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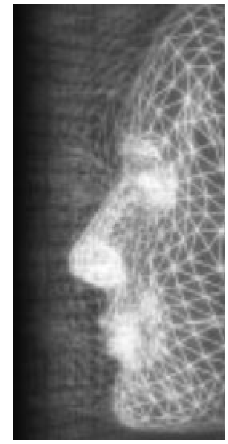

Computer-aided virtual reconstruction of Italian ancient clocks

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Italy has plenty of cultural heritages. The masterpieces are often placed in locations which are difficult to reach, moreover many artifacts, coming from man's creativity, have very complex functioning. The authors of this paper describe their experience in using the computer graphics capabilities in order to reproduce four ancient clocks functioning coming from different Italian regions. The study is based not only on the 3D-shapes reconstruction but also on the simulation of their complex mechanisms in order to mimic their functioning. The realism of the reconstruction allows to use the graphical products in exhibits, museums and also for maintenance programs. The rendering techniques together with an accurate camera path, allow to get into the clock mechanisms and to appreciate all the features (and even secrets) that a simple glance cannot reveal. Copyright © 2006 John Wiley & Sons, Ltd.

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Introduction

Ancient clocks are very fascinating devices. They summarize the aspect of pure mechanics and the philosophical aspect of measuring time.[1,2] A mechanical clock includes very complex mechanisms which interact and work properly in harmony.[3] Studying these devices is not so simple because the clocks are often located in places difficult to reach (such as at the top of high towers) or their conservation state is not so good. Moreover, the actual functioning can be understood only disassembling the entire mechanism, and this operation can be often impossible. Virtual reconstruction of these clocks appears as a precious tool to overstep these difficulties.

The reconstruction of shape and movement can be successfully used for didactical purposes to understand the complex mechanisms included in the frame.[4] Many aspects of the clock can be investigated isolating and zooming only a part of it or changing the speed of simulation. This is important also for the repairs if the clock goes out of order. In fact, even an expert man can be in difficulties[5] because an ancient mechanism is a unique device and in many cases the functioning is known only by the manufacturer or the designer.[6]

Computer graphics appears as a tool that can enable, augment, and enhance traditionally conceived processes of research and dissemination. However, these technologies brought and still bring about a quiet, but profound, revolution in the ways in which knowledge is produced and experienced.

The current computer graphics capabilities allow to build up a realistic virtual scene even using a personal computer with not-expensive hardware resources. Moreover the modern parametric CAD software speeds up all the modeling phases. The available render engines (many of them are freeware in Internet) can improve the visual effects tremendously. It is a common trend of the last years to publish in internet virtual museums about many science topics as witnessed by several authors all over the world.[7–9] Moreover in literature there are some examples about computer-aided simulations and virtual world concerning historical and artistic heritage.[10–13] All these studies have the common feature to be inherently interdisciplinary. This means that metrology, physics, kinematics, dynamics, computer modeling, and history are melted together to offer a complete understanding of the observed cultural masterpieces.

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Clock Mechanics

A mechanical clock is a system made up of several gear trains[14] which, thanks to an input force, rotate at constant angular speed. Usually the output movement is related to an index which has a complete rotation in a precise time period (e.g., in the most common clocks the prime minutes hand has a period of 1 hour, and the hours hand has a period of half a day or a day).

Beside this main mechanism, a mechanical clock has a secondary gear train which operates as an acoustic alarm (for example using bell ring) to inform when an hour or its fractions are completed. This secondary mechanism is driven by an independent system which produces also the power to ring the bells.

There are several ways to transmit the power to the gear trains. Some clocks use flow of the water impacting some rotating blades, some others use spiral springs, but many of them use the gravitational potential of a massive body connected with a rope to a drum.

A very important system included in every mechanical clock is the escapement device (see Figure 1 where an anchor escapement is depicted). Although there are several kinds of this device, its basic function is to control the continuous flow of energy obtained from the spring or from the massive body transmitting by discrete power to the gear trains (escape wheel). To perform this task, the escapement anchor undergoes to an intermittent motion of constant period (engaging and disengaging the escapement wheel) which often produces the classical 'tic tac' sound.

