Title:
Light-weighted Horse Saddletree Through Reverse Engineering and Lattice Structure Design

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Introduction:
Horse saddle is a horse-riding seat able to provide a firm support with comfort, safety, and dynamic balance to the rider. Typically, a horse saddle is composed of a saddletree, a seat made of hard foam and a leather cover with various holding pins. The saddletree (Fig. 1) is the backbone of the horse saddle, and it acts as a shield between the horse and the rider. It uniformly distributes the load of the rider over the horse's back [6], helping to reduce the pressure points on the horse's back and enabling the horse to withstand the rider efficiently.
Saddle trees include metallic elements such as the stirrup bars, the gullet plate, spring steels, and cantle iron. These reinforcements are necessary to strengthen the structure from the fatigue point of view and to provide the proper stiffness with respect to the dynamic loads that may persist [11]. This is particularly true for saddle trees made with laminated wood. Quite the opposite design solutions made by molding reduce the number of reinforcements that are necessary to strengthen the structure, since the adopted materials usually have a better performance in terms of fatigue resistance.

Fig. 1: Different types of English Saddletrees available in the Market [8] (highlighted in red some steel reinforcements).

Steel reinforcements, as the ones shown in Fig. 1, make the saddletree as the heaviest part [10] of the horse saddle, and the involvement of multiple processes pertaining to manufacturing and manual assemblies increases the total development time of the saddletree.

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Fig. 2: Investigated Horse Saddle: Saddle upper view (on the left); saddletree dissected cross section (on the right).

This paper investigates how Topological Optimization (TO) techniques based on Voronoi lattice structure solution, may reduce the mass of a saddle tree, obtaining a single component. The original shape of the saddletree is preserved as a constraint of the design requirements. This constraint has been considered as a functional constraint and its final shape has been acquired from an existing English saddletree via Reverse Engineering (RE) techniques. In the specific workflow of the lightweight design, this step mimics the customized acquisition of the functional surfaces, provided by physical or digital prototypes made according with the horse or the rider (as it happens for example, in the medical or cultural heritage applications [4,7]).

Lightweight design involves research in many fields such as development of new materials, innovative design criteria and solutions such as weight reduction by topological optimization [1,2,3,9]. Cellular structures (foams, honeycombs, and lattices) are excellent for producing lightweight parts with structural requirements, because they may be developed so that material can be placed where it is required. The resulting cell pattern can be defined by optimizing the stiffness, or the energy absorption or the insulation properties over the mass reduction. Voronoi tessellation is one of the approaches used in computer-aided design and graphic domains to build lattice structure with different geometric characteristics [5,12]. From the computational point of view, the optimization may be approached in different ways. In [15], approaches are divided into full-scale and multi-scale ones. In the first case, FEA at the mesoscale length is fully included or taken into account by homogenization. The second case reduces the computational efforts by splitting the analysis in steps related to the length scale. The pattern replication of cells is designed according to the final TO results. Density distribution may lead to multigrade materials maximizing performance/mass ratio. CAD smoothing and manufacturing constraints may improve the feasibility of the final shape design.

In this paper, we apply a multi-scale approach based on implicit geometry formulation. To achieve the desired objectives, a CAD based workflow has been followed from reverse engineering up to the design optimization stage.

<u>Main Idea:</u>

The applied workflow integrates the two stages: Reverse Engineering and lattice based TO, so that the final CAD model may be provided to the Design for AM stage (definition of printing orientation and possible supports, printing parameters, and post processing). In the first stage, the English saddletree has been scanned for the CAD model reconstruction. In the second stage, TO is performed with subsequent lattice structure generation to produce the optimized design.

As described in the next section, the workflow starts from the Reverse Engineering step. It acquires the constrained surfaces that represent the bottom and the top part of the saddletree. The investigated horse saddle is a traditional English saddle (Fig. 2), provided by Uptons saddlery Copenhagen, Denmark and the whole research work was performed with the mutual collaboration of Thürmer Tools, Denmark. The English horse saddle has the standard size of 431.8mm and a weight of 9 kg. The weight of the overall saddletree, made by laminated wood and spring steel where necessary, is estimated to be 2 kg with standard dimensions of length= 411.0 mm, width=260.8 mm, and height=210.0 mm.

