Drum Shape Design and Optimization Using Genetic Algorithms

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Abstract

This paper describes the mechanical design and optimization of a spinning steel drum used as a combat robot weapon. The single-toothed drum design assumes that both drum body and tooth are integrated as a single piece (unidrum). The optimization is based on Genetic Algorithms, finding the design with greatest "tooth bite" while guaranteeing a perfect balancing of the unidrum without the need for counterweights.

Keywords

Genetic Algorithms, Rotor Design, Shape Optimization

Introduction

Mechanical design of combat robots (combots) is always evolving. Sometimes, finding the best solution for a task is not possible or it is too complex to be found analytically. Genetic Algorithms are numerical methods inspired in the natural evolution process to find a locally optimal solution for a given problem. It uses the principle of the evolution of species, the survival of the fittest, in which every individual of a given population is evaluated. In this work, each "individual" is defined as a different drum design, represented by the contour of its cross section. An initial population of random drum designs is combined to result in further generations. The designs with better characteristics to adapt are kept, while the algorithm performs mutations and crossovers to generate even better individuals. At the end of the evolution process, the best design is chosen as a locally optimum solution.

Design Principles

One important issue when designing spinning combot weapons such as disks, drums and shells is regarding the number of teeth attached to them and their height. Too many teeth on a spinning disk, for instance, will make the spinner chew out the opponent instead of grabbing it to deliver a full blow.

There are mainly five things that need to be taken into account when designing a spinning weapon: its inertia, its strength, the number of teeth attached to it, their height, and the speed of both weapon and robots. The tooth bite is defined as the distance *d* (see figure 1) of overlap between a robot weapon and the opponent before hitting it. This distance depends on the number of teeth, the angular velocity ω_b of the weapon, and the relative translational speed $(v_{x1}+v_{x2})$ between the robots, as shown in figure 1.

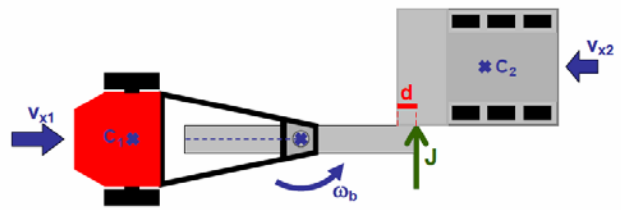

figure 1. The tooth bite *d* of a spinning weapon depends on the robot and weapon speeds, number of teeth and their size.

If the weapon spins too fast, a large number of teeth would make the tooth bite *d* become small, chewing out the opponent's armor instead of binding to it to transfer as much impact energy as possible. Therefore, the use of 3 or more equally spaced teeth should be avoided. Symmetrical spinning bars naturally have 2 teeth, while drums and disks can be designed to have a single tooth to maximize *d*. But the problem with weapons with only one tooth is that they are not easy to be balanced due to their asymmetry. Any unbalancing can lead to large vibrations that can render the robot uncontrollable.

Previous one-tooth design from Team RioBotz [1] were based on stainless steel drum bodies, well suited to absorb impacts, with a single S7 tool steel tooth insert hardened to 54 Rockwell C, and a diametrically embedded counterweight made of a tungsten alloy. Due to the very high costs of tungsten alloys, and due to their relatively low strength, it is desirable to completely eliminate the need for counterweights. To address this, a single tooth design is conceived using a tempered 4340 steel unidrum, i.e., a drum plus tooth made of a single metal piece. The challenge of such drum design is to find an asymmetrical shape that would result in both a single tooth with maximum byte and a perfectly balanced drum without any counterweight or other inserts. The solution to this problem is found using Genetic Algorithms.

Chromosome and Fitness Function

Every individual of a population is defined by what we call chromosomes. They contain all the characteristics of that individual. They can mutate and/or be transmitted to their heirs in the chain of evolution.

One challenge is how to define the chromosomes used to represent the shape of a spinning drum. Chromosomes are discrete quantities, while the drum shape is continuous. To address this, the shape of the drum cross section is modeled as a polygon, generating a multi-faceted design. This polygonal design has 2 advantages: the drum shape can be easily represented by a finite number of variables, and the fabrication process can be performed using a milling machine without the need for a CNC system.

The drum chromosomes are chosen as the distances between the drum center and each side of the polygon, as shown in figure 2. In this example, the combination of the values a-b-c-d-e-f-g-h-i-j-k-l would completely define an individual, i.e., a drum design, assuming the polygon angles had been prescribed.

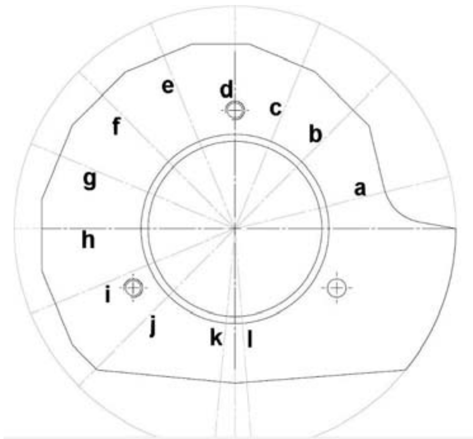

figure 2. Distances defining the chromosome of an individual drum.

Two characteristics need to be evaluated to access the fitness-of-purpose of a drum: the position (C_x, C_y) of the drum center of mass with respect to its spinning axis, which should tend to (0, 0) for a perfectly balanced drum, and the maximum achievable tooth bite *h*. For a linear spiral-shaped unidrum, the maximum tooth bite is essentially equal to the tooth height. But, for a general shape, the tooth bite depends on all chromosome values. E.g., even if the distance *a* is very small in figure 2, leading to a large tooth height, large values of *b* or of the other distances would prevent the entire tooth protrusion from biting the opponent. Therefore, the tooth bite *h* is calculated from the smallest linear spiral that circumscribes each individual design.