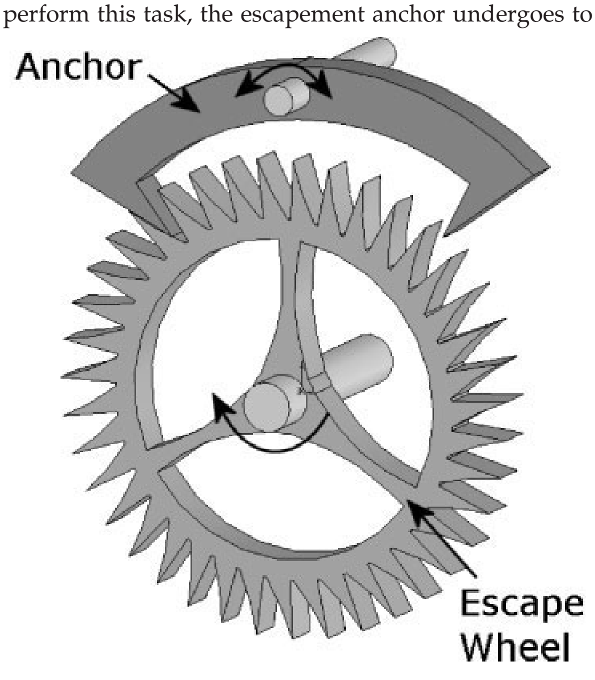

Figure 1. A common escapement device controlled by an anchor.

Thus, this mechanism has to split up the energy coming from actuating system and also restores the power lost during oscillations.

The general configuration requires a rocker (or anchor) and an escapement wheel.

The teeth of the rocker arm are designed to alternatively stop or actuate motion of the escapement wheel which is constantly driven by the actuating force produced by the spring or massive body. The entire oscillation period can be divided into three phases: the first is the *interaction phase* in which the anchor is moved by the wheel (the escapement can have one or two interaction phases); the second is the *final phase* in which the anchor stops; the third is the *return phase*, in which there is reverse motion till a new interaction phase begins.

Michelangelo Canonico's Clock at Lagonegro

The Michelangelo Canonico's clock at Lagonegro (in the neighborhood of Potenza) was assembled and patented during the first years of 1900. It is made up of an external framework made of cast iron where several brass gears are mounted on. The entire clock is characterized by three different mechanisms which interact each other. The first is the charging mechanism which has to transmit power to the clock movement by means of the escapement system. The second is the mechanism for moving the hands and the third is the ringer. All these mechanisms interact by means of meshing gears and levers.

The virtual reconstruction started from the measuring of all the parts using a mechanical caliber. Then, by means of feature-based CAD software, every part has been modeled with high precision. For similar parts a parametric approach allowed to save time for modeling. The textures have been created from accurate pictures of mechanisms. In Figure 2 the actual clock and the virtual model have been depicted. It can be observed the accuracy in modeling components and textured surfaces. In Figure 3 other detailed views of the clock have been presented. An example of the precise reconstruction can be noted observing the rope (Figure 3) wound around the drum.

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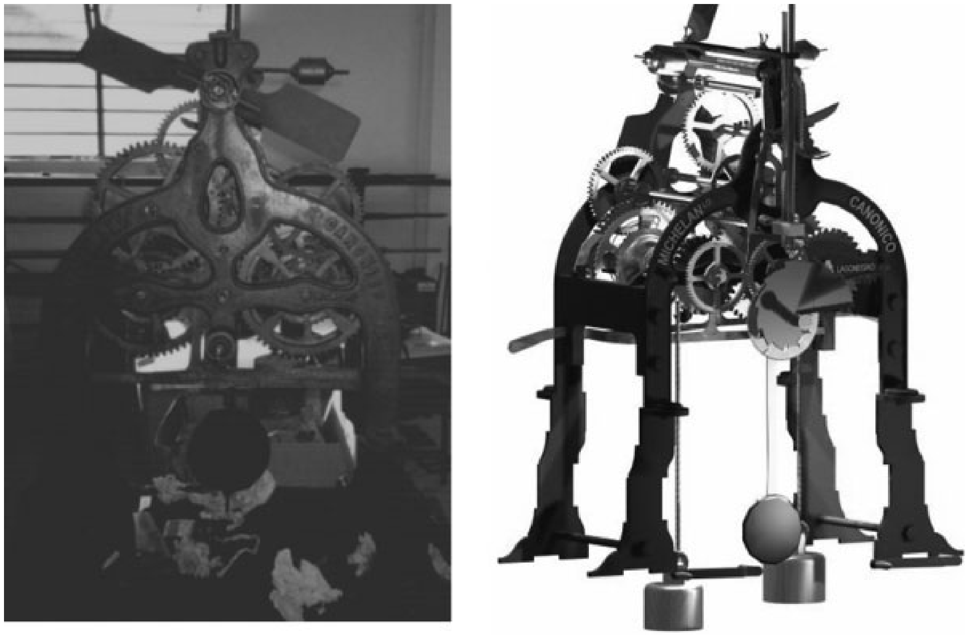

Figure 2. The actual Canonico's clock during maintenance (on the left) and the virtual reconstruction (on the right).