The next step concerns with the TO process. It asks for a preliminary FEA static analysis to assess the critical design issues. For the structural static analysis of the saddletree, boundary conditions are defined using a simplified equestrian jumping physics (Fig. 3(a)). However, jumping over a fence (Fig. 3(b)) and water (Fig. 3(c)) are considered as the critical conditions from the analysis point of view, because these two conditions are subjected to maximum pressure.

Concerning the material, Ultrasint® PA11 black CF (Tab. 1) is selected, since it is a suitable material for lightweight design and Additive Manufacturing via Selective Laser Melting [14]. Ultrasint® PA11 black CF is a bio-derived powder material, commonly used for advanced applications where high rigidity, impact resistance and strength are required. in fact, this carbon-fiber reinforced material can provide optimal mechanical performances of 3D printed structures.

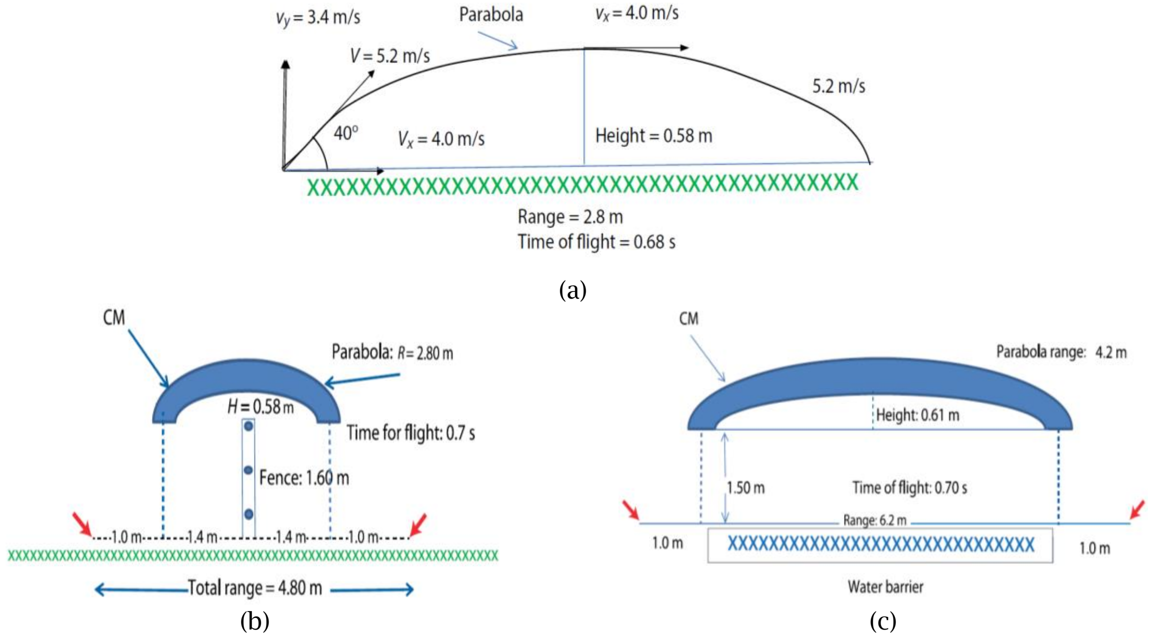
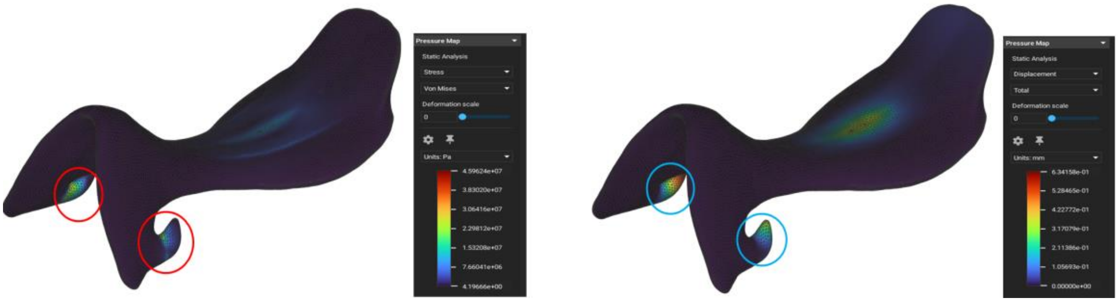


Fig. 3: (a) Simplified equestrian Jumping Physics, (b) Jump over Fence, and (c) Jump over Water [13].

