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Virtual prototyping of medieval weapons for historical reconstruction of siege scenarios starting from topography and archaeological investigations

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Abstract. Chronicles of sieges to castles or fortresses, using "machinae", can often be found in historical sources. Moreover, archaeological excavations of castles or fortresses has brought to light rocks or projectiles whose carving suggests a military usage. Nevertheless, chronicles and discoveries alone, are seldom enough to propose a faithful reconstruction of these machines. Therefore, the aim of this research is the development of methodologies for reconstructing virtual scenarios of sieges, starting from the scarce information available. In order to achieve it, a procedure for the virtual reconstruction of the siege machine has been set up, focusing on typology and dimensions of the machines, also investigating possible fire positions according to topography. The entire procedure has been developed using the siege of Cervara di Roma's Rocca as a case study. Late medieval chronicles (end of 13th Century) report the siege brought by the papal army in order to restore the jurisdiction on the Cervara's stronghold, following the insurrection of a group of vassals headed by a monk named Pelagio. The discovery, in the area of the Rocca, of a stone that could have been used as a projectile confirms what reported. The proposed methodology is composed of two parts. The first one is connected to the study of the "internal ballistics", to understand the performances and to build virtual models of siege machines. The second part is the study of the "external ballistics", then to the positioning and shooting ability of possible machines, analysing the topography of the area. In this paper, we present the feasibility of this methodology through the preliminary results achieved correlating internal and external ballistics.

1. Introduction

This paper supports the multidisciplinary investigations about a better understanding of the dynamics and the possible development of sieges in the Middle Ages, as well as the type and the characteristics of the siege apparatus, also known in the written sources as "machina" or "engine". Engine is a term derived from Latin and the European vernaculars that stands for "ingenium", "an ingenious contrivance" and "ingeniators" are those who designed, made and used them [1].

From the methodological point of view, the approach that is here proposed starts with the analysis of the historical sources and the archaeological evidences, then proceeds with formulating siege scenario hypotheses. They are then evaluated through technical considerations related to territory topography and engineering feasibility. Virtual prototyping represents the engineering method to evaluate the apparatus performances according to the specific topography and siege scenarios discussed by the archaeologists. Unfortunately, the written sources give us very few technical details about the construction, structure

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and effective capabilities of the ancient siege engines. For this reason, the virtual reconstruction is going to include also a preliminary design development of the possible apparatus according to requirements and technologies defined by the archaeologists.

The siege of Cervara di Roma is here reported as a case study for the proposed approach. In fact, its occurrence appears to have been a non-trivial example of military knowledge and practice, due to the strategical position of the Rocca of Cervara – built on a hilltop and characterised by the presence of a very rocky and harsh landscape – apparently very favourable to resist every attempt of conquering by the force.

The paper structure reflects the logical workflow of the proposed approach starting with the sources related to the siege of Cervara and the types of engine documented in that period (Section 2). Then in Section 3, a detailed description of the technical feasibility of the siege engine and its performances is given; and in Section 4 their application to the case of Cervara di Roma is treated, arriving to the presentation of results and their discussion, before conclusion.

2. Historical sources

2.1. The siege of Cervara di Roma

In 1273, Pelagio, a monk from the monastery of Santa Scolastica in Subiaco (Rome, Latium), rebelled against his abbot and took shelter with his companions inside of the Rocca of Cervara, a military stronghold erected on a mountaintop of the Simbruini mountains. To end the rebellion and re-establish his control over his lands, in 1276 the abbot Guglielmo – supported by the papacy – sent an army to besiege the Rocca. The army, leaded by Guglielmo di Borgogna, took the stronghold within two months, thanks also to the use of a siege engine, as reported by the written sources [2]. The archaeological excavations conducted inside of the remainings of the Rocca brought to light traces of the siege along with a stone projectile related with the presence of the siege engine at the siege itself [3]. Because of that, the role of the siege engine appears to have been determinant, as suggested also by the written source. The comprehension efforts have been focused on two main research questions related to the siege engine: the determination of the kind of machine used and of its presumed size and fire range capabilities, determined on the basis of the virtual prototyping of the machine, and the determination of the supposed deployment positions of the machine itself.