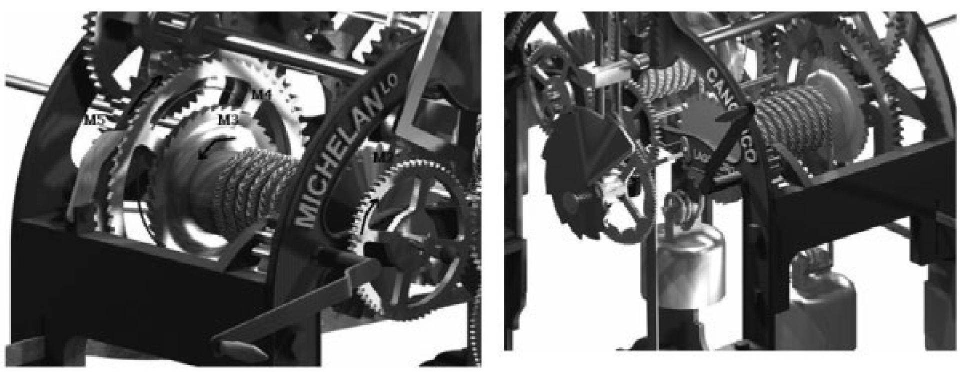

Figure 3. Left and right views of the charging mechanism of the Canonico's clock in a virtual reconstruction.

In order to place the texture on the rope surface in a proper way a special mapping along an helix has been implemented. In this case the cylindrical mapping (which has been used for the drum) has been substituted with an helical mapping:

$$\text{cylindrical mapping}\begin{cases} x(u,v) = R\cos u \\ y(u,v) = R\sin u \\ z(u,v) = v \end{cases}$$
$$\text{helical mapping}\begin{cases} x(u,v) = R\cos u \\ y(u,v) = R\sin u \\ z(u,v) = pu + v \end{cases} \qquad (1)$$

In order to simulate the exact functioning of the entire clock a kinematic analysis has been performed. Understanding the actual functioning of each sub-mechanism and their interaction is a very difficult task. The entire clock has more than 20 gears which mesh together.[15,16] For complex assemblies the movements cannot be known intuitively, but they require a mathematical approach to understand the correct kinematics. Considering two meshing gears mounted on a connecting link we can write the so-called Willis' equation:

$$\frac{\omega_i - \omega_k}{\omega_j - \omega_k} = \pm\frac{z_j}{z_i} \qquad (2)$$

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where ω_i and ω_j are the rotational velocities of i-th and j-th gear, ω_k is the rotational velocity of the connecting rod, and z_i and z_j are the number of teeth of i-th and j-th gear, respectively (the sign $+$ refers to internal gears, the sign $-$ to the external ones).

Applying this formula to all the meshing gears and considering the fixed link on the rotating shaft we can compute the movement for each component. The results of this analysis have been useful to define the keys of animation. The animation keys[17,18] are a sort of reference points in the time history which control the animation. For example to animate an object from position [0, 0, 0] to [3, 0, 0] in a temporal step, one has to implement two keys for the x axis position, one at starting time (value = 0), one at ending time (value = 3). The animation algorithm will provide to interpolate the position of the object throughout the time history using a prescribed law. For each independent part, animation controllers have to be also included to obtain the animation in a proper way. For example the controllers decide the interpolation law (such as linear, harmonic, parabolic, etc.). For each gear we have used a linear interpolation, because they move with constant speed. For the pendulum, we have chosen an harmonic interpolation, because its motion is an harmonic with a constant period. A special law has been implemented for the escapement system wheel, because this wheel moves with discrete steps. So it has been defined a regular repetition of linear interpolation laws delayed of the rest periods.

During these animations the velocity of mechanisms can be changed in order to appreciate also the movements of very slow gears (i.e., those of the hand of months).

Another difficult part to simulate is the unlocking ringing mechanism and the automatic reset system (Figure 4).