Case Study	*Material*	*Young's Modulus (MPa)*	*Poisson's Ratio*	*Bulk Density (kg/m³)*	*Tensile Strength (MPa)*	*Elongation at Break %*
Saddletree	Ultrasint® PA11 black CF	234.44	0.43	540	82	7

Tab. 1: Material Properties of Ultrasint® PA11 black CF [14].

From the numerical simulations, the maximum Von Mises stress is of 45.96 MPa and it is observed at the joints of stirrup bars (Fig. 4(a)). These are the areas which are subjected to the force exerted by the rider's feet when the rider stands on the stirrup iron. The stirrup iron is connected to the stirrup bars, which have a small cross-sectional area. However, the obtained stress value is below the tensile strength (82 MPa) of the selected material, and therefore provides a safety factor of approximately 1.78. In addition, the maximum total displacement of 0.634 mm is also observed at the tip of the stirrup bars on both sides of the saddletree (Fig. 4(b)). Similar results are obtained by adopting the Displacement Point Map as field data and also through different order of magnitude for seed randomness.



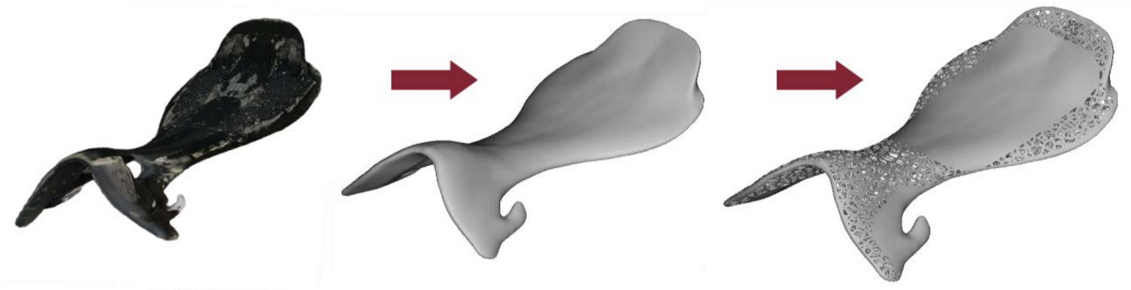
(a) (b)

Fig. 4: (a) Highlight of Max von Mises Stress, and (b) Highlight of Max Total Displacement.

From the lightweight design point of view, the final optimized design also reduces the mass from 2 kg (original saddletree) to 0.4682 kg (final optimized design). Thanks to lattice solution, there is a huge reduction in mass comparing it to the mass of the saddle tree made by injection molding. Power Bed Fusion should be applied with the selected material.

From the methodological point of view, the adoption of 3D acquisition of the starting CAD model confirms the reverse engineering versatility to support shape customization in part design. Then, the adoption of a TO based on nTopology allows to tune the lattice generation based on Von Mises distribution maps used to constraint the seed spacing and the cell strut thickness. Doing so the problem is divided into steps with different significant length scales, from the part length scale of the FEA to the meso-scale of the lattice generation. Functional surfaces have been used here as non-design space where bulk material is maintained, through Boolean operations between the lattice structure and the original implicit models.

Moreover, specific simulation of the achieved stiffness (Max Force/Max Deflection) can be carried out and compared with reference data, in different riding conditions. Finally, a proper design for AM will be investigated in the next, in association to a sensitivity analysis to different cell typologies.



(a) (b) (c)

Fig. 5: (a) Scanned Saddletree, (b) Fully Edited Saddletree, and (c) Final Optimized Saddletree.

Conclusions:

The case study demonstrated the feasibility of the lattice structure lightweight design of the saddletree based on Voronoi volume lattice. The new optimized design preserves the original shape of the saddletree, as required. Adopting a bio-derived powder material suitable for dynamic performance around 76.6% mass of the saddletree is reduced with the final optimized design, thanks to the Voronoi lattice structure, expecting to maintain stiffness requirements under operative load conditions, thanks to the stochastic pattern with graded density, that was defined trough the Von Mises stress map. Hence, the final optimized design is a monolithic structure, which will minimize the several manual assembly processes. In addition, the manufacturing process will be based on Power Bed Fusion (PBF) additive technologies, which will replace all the previous old several conventional manufacturing processes into a single process. This may provide a significant reduction in terms of manufacturing time and costs maintaining or improving the performances in terms of stiffness.

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