to visual objects acting as a model for that data. A visual model will compress a lot of data into one picture (data browsing), so it can reveal correlations between different quantities both in space and time. It can furnish new space-like structures beside the ones which are already known from previous calculations, and it opens up the possibility to view the data selectively and interactively in "real time".

It is easier to understand how to use graphical models, if we consider the statistical modelling case. Statistical visualization uses geometrically based statistical methods to gain insight into the structure of data or data models. Consider the Principal Component Analysis, it can be viewed as a geometrical model that represents observations as points in high dimensional space whose dimensions correspond to the variables. The statistical visualization of the principal components model presents the results of analysis as a group of interacting plots, the purpose being to intuitively communicate the results of the analysis through pictures

States, events and transitions are three of the most fundamental concepts in system modelling. State and events are dual components in that a state change in a system occurs as a result of an event occurrence. Transitions enable the system to move from one state to another during the simulation while under the control of the system input. A *state* describes the system for an interval of time, that is a "snapshot" of a system for some length of time. An *event* is a point in time that designates a change in state; therefore, it is an expression of the fact that this entity has some feature *f*, that this entity is in a state *s* and that the features defining state *s* of that entity are changing or not. It is often assumed that an event naturally accompanies a transition, producing a change in state. The term "discrete event" is normally associated with events that cause changes in state.

From the context of a given abstraction level, all state changes result from an event occurrence. If we are considering only models at a single abstraction level, all events occur due to change in input. These inputs to a model are called external events. An internal event is also an input to the model; however, the input comes from a lower level abstraction model and not from outside the system.

In a visual model, states and events are represented using graphical tools: points, lines, surfaces, volumes. Our visual model serves as a "theory" or "hypothesis" for how a system really behaves over time. Transitions are represented as operations with those units: joining points with lines, fitting surfaces to lines, or "solidifying" connected surfaces in order to represent the formation process of images.

A focus on specific images as state descriptions of the model provides a *declarative* view of modelling, while a focus on the flow of images as event descriptions a *functional* view. In declarative models we build models that focus on visual representations and image-to-image transitions. In functional (or procedural) modelling, we focus on the system as a coupled network of functions each of which takes inputs (actions) and produces outputs (images). For a functional model we do not focus on image transitions; instead we focus on what operations or functions must be executed to get the system from its initial state to its final state.

There are two classes of declarative model that concern us: (1) element mapping methods and (2) set mapping methods with respect to state space. The simplest forms of declarative model are where we specify points in a multidimensional state space with transitions between point pairs. Declarative models are very good for modelling problem domains where the problem decomposes into either discrete temporal phases or irregular spatial phases. Temporal phases are identified as natural partitions over time where each phase corresponds to a specific element. For instance we can take any image and break it into parts. Those parts will be *phases* of the image only in the case they are correlated with the creation process of that image. Phase transitions are accomplished through events which move a system through phase space.

We may also simulate non real systems by varying parameters, initial conditions, and assumptions about our model. Fictional simulations are very popular in the form of role-playing simulation games, and they permit the simulation user to learn about a new environment by exploring it interactively. We learn about an environment in an extremely effective way and modify rules while seeing the effects of our interaction

Social action can be simulated by using visual models. The *theatre* of human activity may be used as a reference for defining an environment and may be thought of as having three parts: a content, a geometry, and a dynamics (Ellis 1994).

The objects and actors in the environment are the content of the visual model. These objects may be described by vectors, which identify their position, orientation, velocity, and acceleration in the environmental space, as well as other distinguishing characteristics such as their colour, texture, and energy. This vector is thus a description of the properties of the objects. The subset of all the terms of the characteristic vector which is common to every actor and object of the content may be called the position vector. Though the actors in an environment may for some interactions be considered objects, they are distinct from objects in that in addition to characteristics they have capacities to initiate interactions with other objects. The basis of these initiated interactions is the storage of energy or information within the actors, and their ability to control the release of this stored information or energy after a period of time. The self is a distinct actor in the environment which provides a point of view establishing the frame of reference from which the environment may be constructed. All parts of the environment that are exterior to the self may be considered the field of action.

The geometry of a visual model of social action is a description of the environmental field of action. It has dimensionality, metrics, and extent. The dimensionality refers to the number of independent descriptive terms needed to specify the position vector for every element of the environment. The metrics are systems of rules that may be applied to the position vector to establish an ordering of the contents and to establish the concept of geodesic or the loci of minimal distance paths between points in the environmental space. The extent of the environment refers to the range of possible values for the elements of the position vector. The environmental space or field of action may be defined as the Cartesian product of all the elements of the position vector over their possible ranges. An environmental trajectory is a time-history of an object through the environmental space. Since kinematic constraints may preclude an object from traversing the space along some paths, these constraints are also part of the environment's geometric description.

The dynamics of an environment are the rules of interaction among its contents describing their behaviour as they exchange energy or information. Typical examples of specific dynamical rules may be found in the differential equations of Newtonian dynamics describing the responses of billiard balls to impacts of the cue ball. For other environments, these rules also may take the form of grammatical rules or even of look-up tables for pattern-match-triggered action rules.

The usefulness of analysing environments into these abstract components, content, geometry, and dynamics, primarily arises when designers search for ways to enhance operator interaction with their simulations. However, it also can help organize theoretical thinking about what it means to be in an environment through reflection concerning the experience of physical reality. I will cover those subjects in the remaining of the paper.