The unlocking mechanism (Figure 4, on the left) allows the clock to start ringing the two bells. It consists of a rack, which engages the lever of a coma shaped cam, and it does not permit the rotation (locking) of ringing lever till the hands indicate the passing of a quarter of an hour. A different sound is emitted when an hour is passed. The automatic reset system is necessary to restore the starting condition after ringing in order to permit the clock to ring again. This system (Figure 4, on the right) consists of a stepped cam which engages one end of the ringer rack. During its turning, the rack is first guided downwards and then it is brought back to its starting position. The duration of this movement causes the bell to ring one or many times.

The produced animations, together with a large amount of explanations about the parts and the functioning of each mechanism can now be appreciated at 'Canonico's tower clocks exhibit' at Rivello, in the neighborhood of Lagonegro (Potenza, Italy).

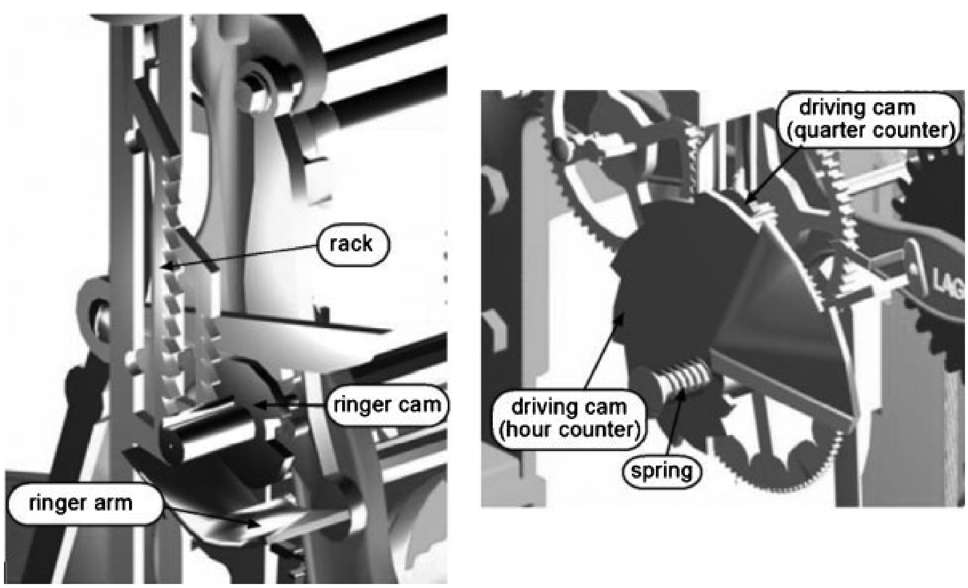

Figure 4. Unlocking ringing mechanism (on the left) and the special cam which makes the bell ring and reset the mechanism (on the right).

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Astronomic Tower Clock in Venice and Brescia

An astronomic clock is a mechanism which counts not only the passing of hours but also the passing of the months, computes the lunar phases and the position of the sun in the zodiac. All these information are provided using circular concentric panels (Figures 5–7) and are powered by the same mechanism. Thus in this kind of clock many gear trains with very high-speed ratio are present. This peculiarity is ensured by the presence of

Figure 5. Astronomic tower clock in Venice: a picture from S. Marco square (on the left) and mechanisms rendered reconstruction (on the right).

Figure 6. Astronomic tower clock in Brescia: a picture from Piazza della Loggia (on the left) and astronomic mechanisms rendered reconstruction (on the right).

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Figure 7. The front panels (Venice, on the left; Brescia, in the middle and Clusone on the right).

epicyclical gears[19,20] which mesh together. An accurate reconstruction has to compute and then reproduce these movements properly because just a small mistake can propagate causing consistent errors in all the clock mechanisms.

For the reconstruction of the clock in Venice, the computer modeling has been based on the drawings reported in the book of Dr. A. Peratoner.[21]

For the reconstruction of the clock in Brescia a direct measurement has been performed accessing to the mechanisms. For both of clocks, kinematics animations have been built up using the same approach discussed in the previous section.

The tower clock of Venice, which is placed in Piazza S. Marco, has been built in 1493 by Gian Carlo Ranieri and modified first in 1755 by Bartolomeo Ferracina and then in 1857 by Luigi de Lucia. The clock is made up of four mechanisms: one for indicating the passing of the time, one for ringing the hours, the third for special ringing at midnight and midday, and the fourth for the movement of the statues of Magi at the top of the tower.