In addition, a third term is considered in the fitness function to avoid highly non-convex solutions. Non-convex solutions are more difficult to fabricate, and tend to concentrate stresses. The fitness function to be minimized in the Genetic Algorithm is then defined as

$$fit = \frac{w_1}{h^2} + w_2\left({C_x}^2 + {C_y}^2\right) + \frac{w_3}{c^2} \quad (1)$$

where *c* is a value that indicates how convex the solution is, and w_1, w_2 and w_3 are user-specified weight factors that define the importance of, respectively, the tooth bite, the drum balancing, and its convexity. The individuals with *lower* values of the above fitness function are better candidates for the drum design. New generations are then calculated from the “mating” of such better individuals, including random mutation.

Simulation: Evolution Process

In order to simulate the evolution of the population, it is necessary to define the parameters:

- number of sides of the polygonal drum (*n*);
- maximum drum radius (R_{max}), located at the edge of the single drum tooth;
- minimum value of each chromosome (r_{min}), to avoid drums with very thin wall thicknesses;
- number of generations in the evolution process (*N*);
- size of the population of each generation (n_p);
- number of best individuals that are chosen to survive without any mutation (elite count, n_e);
- crossover fraction (c_f) and function;
- mutation function; and
- values of the weight factors (w_i).

The details on the choice of each of the above values are beyond the scope of this work, since they’re too lengthy to be described here.

The simulation is implemented in the MatLab software using its Genetic Algorithm Toolbox. The chosen algorithm parameters are n = 18, r_{min}/R_{max} = 0.75, N = 10,000, n_p = 100, n_e = 5, c_f = 0.7, w_1 = 2, w_2 = 15 and w_3 = 30. The result is presented in figures 3 and 4, normalized by R_{max} to result in dimensionless distances between 0 and 1. This normalized design can be applied to any drum size, by simply multiplying all distances by an arbitrarily chosen R_{max}. Note that a linear spiral was included in the initial population, even though it would result in a completely unbalanced solution. Figure 3 shows the shape of such original spiral, the shape of the best individual (with lowest fitness value) after 5,000 simulated generations, and the locally optimum shape from the best individual of the $10{,}000^{th}$ generation. Figure 4 shows the convergence of the drum center of gravity (normalized by R_{max}) to its desired (0, 0) position, resulting in a perfectly balanced design with the highest tooth bite.

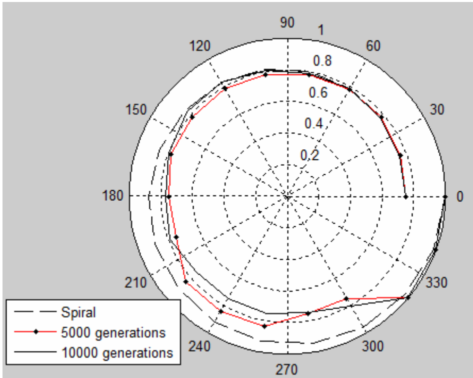

figure 3. Drum shape evolution from the original spiral.

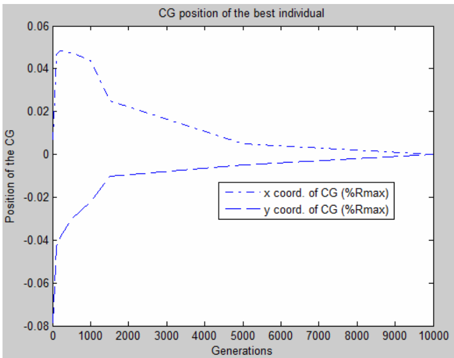

figure 4. Variation of the position of the center of gravity of the best individuals (drum designs) of each generation.

After observing the nearly flat shape of the optimal solution in the regions between 220° and 320° in figure 3, the algorithm is re-evaluated considering only 2 flat sides in such region. This new optimal solution is very similar to the previous one, but it is easier to machine due to the reduced number of facets. Nicknamed “snail drum” due to its snail shape, this genetically designed 70lb steel drum is presented in figure 5, before attached to the heavyweight combot Touro Maximus.

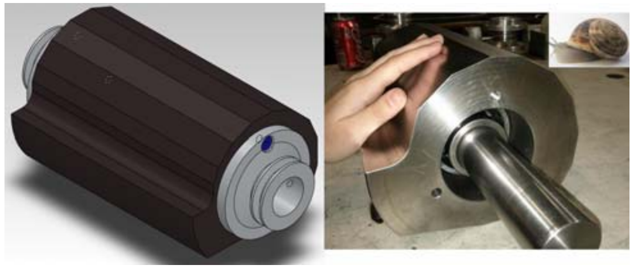

figure 5. Touro Maximus’ spinning weapon: the Snail Drum.

Conclusion and Future Works

In this paper, Genetic Algorithms were used to find the best solution for the shape of a single-toothed polygonal unidrum. The fitness function considered both drum balancing and tooth bite, dealing as well with convexity issues. In the converged design, the shape of the tooth notch was later smoothed using Mattheck’s variable radius approach [2], decreasing its stress concentration from 1.5 to 1.1. Future works include the calculation of the continuous (curved, i.e. non-polygonal) version of the Snail Drum, to be fabricated using CNC machines.

Citations

[1] Meggiolaro, M. A.; “*RioBotz Combat Robot Tutorial,*” Createspace Pub. Co., 2009.

[2] Mattheck, C., “Teacher tree: The evolution of notch shape optimization from complex to simple,” Engineering Fracture Mechanics, vol. 73, n.12, pp. 1732-1742, 2006.