2. Archaeological models

Our society is not a passive entity, but a dynamic and heterogeneous system of individuals related by a complex set of "social" actions. We are able to reproduce our society, because we work together, and as a result, we are involved in collective action. Archaeology is a discipline dealing with the *history* of our society, that is, those processes, which have *caused* our present. We are looking for how a social system has been generated, how relationships between individuals or subsystems change, and produce tensions and conflicts, and those tensions and conflicts are being resolved by means of other tensions and conflicts. This is the system we want to model.

In this approach, emphasis is not directed to empirical things, but to events and non-observable concepts-processes or social actions. In this sense, the goal of archaeology would not be the documentation of ancient sites and objects, but studying the dynamics of society. We are looking for the formation process of our own social actions, using ancient artefacts as their observable consequences at specific time intervals. The purpose is to discover what cannot be seen in terms of what is actually seen.

This goal leads us to the concept of *cause*. What is "cause"? The most common answer is "the way an entity becomes what it is" (SALMON 1984; CARTWRIGHT 1989; EELLS 1991); in our case, the "cause" of the society is the way this society has been formed, organised and determined, that is, how social actions produce social organisation. We can also say that a cause is the set of conditions, which determine the existence of any entity or the values of any property. Consequently, our primary objective is not the cause of the archaeological record, but the formation process of society. To speak about the cause of society is to speak about the processes, which determine and generate social organisation. Consequently, we should study how social interaction produces social organisation, and not mere associations between objects. This is not possible if we do not use the archaeological record to infer the past performance of social actions. We are studying then a double causality chain.

We do not have direct evidence of social actions performed in the past, however, through time, social actions have produced as a consequence some observable modifications on natural things, and some of these modifications have been preserved until today. Archaeological artefacts have different shapes, different sizes, different compositions, and different textures, and they appear at different locations. Shape, size, composition and texture values vary from one location to another, and some times this variation has some appearance of continuity, which should be understood as variation between social actions due to neighbourhood relationships.

We should create an archaeological model to understand how the production, use, and discard of artefacts through time and space produces some specific regularities between the shape, size, composition and texture of artefacts from different location in space and time. Observable properties can be represented using graphic tools and geometric language, consequently, we can use a "visual model". The idea is not to take a "picture" of the artefact, but to decompose empirical information in terms of its location marks (shape, size, location) and retinal properties (texture, composition):

– A pattern of changes in light wavelength and surface-reflectance, that is, *colour transitions*.
– A pattern of changes in edge orientation (curvature), that is, *shape transitions*, where an edge is an abrupt change in luminance values.
– A pattern of changes in luminance variations in a scene with non-uniform reflectance, that is *texture transitions*.

– A pattern of discrimination between edges at different spatial positions, that is *topology transitions*.

– A pattern of discrimination between edges at different spatial-temporal positions, that is, *motion transitions*.

We pretend a precise mathematical description of a real object to simulate causal processes according to the inherent geometrical properties of the described entity.

The resulting "visual" model should help us in explaining observed differences in those features and explain the sources or causes of that variability. Although expressed graphically, the model is a projection from a theory that means one of the possible valid results from this theory.

All that means that in archaeology we should deal with events and not with objects. The fact that a vessel has shape *x*, and the fact that a lithic tool has texture *t* are events, is the result of some event, which produced a specific transition from a previous state (for instance, a mass of clay) to a next state (a vase). That is, a social action has been performed at this spatial and temporal location (event), giving as a result an artefact with some specific shape and texture properties, among others.

In general, production, use and distribution are the social processes, which in some way have produced (*cause*) observed differences and variability (*effect*). The purpose of any archaeological model should be to allow the understanding of the causal dynamics of social actions, and it is obvious that we do not have enough with a simple description of artefacts to do so. For instance, some tools have different use-wear texture, because they have been used to cut different materials. Some vases have different shapes because they have been produced in different way. Graves have different compositions, because social objects circulated unequally between members of a society and were accumulated differentially by elite. Different buildings have different sizes, shapes, topologies because they were used for different purposes…

Although we do not know what actions have produced what material consequences, we can relate the variability of observable features (shape, size, composition, texture and location) with the variability of social actions through time. Why stone axes in a specific location in space and time have different shapes and sizes? Why the graves from this cemetery have different composition? Why those pottery sherds have different texture? It is impossible to answer why "stone axes" or any other archaeological entity have different shapes and sizes, if we cannot measure or describe its shape, size, texture, composition or location. The goal of the analysis is not to describe, but to understand why the described entities have those "visual" features and not others. Consequently, we can infer the variability of social action from the variability of archaeological record, and we can infer social organisation from the variability of inferred social actions.

Let we consider three different examples of archaeological causal modelling, at three different levels of generality:

– the formation process of an archaeological artefact;
– the formation process of an archaeological site;
– the formation process of a society.

The most basic archaeological problem has always been that of determining the use function of a prehistoric tool. We know some observable properties of the tool (shape, size, texture, composition and location), and we want to infer how a specific use (or reuse) generated or determined the observable properties. Observable properties can be represented by means of a visual model, by stressing shape/size features, or texture/composition ones. In this first case, we have some independent variables, which can be represented geometrically, giving a model of shape and texture, and we have also dependent variables describing the use (or production) of that tool. The aim of the model is to *understand* how a use action (characterized by its properties: energy, movement, purpose) modifies geometric parameters which control the visual appearance of that tool. By following the formation and the deformation as well as the motions of these systems in time, one will gain insight into the causal dynamics of use/shape or production/shape.