2.2. Siege engines

From an historical and archaeological point of view, the siege engine employed in the siege of the Rocca of Cervara was almost certainly a trebuchet. Sporadically attested starting from the Early Middle Ages, this kind of siege engine saw a widespread adoption during the Crusades period and by the 8th century had evolved from the traction trebuchet – driven exclusively by human power – into the counterweight trebuchet, where the propulsion force was supplied by a counterweight installed at the end of the swinging arm of the machine. Technically more sophisticated and more powerful than the traction trebuchet, it was probably a counterweight trebuchet the engine used to besiege Pelagio and his fellows. Despite its large diffusion on the medieval battlefields, today we possess very few details about the construction and the characteristics of that siege engine. Absent from the byzantine military treatises of the 6th and 10th centuries – more focused on the roman military tradition and in spite of its usage being attested in the byzantine world starting from the 6th century [4, 5] – the trebuchet makes its first appearance in the military literature with the famous treatise of Mardî al-Tarsûsî written for Salâh al-Dîn in the second half of the 12th century, where the author offers a thorough analysis of the traction trebuchet. The absence of military treatises in the medieval western world until the very late medieval or the Renaissance period, leaves us with very few details about the characteristics of the counterweight trebuchet. We have a certain number of mentions in written sources such as war chronicles along with a variety of drawing and illuminated codes illustrations.

Given the very few archaeological remains of these machines – due to the perishable nature of the materials they were made of – the reconstruction of the machine used in the virtual prototyping process has been based on the iconographical evidence available from the manuscripts and on the characteristics identified by the scientific literature on the matter [1, 4, 6, 7, 8]. Further elements were provided by the dimensions and weight of the stone projectile found during the archaeological excavation at the Rocca of Cervara, whose weight clearly suggested the need for a counterweight trebuchet for its throwing.

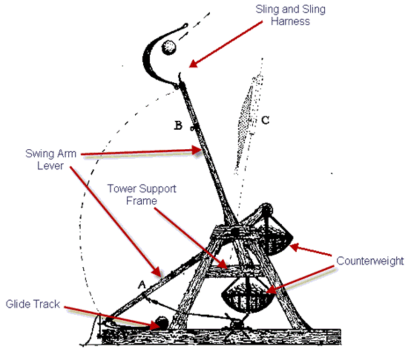

Figure 1. Example of counterweight trebuchet.

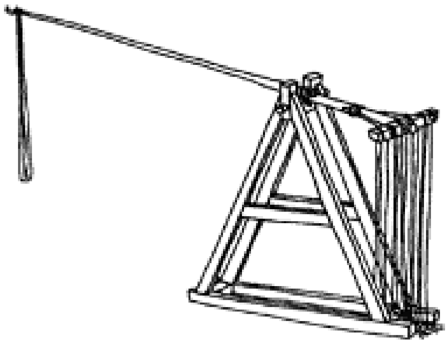

Figure 2. Example of traction trebuchet.

A preliminary analysis of the terrain characteristics of the area has been conducted to locate all the probable places for the deployment and operation of a machine satisfying our preliminary requirements. With the help of a GIS system, we analysed a digital terrain model to extract slope and altitude data and then we elaborated a model able to identify on the terrain all the areas having a suitable slope (< 20°) and altitude in relation to Rocca position. The preliminary results of the analysis confirmed the need for a machine able to reach a firing range greater than that of the traction trebuchet (> 100/125 m) [4], finally aiming our efforts toward the investigation of the capabilities of a counterweight trebuchet.

Trebuchets were often transported in pre-made pieces and the assembly was finalized on the siege location, therefore always requiring the presence of some specialized personnel to set up and operate the machine. As an example of this, see the presence of some German engineers in charge of the trebuchets in the army of the king Erik Emune of Denmark in the 12th century [9]. The Chronicle of Guglielmo Capisacchi da Narni [2, 3] reports the besieging army as being “of not small dimensions” and equipped with the siege engine, confirming us in the impression of the presence of a high degree of expertise and coordination in the execution of the siege.

The Chronicle doesn’t give us any clue about the possible use of the trebuchet to open a breach in the walls of the fortification and from the actual condition of the masonry of the walls themselves (heavily restored in the last century) is impossible to establish if that was actually the case. From the weight and dimensions of the found projectile that could have been a real option, but certainly even the bombing of the battlements and the interior of the fortress must have had a devastating effect on the morale and the resistance capability of the besieged.

3. Technical feasibility

Obtaining a virtual model of a counterweight trebuchet suitable for a specific siege scenario means to provide type, structure, material and reasoning of its practical usage during the siege. In particular, it is necessary to evaluate solutions related to how they built and maintained it, considering constraints related to the topology of a suitable area where placing it and shooting safely a projectile on the target.