The tower clock of Brescia is placed in Piazza della Loggia (see Figure 6). It has been built in the XVI century by Paolo Gennari (who designed the mechanical parts), Gian Giacomo Lamberti (who designed the front panel). The most interesting mechanism is that of the astronomic panel which is depicted Figure 6 on the right.

Special textures concerning the front panels (Figure 7) have been applied to the external surface of both of the clocks. These textures have been captured by detailed digital pictures. These pictures have been split in concentric rings in order to be applied to different gears which turn at dissimilar velocity.

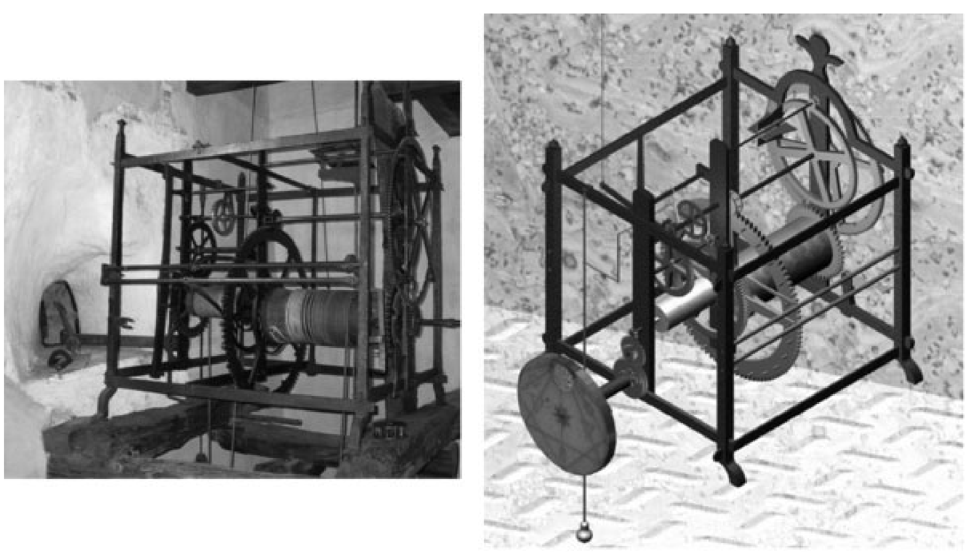

Figure 8. Fanzago's planetary clock (on the left) and the virtual reconstruction (on the right).

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Fanzago's Planetary Clock at Clusone (Bergamo)

The planetary clock at Clusone has been designed and manufactured by Pietro Fanzago in 1583. The frame and the gears of the mechanisms are made of wrought iron and the moving counterweights are two stones.

The hand of the hours indicates the passing of the time on a front panel which is divided into 24 sectors. On this surface there are three circular concentric parts which are moved by different gear trains and rotate counter clockwise. The first indicates the passing of the months, the zodiac signs and the duration of the night (which depends on the month of the year). The second indicates the lunar phases and the third mimics the relative movement between the Hearth and the Moon.

Also for this clock an accurate kinematic study (see Clock Mechanics Section for details) has been necessary to perform a correct simulation.

A rendered view of all the three mechanisms is presented in Figure 8 (on the right) together with a picture of the actual clock (on the left).

Conclusions

Computer graphics play an important role in communication. In this paper the authors show their experience in modeling and simulate complex mechanical systems such as those of ancient clock. In many cases this virtual reconstruction is the only way to share the knowledge of these beautiful devices all over the world. The correct modeling of these clocks requires an accurate kinematics analysis. In particular because an approximate simulation is not able to describe the precise interactions and movements which allow the clock to indicate the passing of the time without sensible mistakes also after years of continuous functioning. An accurate study is also necessary in order to reproduce correct surface textures. When a direct access to the clock is possible, this task can be achieved with the help of digital picture, otherwise the materials can be implemented ad hoc. After the entire model is completed some animation details and movies can be extracted in order to produce divulgative material both for didactical purposes and for sharing knowledge in museums and exhibits. For example, thanks to the work of this research unit, the computer graphics reconstruction of the first of the discussed clock (that of Canonico) has been included in a local museum and the simulation has been over projected in a special room. The methodology herein presented can be applied to several cultural heritage devices. The main aim is to promote the idea of virtual museums which can be accessed from all over the world giving the opportunity to appreciate the artifacts without moving from own home or even thousand miles away from the actual masterpiece.

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