Our second example is a bit more complex. We know that archaeological objects were *caused* in the past, but since the action which originated them, other actions have been produced with that tool, or in the neighbourhood of that tool, and all those actions are also responsible of the artefact's visual appearance. That is, the causal nature of social action is fast never the only cause of the shape, size, composition, texture and location of the archaeological record. The idea is to visualise how the artefacts' physical properties have been modified all along the period since its deposition until the archaeological excavation (and even later!). There are two modalities:

– We can build a geometric model of the shape, size, texture, composition of the object, as dependent variables, and a geometric representation of energy and movement of natural process acting upon the objects. For instance, the formation process of a ruin. The different historical states of a house can be represented geometrically. Instead of a passive movie where construction/destruction states pass one after another, we can visualise different social and natural processes which generate modifications in the shape, size, texture, composition and location of that house, both adding new elements, deforming previous elements, or deleting some structures.

– We can build a geometric model of objects locations, representing the *topology* of the archaeological record using points, lines and surfaces. It is not the individual object, but its *depositional context* what we want to visualise. For instance a geometric model of geologic contacts under and over the archaeological record, in order to visualise the layer where objects have been found. The geometric modelling of that layer is characterised by the use of dependent variables (shape, slant, tilt, orientation, etc.) and the description of natural process (erosion, accumulation, disturbance,…) producing the specific values of the geometric model at each state.

The third example is the most complex case. What does it mean to visualize a *society*? According to the standard definition of shape, a society has size and location, therefore it has also shape. It does not mean, that a society is like a cylinder or a sphere, but the topology of the society (the network of interaction links among social agents and social institutions) can be described using points and lines, what gives the possibility of generating a visual model of social dynamics. The main objective is the spatial correlation of different social actions: how the spatial distribution of an action has an influence over the spatial distribution of other(s) action(s). Given that *social interaction* is the formation process of social dynamics, we can describe "social space" as a structure defined by the network of spatial dependencies between social actions (Barceló, Pallarés 1996, 1998). As a result, in order to study social spaces we should discover the *spatial* properties of social interaction. Our objective is then to visualise how a social action "varies from one location to another". Social actions are performed in an intrinsically better or worse location for some purpose because of their position relative to some other location for another action or a reproduction of the same action. The analysis then pretends to examine if the characteristics in one location have anything to do with characteristics in a neighbour location, through the definition of a general model of spatial dependence.

In this latter case, what we are really *visualizing* is the directionality of social action, and this can be done by means of the analyses of centres of activity as *places of attraction*. The basin analogy is very appropriate for studying the formation and consequences of attraction; as it is the analogy of the gravitation law for studying spatial interaction. It is important to take into account those social activity areas, and therefore, response surfaces, are not maps of social actions, but representations of the spatial density of the material consequences of those actions. We do not know where the action was performed, but the location of some of its material consequences. Calculating the spatial density of those consequences, and assuming that a measure of density is a function of the probability an action was performed in that point, we can say that the area where spatial density is the highest, is the attraction point for all material consequences.

In all cases of archaeological modelling, there is not any direct, mechanic or necessary connection between cause and effect. Some times, the social action is performed in one location, but the expected effect is not produced, because different unobservable actions can produce the same observable archaeological features, and the same action may not produce always the same archaeological features, because it is produced in different circumstances. The apparent ambiguity between social cause and material effect should not be confound with *indeterminism*. All elements of the archaeological record, including location, have been caused by social actions. There are many actions and processes, both social and natural having acted during and after a primary cause, and also primary causes act with different intensities and in different contexts, in such a way that effects may *seem* unrelated with causes. In most real cases, we should speak about multiple causes and complex causal relationships, rather than indeterminism or intrinsic randomness. The fact that we cannot *predict* the material outcome (*shape, size, composition, texture*) of a single action, does not mean that an archaeological feature cannot be analysed as caused by a series of social actions and altered by other series (or the same).

The practical solution to this paradox is to consider that a social action or sequence of social actions will be causally related with a *state change* if and only if the *probability* for the new state is higher in presence of that action that in its absence. Causal significance of a factor *C* for a factor *E* corresponds to the *difference* that the presence of *C* makes on *E*. That is, changes in shape, size, composition, and texture are not determined univocally by production, distribution and use acts, but there is some probability that in some productive, distributive or use contexts, some values are more probable than others.

Consequently, *cause* or *determination* can be defined as a probability function between social action (production, distribution, use) and material appearance (*shape, size, composition, texture*). Visual models can contribute to the understanding of the *probabilistic* nature of causal relationships, by introducing features such as *fuzziness*, which may be represent in geometrical terms (iso-lines, contours, cost-surfaces, etc.).

3. Components of archaeological models

For a model to be useful, it is essential that, given a reasonably limited set of descriptors, all its relevant behaviour and properties can be determined in a practical way: analytically or numerically.

The first step to build a simulation model of a real archaeological system is to gather data associated with that system. Data can be in either symbolic or numeric form. Typically, numerical data are obtained from the real world through the use of human senses or instruments. Nominal data are obtained from archaeologists using interviewing methods of knowledge acquisition techniques developed to obtain qualitative knowledge.

Model components, which serve as fundamental building blocks for models, take on the data values. Sample components include state, event, input, output, parameter and time. Such components are coupled together using declarative and functional perspectives to form *models* (FISHWICK 1995).