Due to the vastness of this kind of design problem, we decided to consider two main fields of analysis, conducted in parallel: the so-called internal and the external ballistics analysis. Although these analyses are typical of firearms, we decide to adopt them to distinguish the two basilar technical studies necessary to face this problem: the siege engine design and its selection according to the performances required by the target. Internal ballistics concerns with defining the way of functioning of the trebuchets and their dimensions. For the external ballistics analysis, instead, we are referring to all issues connected to the trajectory, the positioning and the topography of the area in which machine and target are placed.

Considering the timing of an attack, the internal ballistic is connected to all the issues starting from the activation of the machine to the moment when the projectile leaves. It defines the way the siege engine works. The external ballistics analysis is connected to the engine final performances, so that it is related to the choice of positioning area, and, mostly, to moments following the detachment of the projectile, during "flight", in terms of trajectory issues.

3.1. Internal ballistics: aim

Siege machines have had a significant development in their history, and obviously it conducted to a wide range of types and solutions. In this work, we limited the analysis onto trebuchets, due to the fact that, in the case of Cervara di Roma, this type of machine seems to be the used one, both for its diffusion at that age and for its launch capability.

In order to understand the capabilities of this typology of machines, three models have been studied, varying the level of technological progress. In fact, starting from a trebuchet with a fixed counterweight at the end of the shorter arm (Type A, in Figure 3), we added technical solutions oriented to the increase of performances, as reported in literature. One solution is a hinged counterweight (Type B in Figure 4), the other is a sling for positioning and launching the projectile (as added in Type C in Figure 5).

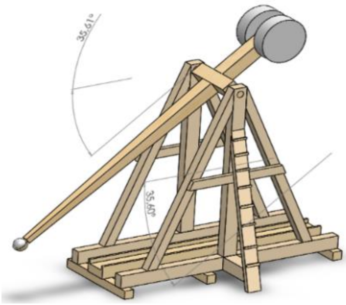

Figure 3. Type A model trebuchet with fixed counterweight.

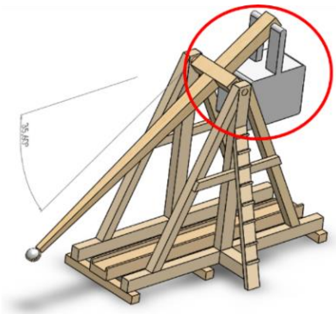

Figure 4. Type B model trebuchet with hinged counterweight (circled in red).

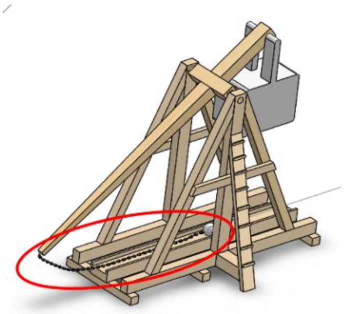

Figure 5. Type C model trebuchet with added sling (circled in red).

From the structural point of view, considering loads as concentrated masses, the maximum bending moment is always placed in correspondence of the fulcrum of the launcher beam. This obviously defines the dimensioning of the structure in terms of resistant section.

Nevertheless, several input have to be defined for achieving the effective dimensions of the machines, and sensitivity analysis can be conducted varying these input into their ranges.

The main inputs are:

- Counterweight Mass (M_{cw}),
- Projectile Mass (M_p),
- Length of Launcher Beam (L),
- Ratio ($\frac{L_2}{L_1}$) between lengths of longer (L_2, the part that connect the projectile site and the fulcrum) and shorter arm (L_1, the connection between fulcrum and counterweight).

In addition, some assumption has to be done regarding:

- materials (generally wood, function of the geography of the site),
- initial and launching angle,
- height of the fulcrum,
- clearance between counterweight and the ground floor during motion (connected to the L_4, length of the arm that connects the hinge with the hinged counterweight, if present)
- length of the sling (L_3, only for Type C).

This type of sensitivity analysis can lead to the definition of the section lengths (assumed to be square), and of $\overrightarrow{V_0}$ values, the velocity of the projectile at the moment of launch that is directly connected to the maximum reachable range.

3.2. *Internal ballistics: results*

Sensitivity analysis has been preliminary approached with analytic and energetic formulation, inside Mathematica, spanning significant ranges for M_{CW}, M_P, and geometric configuration of the beam (L_1, L_2). It assumes poplar wood as material for all the pieces (with density of about $400\frac{kg}{m^3}$; shear yield stress of about 4.8MPa, static friction coefficient between 0.25 and 0.5 and kinetic friction coefficient of 0.19).