The definition of input is relative to the particular system being described. That is, an input is simply a state that has a controlling influence on a system which does not contain the input state. So in general, an input is just another kind of state except that it permits us to place boundaries around what is considered to be "inside" and "outside" of a system. An *output* is a function of the system state and the input. The input for a system is something that controls the system's behaviour and the output is an observable entity.

Archaeological Input Data can be described in the following ways:

3.1 *Bi-dimensional modelling*

T time location (independent variable)
$\mathbf{W}_1, \ldots \mathbf{W}_n$ dependent variables

In this case, we are involved with two-dimensional data sets, which contain only a single value at every temporal location. This is the classical example of temporal seriation, where a single line or curve explains the relationship between *time* and any other quantitative variable, for instance: population, quantity of artefacts, quantity/diversity of production actions in a single location, etc. In this case, states and events are represented as points, and transitions as lines joining points. The causal process is represented in terms of a linear *trajectory*.

3.2 *Three-dimensional modelling*

X,Y 2D point co-ordinates: longitude, latitude (independent variables)
Z height or depth (as dependent variables)

Here, we deal with the problem of *shape.* It is defined as the information that is invariant under translations, rotations and isotropic rescaling (SMALL 1996), that is, those aspects of the data that remain after location and scale (size) information are discounted. It is then a quantitative property about spatial location and size. Everything that has *size* and location has *shape*. Shape is a field for physical exploration: it has not only aesthetic qualities, nor is shape just a pattern of recognition. Shape also is determining the spatial and thus the material and the physical qualities of social actions.

The lack of any time variable makes this kind of models an example of static models, without transitions. That is, if we should simulate historical dynamics, we need *time* and shape/size parameters. However, although static, shape models are very interesting for understanding real objects. The resulting geometric model is used to calculate some new parameters and variables, which should be relevant to understand "shape dynamics": curvature, length, thickness, height, volume, *surface gradient* (the rate of change of depth in the *x* and *y* directions) and *surface normal* (orientation of a vector perpendicular to the tangent plane on the object surface).

Three-dimensional models are mistakenly considered as "virtual models". In fact, most of the literature on "Virtual Archaeology" (see examples in Barceló *et al*. 2000) are nothing more than computer generated shape models. As we will discuss along this paper, "Virtual" Archaeology means much more than "shape" reconstruction.

3.3 *Four-dimensional modelling*

X,Y,Z	3D point co-ordinates: longitude, latitude, height/depth (independent variables). A shape model.
$W_1, \ldots W_n$	dependent variables

It seems obvious that we should "imitate" the real world, therefore we should describe an object by more than just shape properties. We can add more dimensions to any shape model to understand texture in terms of *spatial* dynamics, that is, how location determines other retinal properties. Visual characteristics can be subdivided into sets of *marks* (points, lines, areas, volumes) that express position or shape and *retinal properties* (colour, shadow, texture) that enhance the marks and may also carry additional information (Foley, Ribarsky 1994). This is why we should take into account "retinal properties" in the geometric model: each surface appearance should depend on the types of light sources illuminating it, its properties, and its position and orientation with respect to the light sources, viewer and other surfaces. Variation in illumination is a powerful cue to the 3D structure of an object, because it contributes to determination of which lines or surfaces of the objects are visible. *Texturing* is a method of varying the surface properties from point to point in order to give the appearance of surface detail that is not actually present in the geometry of the surface. Nevertheless, the goal is not to obtain "well illuminated models", but to explain spatial relationships using lighting and shadow models. The goal of the visual model should not be "realism" alone, for the sake of imitation, but in order to contribute to understanding of the simulated entity. Taking into account global models of illumination for understanding *position* and *relative location*, or including texture information into the geometrical model, can help us to understand geometrical properties which are too abstract to be easily understood. It is the ability to view from all angles and distances, under a variety of lighting conditions and with as many colour controls as possible, which brings about real information (Ebert *el al*. 1995; Forte 1997).

The most typical example is that of a 3D map, showing a visual representation of the relationship between soil type, hydrography (dependent variables) and topographic position (independent variables: a shape model of a territory or landscape). It is also the case of use-wear texture draped over a shape schema of an artefact (Barceló *et al*. 2001). This is a *3D+1D model*; the more dependent variables the system has, the more complete the resulting model is. We are not limited to 4 variables (x, y, z, w), but we can in fact relate two or more three-dimensional models (x_1, y_1, z_1, w_1), (x_2, y_2, z_2, w_2). For instance, we can analyse the dynamics of the interaction between *content* (a three-dimensional shape model) and *container* (another three-dimensional shape model). Sometimes, *content data*, although originally in three dimensions, are represented bidimensionally. For instance, in geographic modelling vegetation maps are represented by means of polygons or lines.

As in the previous case, four-dimensional models are mistakenly considered as "virtual models". Using textures, and studying light properties on the surface of objects we have built a better visual surrogate of a real entity, but we have not yet created a visual model to understand reality. Virtual Archaeology should go beyond "picturesque" reconstruction.

3.4 *Multi-dimensional models*

X,Y,Z, T	4D point co-ordinates, longitude, latitude, height/depth, time (independent variables)
W_1, ... W_n	dependent variables

We introduce here the time dimension. We are trying to "see" how time is involved in the changing pattern of shape/texture modification. It is a four-dimensional model of spatial dynamics "plus" its temporal dynamics.