Virtual models of the three types of machine have been obtained into a parametric CAD, and they have been also imported in a multibody simulation software, Hyperworks Motionview, to evaluate, in addition, the influence of friction factor, which could be extremely complex with the analytic and energetic formulation. Results of this study are summarized in Figure 6. Assuming horizontal slope for the terrain, optimal launch conditions are related to 45°, so that the maximum range turns out to be: $R_{max} = \frac{V_0^2}{g}$.

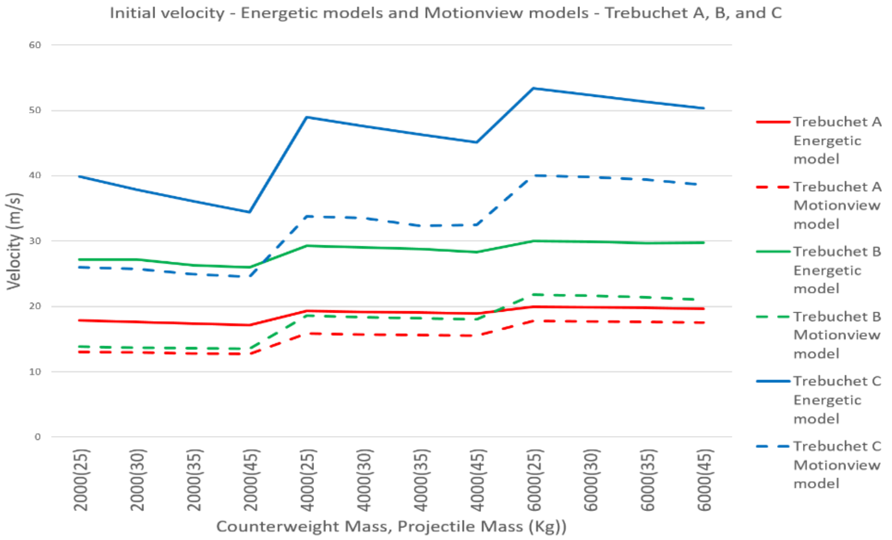

Figure 6. Sensitivity analysis according to M_{CW}, M_P, and type of machine, with and without friction.

As shown in Figure 6, changing the type of trebuchet, performances increase according to M_{CW} and decrease with the M_P (values fixed at 25, 30, 35 and 40 kg). Lower values of M_{CW} reduce the effect related to the type of machine, while higher values make more evident the improvements due to Type B and C. Obviously the presence of friction reduces the velocity (in the legend of Figure 6 it is related to Trebuchet with flag "Motionview"), nevertheless, additional studies must be done to evaluate the presence of metal parts in the hinged connections. In fact this solution, when suitably lubricated, would lead to lower friction coefficients than in the case of wood-wood, mitigating the reduction in the resultant performances.

3.3. *External ballistics*

The internal ballistic analysis have been conducted considering that the virtual attack could take place in a "flat" zone, admitting the target placed at the same height level of the launching point.

In real positioning, there are several differences with this ideal case, connected to issues not directly correlated to machine functioning. Generally, there is a difference in terms of height between the target and launching point, and three characteristic angles have to be defined (Figure 7):

- α, the launching angle that has to be optimised;
- β, the angle due to the inclination derived by planar and height differences between launching point and target (T),
- γ, the local slope of the area where the machine is placed.

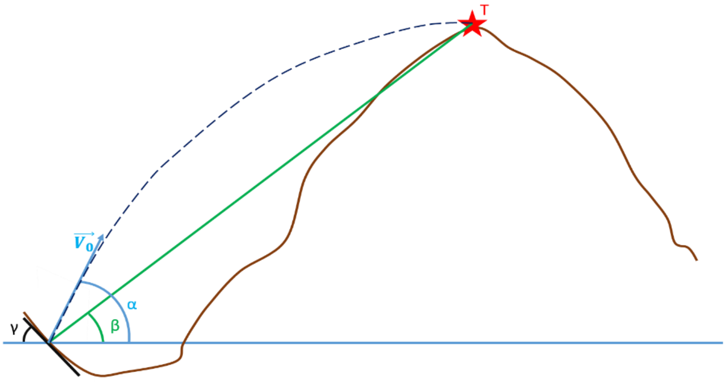

Figure 7. Characteristic angles in an external ballistic problem.

For what concerns γ, the local slope angle, there are several technical observations to do. Firstly, from the literature, it is known that often these types of machines were transported in parts and assembled *in situ*, so that, the local slope had to be limited to guarantee the possibility to move pieces of several meters of length and to assembly the machine safely. Analogous issues can be highlighted for the possibility of functioning, partially solvable through the usage of artificial basements, to avoid excessive slopes, or through operations of ground levelling. What has to be clear is the fact that the relative launching angle (in a reference system solid with the machine) is equal to the difference between α and γ, and it must be limited and close to 45° to guarantee the functioning. Due to this, only areas with γ < 20° have been examined.

The optimal launching angle, α, can be optimised according to β, the inclination angle, to obtain the maximum range R_{MAX} (depending by the V_0). But, two different cases must be considered: one with the T at a higher level respect to the launching point, the other with the T at a lower level.

For the ascent case:

$$\tan\alpha_{opt} = \tan\beta + \sqrt{(\tan\beta)^2 + 1}; \quad \text{which gives } R_{MAX} = \frac{V_0^2}{g}\,\frac{(\tan\beta)^2+1}{(\tan\beta)^2+1+\tan\beta*\sqrt{(\tan\beta)^2+1}};$$

for the descent one:

$$\tan\alpha_{opt} = -\tan\beta + \sqrt{(\tan\beta)^2 + 1}; \quad \text{which gives } R_{MAX} = \frac{V_0^2}{g}\,\frac{(\tan\beta)^2+1}{(\tan\beta)^2+1-\tan\beta*\sqrt{(\tan\beta)^2+1}}.$$

It can be seen that, respect to the “flat” case, the one with the target in ascent has a R_{MAX} smaller, due to the multiplication of the $R_{MAX\text{-}FLAT}$ for a quantity lower than 1. Likewise, the second case has an R_{MAX} higher, due to a multiplication for a quantity higher than 1. So that, it is visible as the descent is favourable and the ascent has a negative effect on the launching capacity.

The developed procedure for external ballistics analysis starts with the GIS acquisition in an area close to the target. The first step is the analysis and the selection of areas with local slope γ < 20°, then, for all the selected zones, β and α_{opt} are calculated. Every distance with the target is also obtained. The substitution in the R_{MAX} formulation (for the respective case) furnishes the minimum value of V_0 to reach the target. These data can be crossed to what found in internal ballistics in order to select possible types of trebuchets and their dimensioning for each of the selected areas.

4. Application for the siege of Cervara di Roma

This section presents a resume of the developed procedures applied to Cervara di Roma [10]. The input data are:

- the archaeological finding, in the fortress area, of a limestone with an average diameter of about 0.3 m and a weight of about 30kg. The level of finishing and the quite symmetric shape of the stone have led to attribute it the role of projectile of a siege engine.
- the GIS acquisition of an area of about 250 m of radius centred nearby the fortress. This represents a credible range of action for the found projectile. We assume the area of the siege identical in topographical terms to what it was in the 13th century, nevertheless, no chronicles, documents or treatises have been found that report catastrophic events, as earthquakes, or landslides in the region.

In terms of internal ballistics, the parameters described in Section 3 can be set in the ranges reported in Table 1.

Table 1. Ranges of input parameters used for trebuchet models for Cervara di Roma analysis.

Input parameter	**Range (Unit of Measurement)**
Counterweight Mass (M_{CW})	2000 - 6000 (kg)
Projectile Mass (M_P)	25 - 40 (kg)
Length of Launcher Beam (L)	6 - 10 (m)
Ratio L_2/L_1	2 - 4

GIS acquisition of the area, with the fortress highlighted, is reported in Figure 8. In Figure 9, the local slope angle, γ, is also reported. Four areas (Z1÷4), with an average γ close to 20°, can be individuated. These are the suitable areas for positioning trebuchets. It has to be highlighted that data obtained by the GIS acquisition furnished local slope for sections of about 1 m^2 each. Resampling operations and the calculation of local slope average are useful to consider wide local areas that can allow the machine positioning.

In the Cervara di Roma case study, it has to be highlighted that no wide transformation and changes of the altimetry have been reported in written sources. Operations aimed at local levelling, in terms of slope, could be generally considered, but, in the case of Cervara di Roma, they are not applicable due to the imperviousness of the area, as reported in historical literature. So that, the current topography has been considered analogous to the ancient one.