Animation is the geometric technique used to represent transitions in a temporal multidimensional model. It can be defined as any changes occurring on the screen during viewing time. To achieve a simulation, the animator has two principal techniques available. The first is to use a model that creates the desired effect. A good example is the building of a house, or the growth of a green plant. Here changes are the different steps of construction or growing. Typically, motion is defined in terms of co-ordinates, angles and other shape characteristics. It can be obtained by *dynamic equations of motion*. An animated sequence can be produced by specifying how physical properties change from frame to frame. Each frame represents a state of the model and frame animation is used to specify the behaviour of the system over time using only state specifications at discrete points in time. These features are merged with geometrical modelling and behaviour laws to form a more realistic virtual model. Object behaviour may be modelled to follow simple Newtonian laws or more complex reflexes (so-called "intelligent agents").

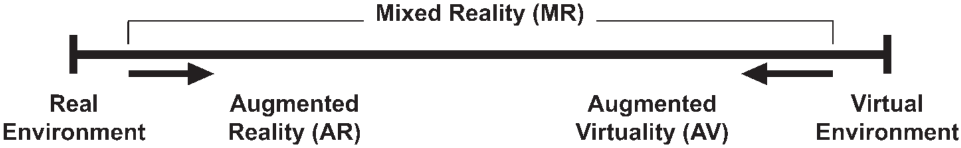
In the next generation of animated systems, motion is planned at a task level and computed using physical laws. This means that research will tend to find theoretical and physical models to improve the animation. The main purpose is not a validation of the theoretical models, but to obtain a graphic simulation of the motion that is as realistic as possible (THALMAN, THALMAN 1994; BRYSON 1996). Another approach is the possibility to link animation to an expert system, where theoretical knowledge has been represented in form of production rules. This provides the opportunity to use scientific knowledge to simulate the behaviour of objects within a modelled environment.

4. TOWARDS ENHANCED OR AUGMENTED REALITY

We need much more than a visually "realistic" geometric model to understand archaeological systems. We also need "dynamism and interaction". A dynamic model is a model that changes in position, size, material properties, lighting and viewing specification. If those changes are not static but respond to user input, we enter into the proper world of Virtual Reality, whose key feature is real-time *interaction*. Here real-time means that the computer is able to detect input and modify the virtual world "instantaneously" at user commands. By selectively transforming an object, that is, by interpolating shape transformations, archaeologists may be able to form an object hypothesis more quickly. The hope is that the archaeologist will "perceive patterns" in the *virtual* environment more readily than in visual models like maps, drawings or simple photographs.

Augmented Reality has been defined as the simultaneous acquisition of supplemental virtual data about the real world while navigating around a physical reality (DURLACH, MAVOR 1994; BUXTON 1997; MILGRAM, YIN 1997; BILLINGHURST, KATO 1999). In an Augmented Reality Environment the computer provides additional information that enhances or augments the real world, rather than replacing it with a completely virtual environment. One of the objectives of AR is to bring the computer out of the desktop environment and into the world of the user working with a three-dimensional application. In contrast to so called "virtual" reality, where the user is immersed in the world of the computer, Augmented Reality incorporates the computer into the reality of the user. The user can then interact with the real world in a natural way, with the computer providing information and assistance. It is then a combination of the real scene viewed by the user and a virtual scene generated by the computer that augments the scene with additional information. The virtual world acts as an interface, which may not be used if it provides the same experience as face-to-face communication; it must enable users to go "beyond being there" and enhance the collaborative experience (BILLINGHURST, KATO 1999). This enhanced perception is directed towards data contexts that can enhance the interpretative process.

Milgram (Milgram, Kishino 1994; Milgram, Takemura 1994; Milgram, Drascic 1995) describes a taxonomy that identifies how augmented reality and virtual reality work are related. He defines the Reality-Virtuality continuum shown as follows:



The real world and a totally virtual environment are at the two ends of this continuum with the middle region called Mixed Reality. Augmented Reality lies near the real world end of the line with the predominate perception being the real world augmented by computer generated data. *Augmented Virtuality* is a term created by Milgram to identify systems which are mostly synthetic with some real world imagery added such as texture, or by mapping video onto virtual objects (shape models). *Augmented Virtuality* describes that class of displays that enhance the virtual experience by adding elements of the real environment. This is a distinction that will fade as the technology improves and the virtual elements in the scene become less distinguishable from the real ones.

The best way to develop interfaces for enhancing interactivity is to focus on the *communication* aspect. Rather than using new media to imitate face-to-face collaboration, researchers should be considering what new attributes the media can offer that satisfy the needs of communication so well that people will use it regardless of physical proximity. So one way to develop effective collaborative interfaces is to identify unmet needs in face-to-face conversation and create interface attributes that address these needs (Hollan, Stornetta 1992).

There are many examples of Augmented Reality. For instance, merging graphical representations (visual models) with the view of the real object clearly presents the relationship between the data and the object. With sufficient graphic and computing power, it is possible to create and animate virtual objects, and enhance our perception of those visual models by overlaying conceptual labels on known objects. Instructions for determine provenance, function, chronology, etc. might be easier to understand if they were available not in the form of manuals with text and 2D pictures, but as 3D drawings superimposed upon the objects themselves, telling the archaeologist what to do and where to do it.

In other words, the augmented-reality world is like the real world but adorned with useful computer-generated “Post-It” (Rose *et al*. 1995). In a Virtual Museum, Virtual 3D “post-it” notes and movies may be applied to museum objects. The Museum becomes then a place were visitors interplay with an historical explanation of their past, by manipulating and transforming the displayed visual simulation, according to suggestions made by the visual models. Because the virtual world corresponds to the real world, the graphics drawn by the computer will appear to the user to be in the real world. 3D shape/texture models and text overlaid on the surrounding world could explain how to move, explain, or understand archaeological record social dynamics and historical trajectories, without requiring that the user refer to a separate paper or electronic manual (Sanders 2000).

We can also imagine a translation from computer assisted surgery to archaeology. Tools are being developed to support image guided surgery. Such tools enable surgeons to visualize internal structures through an automated overlay of 3D reconstructions of internal anatomy on top of live video views of a patient. Computer scientists and surgeons are developing image analysis tools for leveraging the detailed three-dimensional structure and relationships in medical images. Sample applications are in preoperative surgical planning, intraoperative surgical guidance, navigation, and instrument tracking. Using specific equipment, surgeons can peel back a shape/texture model of the patient skin and see where the internal structures are located relative to the viewpoint of the camera. Thus the surgeon has X-ray vision, a capability which will be needed more and more as we continue moving towards minimally-invasive surgeries (Höhne *et al.* 1994). Basically, applications of this technology use the virtual objects to aid the user's understanding of an environment. For example, we can scan a buried archaeological structure (a wall) with remote-sensing sensors (geo-magnetic or geo-radar surveying), then overlay a three-dimensional model of the structure on top of the surveyed area. The goal is to give the archaeologist "X-ray vision," enabling him/her to "see inside" the earth. If a goal is to show the archaeologist where an object is located, the system must determine whether built structures or sedimentary accumulations block the object. If it is buried, it will be displayed so that it appears to be seen through the blocking structures; if it is already visible in the real world, it need not be drawn at all.

At the Quantitative Archaeology Lab (Universitat Autònoma de Barcelona, Spain) we are involved in building a similar "intelligent visualization system" for augmenting the perception of archaeologists during fieldwork. The system overlies stratigraphic visual models on orthorectified photographs of archaeological layers, in such a way that archaeologists can understand internal structures by merging visual models of objects, archaeological structures, archaeological contexts, sedimentary units and the like. By linking a video simulation of sedimentary process, we can explain the specific formation process of the archaeological site. The system is not yet able to act at run time *during excavation*, but it enhances the perception of archaeologists when studying why archaeological objects and structures appear where they have been unearthed.

One difficulty in augmenting reality, as defined here, is the need to maintain accurate registration of the virtual objects with the real world image (Drascic, Milgram 1995). What interests us the most is the possibility of taking a computer representation of the object of interest and matching it spatially to the real one. Once this registration is established, we can introduce tracking technology to maintain correspondence between the visual model and reality as the archaeologist interacts with the archaeological record. Consequently, the key aspect in enhanced archaeology is the link between the real data and the visual model used for explanation. When you merge the real world and the virtual world, it has to look as if they belong together. As you move around, the computer graphics have to be told how to re-render the virtual scene. You need to know where to display the virtual world, when to display it, and what to display. This often requires detailed knowledge of the relationship between the frames of reference for the real world, the camera viewing it and the user. In some domains these relationships are well known which makes the task of augmenting reality easier or might lead the system designer to use a completely virtual environment.

An Augmented Reality model should track the movements of the user and re-renders the virtual scene accordingly. But, the model also needs to track the movement of real objects in the scene - a process that is very difficult to achieve. Tracking virtual environments is usually computed by the use of head-mounted displays to overlay graphics of virtual objects on top of real-world objects. With partially transparent "see-through" displays, the user can simultaneously view the real world as well as the computer-generated graphics. The easiest way is by placing coloured dots on a variety of objects, then we can solve the tracking problem using a hand-held video camera. The dots serve as points that give the computer system a frame of reference on which the virtual world is rendered. As they move, the video camera transmits the new position to the computer and the virtual world is re-drawn accordingly.

Augmented Reality systems can be very complex when integrating sensors and computer generated visual models. The TransVision system, for instance, is an attempt to use Augmented Reality (AR) technology for collaborative designing. The system uses the palmtop video-see-through display instead of bulky head-mounted displays. The user can see a computer-generated 3D model superimposed on the real world view. The position and orientation of the display are tracked by the system such that the computer-generated model appears to occupy real space (http://www.csl.sony.co.jp/person/rekimoto/transvision.html).

At the Colorado School of Mines, geologists have been focusing on sensing the identity and locations of real world objects with respect to the user so that overlay graphics can be drawn accurately registered to the real world objects. They have been using a combination of head-mounted cameras and head-mounted inertial sensors (gyroscopes and accelerometers). A helmet incorporates an optical see-through stereo display mounted in front of the user's eyes, three colour CCD cameras mounted on either side of and on top of the helmet, and inertial sensors mounted at the rear of the helmet. A stereo display electronics module separates the odd and even fields from the video image and displays only one field for each eye, thus allowing different images to be displayed for each eye. Shifting the graphics overlays presented to each eye provides three-dimensional overlay capabilities. The video cameras are remote head devices which allow the camera heads to be extremely small and light weight, with the camera control units being placed off-platform from the user. Positioned on the rear of the helmet are inertial sensors consisting of a three-axis gyroscope and three orthogonally mounted single-axis accelerometers. The helmet is tethered to an IBM PC compatible computer which performs data processing and graphics generation.