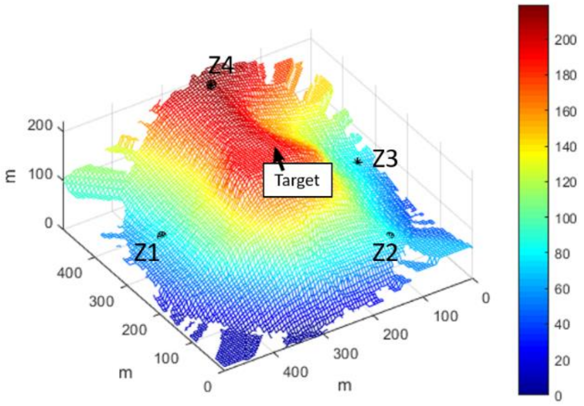

Figure 8 Altimetry of the zone..

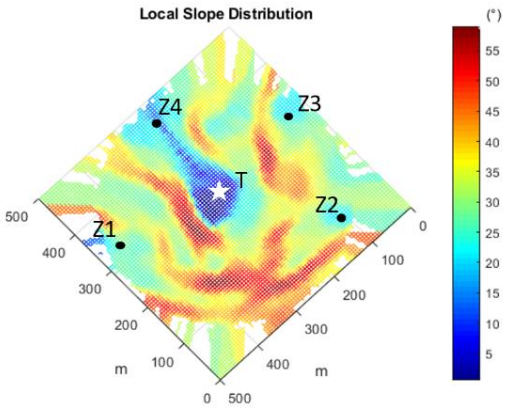

Figure 9. Local slope angle (°).

Extracting from the GIS data the central coordinates of the 4 areas of launch, average β and α_{OPT} can be evaluated. The distance between each zone and the target can be used to determine the minimum V_0 requested to reach it. Results are resumed in Table 2, using as central coordinates of the areas, the relative positions, *Rel*, from the point with lowest altitude.

Table 2. Data obtained for Z1, Z2, Z3, Z4 points of launch.

	X (Rel) [m]	*X (Rel) [m]*	*X (Rel) [m]*	*Local Slope [°]*	*Condition of Launch*	*Distance [m]*	*β [°]*	*α_{OPT} [°]*	*V_0 min [$m*s^{-1}$]*
Target	275 (0)	220 (0)	190 (0)						
Z1	296 (21)	431 (211)	77 (-113)	26.0	ascendent	212	28.1	59.0	55.3
Z2	84 (-191)	112 (-108)	78 (-112)	20.5	ascendent	219	27.0	58.5	56.0
Z3	296 (21)	39(-181)	80 (-110)	21.0	ascendent	182	31.1	60.1	52.1
Z4	453 (178)	230 (10)	220 (30)	11.0	descendent	178	9.6	40.2	38.2

Crossing these external ballistics data with the charts of trebuchet performances discussed in Section 3 (Figure 6), we obtain that:

- Type A trebuchet cannot be applied with the chosen range of parameters in the selected zones;
- Type B can be applied only in Z4 (descendent case) in few combinations of imposed parameters;
- Type C can be applied in every of the four areas of launch, with a high number of possible combinations of parameters, giving the possibility of a choice in function to easiness of functioning.

5. Conclusions

Through the developed procedures and the sensitivity analysis, the hypothesis of use of a trebuchet by the papal army in the siege of Cervara is reinforced. Trebuchet models confirmed the technical progresses, in terms of performances, due to the introduction of hinged counterweight and sling. The procedures developed, distinct in internal and external ballistics analysis, have shown 4 possible areas that may be successfully attacked by Type C, while Type B can be effective only in descendent terrain and Type A can work only assuming specific anti-friction solutions like metallic hinge.

This research work, in the hope of authors, will be the initial part of a wide study, future developments will be about the analysis of friction factors, connected to archaeological researches on metallic materials, trying to characterise them. Moreover, a better description and assembly analysis will be also made to focus the engine set-up and the men necessary to manoeuvre it.

In the next period, the study will focus on the air resistance analysis. In fact, it has not been considered because the obtained values of velocity are lower than the limit velocity calculated for an ideal sphere equivalent to the analysed projectiles. The consideration of air resistance could conduct to a reduction of about 10÷20% in terms of performances, thus maintaining the possibility of reaching the target from the selected areas. The goal is to consider specific wind maps of the siege area in order to develop an accurate analysis of the issue. This represents the one of the main further developments of the research, for improving the accuracy of the procedures.

The entire procedure, developed on the Cervara di Roma case, will be applied on other sites for other siege machine virtual reconstructions, focusing not only on trebuchet, but to the entire field of siege engines.

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Section 2.2 (*Siege engines*) has been developed by Lorenzo De Lellis.

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