They have developed techniques to automatically detect and track fiducial targets, consisting of high contrast concentric circles (CCC's). These targets are unique features that can easily and reliably extracted from the images. To further simplify the correspondence process, the target points are arranged in a distinctive geometric pattern. Using a simple thresholding operation, the black and white regions are easily separated, or segmented. Given the large contrast between the two regions, a wide range of threshold values will work. Next, morphological image filtering operations are performed to eliminate small white or black regions. These filtering operations consist of an erosion followed by a dilation to eliminate small white regions, and c dilation followed by an erosion to eliminate small black regions. Next, a connected component labelling operation is performed to find connected white and black regions, as well as their centroids. The centroids of black regions are compared to the centroids of white regions - those black and white centroids that coincide are CCC's. The geometric pattern of the CCC's allows the correspondence of the detected features to the model to be determined. The pose of the object relative to the camera is computed by the simple and fast Hung-Yeh-Harwood pose estimation method. The inputs to the pose algorithm are the centres of the four corners CCC's, the target model, and a camera model. The pose algorithm essentially finds the transformation that yields the best agreement between the measured image features and their predicted locations based on the target and camera models (http://egweb.mines.edu/whoff/projects/augmented/default.htm).

Alternatively, hooking a GPS system to a wearable computer and mapping software allows the user to track himself while exploring a city. By using optical flow (comparing consecutive images to determine the direction of motion) not only can the movement of a user's head be tracked, but warnings can be given of approaching objects for the visually disabled. By implementing a local beacons or a dead-reckoning system in the workplace, much more advanced applications can be developed. Examples include virtual museum tour guides, and archaeological remains overlays in restored buildings (RYAN *et al.* 1999).

A recent book about Virtual Reality in Archaeology (BARCELÓ, FORTE, SANDERS 2000) provides some examples of Augmented Archaeologies, that is, systems where users can become "immersed" into a virtual world. The paper by BROGNI *et al.* (2000) is a good introduction into the subject of interactivity. Their system allows total access to the information about the archaeological artefact, by means of an environment with text-windows and buttons (Graphic User Interface), which allows us to interact with the application and choose the consultation. The screen is held by the user and pointed along the line of sight to the real position, where the artefact would be located. At present this application is used for the representation of an Egyptian glass flute, but it is a suitable platform for every artefact, and the virtual environment could even be a tomb, or an ancient palace. The visitor gives orders by touching the screen on graphic buttons, located on the side of the screen, which are easy to hit with the same fingers holding the screen. At the same time the tracking sensor gives all the information about the movement in the real space relative to the central system, which can prepare the new image for the screen according to the new point of view. During the virtual exploration, it is possible to retrieve particular information about the figures in the decoration of the flute. By touching a button, the virtual exploration stops and a window opens with a photograph and an explanation text.

A different sense of "interactivity" is explored by KADOBAYASHI *et al.* (2000). They introduce the idea of Meta-Museum, which is a new environment where experts and novices can easily communicate with each other so that they can share broad knowledge related to all aspects of humans and nature. A practical formation of Meta-Museum would be a combination of traditional museums that have physical objects and virtual museums that have digital information. KADOBAYASHI *et al.* 2000 have developed the VisTA and VisTA-walk systems based on the Meta-Museum concept. These systems simulate the transition process of an ancient village. The expected users of VisTA will be archaeologists and the users of VisTA-walk will be museum visitors, although this is not a strict definition. Users (here it may refer to experts) can visualise the transition process through real-time 3D computer graphics after they interactively set the value of each building's lifetime. Users intuitively learn the ancient landscape of the site because they can walk through the reconstructed 3D CG village. The systems provide intuitive information access through the selection of objects such as buildings in the 3D CG scene. Hence, VisTA will serve the users as a tool for helping them research and easily make good presentations. They propose a new interface, a full-body and non-contact gesture interface, for exploring cyberspace that does not require visitors to wear extra devices; at the same time it is easy to use and can provide an immersive walk-through and information accessing capabilities.

It is interesting to compare the Meta-Museum concept with the Nu.M.E. concept in the paper by Bonfigli and Guidazzoli (2000). Here virtual interaction is obtained through Internet and a series of web documents. Interacting with the Nu.M.E. interface the user begins with the virtual reconstruction of the city as it is nowadays and travels backward in time using the time-bar. As the user travels back in time, recent buildings change into the ground and ancient buildings that no longer exist pop up. To make sure that the visitor understands that he/she is seeing only as much as the historical sources can justify, each building is accompanied by an HTML document compiled by a historian. These hypertexts contain references to the historical resources and can be consulted at any time during the visit. Bonfigli and Guidazzoli offer a detailed examination of the Virtual Historic Museum of the City of Bologna example.

Frischer *et al*. (2000)'s Rome Reborn project, integrates all archaeological and art historical information, and the different interactivity approaches designed, from video editing to Internet access. Specially interesting is the CAVE approach to total immersion, very similar to that proposed by Kadobayashi *et al*. 2000. A CAVE is an immersive virtual environment, typically 3 x 3 meters in size or larger, in which the computer model is projected onto the walls, floor, and ceiling. In a CAVE, a guide can take visitors on a live, interactive tour of the 3D computer model, answering questions and giving views of the site that even the ancient visitor could not see or see so well.. A teacher whose expertise pertains more to the use or history of the site than to its construction might use a videotape with a virtual tour of a site given by an archaeologist or architectural historian. The same videotape can be used in the auditorium of a museum or archaeological site to provide an orientation for visitors (see also Vote *et al*. 2001 for a similar approach).

Another augmented archaeology model is the Greek ARCHEOGUIDE project (http://archeoguide.intranet.gr/). It provides new ways of information access at cultural heritage sites in a compelling, user-friendly way through the use of 3D-visualization, mobile computing, and multi-modal interaction. The system will provide the following features to visitors:

a) Accessing information in context with the exploration of the site through position and orientation tracking.

b) Personalized and thematic navigation aids in physical and information space through the use of visitor and tour profiles taking into account cultural and linguistic background, age and skills.

c) Visualization in 3D of missing artefacts and reconstructed parts of damaged sites on Head Mount Displays.

d) User friendly multi-modal interaction for obtaining information on real and virtual objects through gestures and speech. In addition, tools enabling site administrator to organize the presentation of site information in creative ways will be provided.

The ARCHEOGUIDE system consists of a site information server and a set of mobile units that are carried by visitors. A wireless local network allows the mobile units to communicate with the site information server. In addition, the site will be furnished with the elements necessary for a tracking system to sense the position and orientation of users wearing the equipment. The site server maintains a database with all information pertaining to the site. The contents can be accessed and downloaded to the mobiles over the wireless network. In addition, the site information server incorporates software that allows the creation of new content through the exploration of the 3D model of the site. The mobile units comprise a Head Mounted Display (HMD), a camera, microphone, earphone and a lightweight portable computer with a simple input device. The portable computer is equipped with devices allowing it to communicate with the site information server through a wireless data communication network and devices that sense the position and orientation of the user. The mobile units maintain a local database that stores a subset of the site information pertaining to a particular area of the site for a particular user and visit profile. As the user moves around in the site the mobile units communicate with the site information server to download information relevant to the new area of the site the user has entered.

Cultural site visitors will be provided with a see-through Head-Mounted Display (HMD), earphone, and mobile computing equipment. A tracking system will determine the location of the visitor within the site. Based on the visitor's profile and his position, audio and visual information will be presented to guide and allow him/her to gain more insight into relevant aspects of the site.

In all those cases, it is easy to see that Augmented Reality does not simply mean the overlying of a 3D reconstruction of an ancient building over a real world archaeological scene. The visual model or simulation generated through a computer is intended to complement the real world on which it is overlaid. The idea is to match the computer's virtual world to the real world, in order to augment the user's view of the real world with additional information.

This is the same as *seeing what cannot be seen*. Sometimes, the phenomenon to be visualised cannot be seen because most of it is hidden, or we have only some partial information about its physical location and properties. In this case, fragmented data are represented as scattered *x, y, z* input data sampled at irregular locations. The goal is here to "augment" available information by calculating missing information from nearest neighbour points. When input data is really very incomplete, we should fill the gaps with information that does not proceed from the data. We need to build the model first, and then use it for simulating the real object. In most cases, we create "theoretical" or "simulated" geometric models. Here "theory" means general knowledge about the most probable "shape" of the object to be simulated or prior knowledge of the reality to be simulated.

The procedure is as follows: we transform perceived data as a sequence of points, and we try to interpret the type of shape, assuming some dependent preference function. Once the type is decided, the closest fit is determined using different numerical techniques. Then, given a partially damaged input, we augment the empirical world by generating those points and geometric units that were not available.

Consequently, we use general models and particular constraints as mechanisms for enhancing archaeological reality and modify a preliminary hypothetical geometrical model into another that satisfies the constraints. Finding the geometric configurations that satisfy the constraints is the crucial issue to link computer generated models with computer mediated perception of archaeological data.

5. Conclusions

Schmalsteig *et al*. 1996 identify five key advantages of Enhanced Reality environments:

– *Virtuality*: objects that don't exist in the real world can be viewed and examined.

– *Augmentation*: real objects can be augmented by virtual annotations.

– *Cooperation*: multiple users can see each other and cooperate in a natural way.

– *Independence*: each user controls his own independent viewpoint.

– *Individuality*: displayed data can be different for each viewer.

Reality is not a set of points, lines, surfaces, sections or blocks. The possibilities of using geometric elements to visualise numerical data do not signify that the data in real life correspond directly to abstract geometric elements. Any "visual model" is only a spatial pattern of luminance contrasts, and it should explain how the light is reflected. The model is composed of visual bindings which can be subdivided into sets of marks (points, lines, areas, volumes) that express position or shape, and retinal properties (colour, shadow, texture) that enhance the marks and may also carry additional information. Visual models are then "interpretations" of real data, and it should be made evident how one gets from the perceived reality to the explanatory model.

A model cannot be true or wrong, because it does not belong to reality. It is a projection from theories, used to know if our hypotheses are true, wrong, probable, or mere possible. Consequently, a scientific theory must be composed of models and hypothesis, linking models to reality.

For the moment, we are restricted to the creation of virtual environments, whose purpose is to sense, manipulate, and transform the state of the human operator or to modify the state of the information stored in a computer. Future advancement of virtual reality techniques in scientific visualization should not be restricted to "presentation" techniques, but to explanatory tools. I'm suggesting to use VR techniques not only for description, but for expressing all the explanatory process. An explanation can be presented as a visual model, that is as a virtual dynamic environment, where the user ask questions in the same way a scientist use a theory to understand the empirical world. A virtual world should be, then a *model*, a set of concepts, laws, tested hypotheses and hypotheses waiting for testing.

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ABSTRACT

In this paper, a general framework for using Virtual Reality techniques in the domain of Archaeological Visualisation is presented. It is argued that "visualising" is not the same as "seeing", but is an inferential process to understand reality. A definition of Enhanced Reality is also presented, and how visual models can be used in order to obtain additional information about the dynamic nature of historical processes and archaeological data.