Structural and Topological Optimization in Robot Design

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Abstract

This work focuses on implementing and applying procedures to optimize the structure of a robot. This research addresses the problem of determining the optimal topology which maximizes the rigidity of bodies subject to local stress by uniting structures with different densities and materials.

This methodology provides a functional analysis of the robot in operation from a three-dimensional elastic perspective with a view to deriving the best configuration.

After a description and an analysis of current optimization techniques, topological and geometrical methods, SKO (Soft Kill Option) are implemented in a FEM code to appraise the robot’s components and to allow multiple dynamic loading conditions. We discuss about some solutions obtained by the classical approach of scaling the stress maximum associated only by assigning weights and dimensions, and then the results obtained with the new methodology.

The proposed methodology was applied to studying a ‘Tribot’ robot (fig. 1). The Tribot has three parts: two split driving parts and a manipulator with modular behaviour. Topological optimization includes aspects such as redrawing size and shape of component. By using the methodology of rapid prototyping (RP) the solutions were assessed quickly and particularly lightweight. Reliable modular structures were built.

1 Introduction

Robotics research is currently focusing on developing autonomous robots to perform tasks in uneven and hazardous environments. Today, there are a growing number of situations which endanger human life (e.g. landmine clearance) and evermore inaccessible environments (e.g. space, marine and volcanic environments) hence the need to develop self-organizing robots for a variety of environments. So, what is required is a robot with high static and dynamic stability which can operate in different environmental conditions, climb over obstacles and carry a considerable payload. Over the last decade, therefore, numerous researchers have developed robots based on the behavioural or architectural characteristics of insects [1, 2 and 3].

The main purpose of this study was to optimize an existing robot called ‘Tribot’ [4] (Fig. 1).

Tribot is a wheeled robot that takes advantage of the solutions proposed by other researchers and combines some positive aspects of existing robots. It was inspired by the great agility and adaptability of insects which manoeuvre in harsh terrains by virtue of their physical structure and which can be mimicked by control mechanisms coordinating the movement of wheels.

Tribot’s optimization is based on the experimental observations of insects with regard to mechanical design and locomotion control strategies [5 and 6]. In particular a procedure for structural and topological chassis optimization was developed. The optimization phase of the new robot, using FEM and multibody models [7], was aimed at improving specific characteristics: speed, payload and climbing capabilities.

The bending-torsional characteristics of the robot’s chassis are fundamentally important for guaranteeing performance in terms of stability and low vibration. Lacking suspension units, chassis and locomotion sistem must be able to completely absorb surface irregularities. An original modular wheel mechanism was developed with the aim of ensuring stability for the images scanned by the cameras which must recognize the morphological characteristics of objects and obstacles. Chassis optimization is performed increasing torsional stiffness to favour a more rapid vehicle response, while restricting bending stiffness. After the optimization process some control components (for example electronic cards) have structural functions and some structural parts simultaneously perform several functions.

High structural efficiency in terms of stiffness/weight ratio was obtained by harmonizing bending and torsional characteristics of robot.
2 Robot structure

To evaluate robot performance and propose innovative ideas aimed at improving the mechanics of the system, a 3D flexible multibody robot model was developed, using parametric software to define its geometry and mass properties.

To duplicate the extraordinary agility of insects, at least in part, the robot has three sections: two split driving ones and a manipulator with modular behaviour.

The robot prototype represents a good compromise in terms of number of D.o.F. The drive parts are jointed with an elastic gimbal that allows for correct vehicle tilt during various manoeuvres. This constraint is the right compromise between the need for rigidity of the drive part joint and the necessary deformability which allows the robot to adapt to different surfaces. A rigid revolute joint connects the manipulator to the front drive part. The robot prototype is shown in fig. 2.

![Fig. 2 3D complete model of Tribot.](image)

Fully assembled, Tribot weighs 2.1 kg. It is 30 cm long, 19 cm wide and 24 cm high.

2.1 Locomotion systems

Several studies have considered the control and modelling processes in walking robots, but few have reported quantitative results regarding the motion characteristics of the system, that is an analysis of the mechanical forces developed during movement. So, this research aimed at redesigning and developing an existing prototype of the robot's wheels.

With the aim of obtaining a bio-inspired wheeled robot which is adaptable, able to operate in harsh terrain, and climb over obstacles, a modular wheels mechanism was developed. A wheels system which achieves significant speed was obtained by coupling two-wheels. Each wheel is made up of three hook-shaped arc segments allowing the robot to jump and climb obstacles.

To actuate the angular shift between the two wheels of each system a jaw clutch was used. An electromagnetic piston actuator imposes a translation of the jaw clutch and the angular shift (60 degrees) between the two wheels is achieved when the control chip supplies the input. In this way, the two different configurations are possible. In the first configuration (fig. 3a) a complete circular surface is available, in the second (fig. 3b) only the three hook-shaped arc segments can operate.

![Fig. 3 Configuration of wheel unit parts: a) complete circular surface b) three hook-shaped arc.](image)

The use of rapid prototyping to achieve the three parts (wheel 1, wheel 2 and jaw clutch) of the wheels mechanism allows to get a quick determination of optimum tolerance through a simple and effective verification of the same. Realizing, in fact, the parts of the wheels mechanism through prototyping and using the allocation of tolerances on profiles which engage with composite tolerance in accordance with ASME Y 14.5m [8, 9 and 10] you can use references A and B and A' and B' (fig. 4a).

To proper operation of the wheel 2 of the wheels mechanism must fit perfectly his face \( f_{2a} \) on the face \( f_{1b} \) of the wheel 1. The wheel 1 must rotate coaxially to the wheel 2 about an axis perpendicular to its face \( f_{1a} \).

The plan A for the wheel 1 and the plan A' for the wheel 2 are the primary reference for the allocation of tolerances and coincide with the base surface in the process of prototyping. The references (B and B') will be the main axis of symmetry of the two wheels.

With such references, using the composite tolerance and a precise definition (with tolerances of flatness and total oscillation) of the surfaces \( f_{1b} \) and \( f_{2a} \) you get a perfect fit of wheel 1 and wheel 2. A system of similar references (A', B') is used to check for errors in fit of the jaw clutch on the wheel 2. After verifying that the parts are modeled in ABS with a precision between the tenth and the hundredth of a millimeter over possible "theoretically correct" it was possible to calculate the best composite tolerance (tolerance of shape, orientation and position of cylindrical surfaces) shown in fig. 4b.

The easy verification of the tolerance values directly in the construction phase can improve the errors of the features with great benefits to the accuracy of the couplings obtained.

![Fig. 4a Datum in wheel unit parts.](image)

A multibody model of the mechanism was simulated with Hertzian cylinder-cylinder contact joints with friction applied which allowed us to estimate the optimum dimensions and geometrical tolerances. Rapid prototyping
of all the components of the system (in ABS plastics) initially allowed us to adjust the stiffness and damping values in the contact match simulated in ADAMS, and then test the merit of the results.

With modular wheels mechanism and using servomotor for torque, a simple and effective control of wheels position is achieved and the system is more adaptable. The velocities, accelerations and actuation forces were computed using the multibody model. The model’s joints are real and take into account clearance, mass and joint friction. By configuring the robot wheels non-continuously, the robot is better able to grip surfaces and move forward (fig. 5), but only with complete circular surface is possible to minimize the vibration.

The following graph (fig. 6) shows the forces exchanged with ground and the Centre of Mass (CM) velocity in the two configurations during the jump of a step. With modular wheels mechanism was possible have constant velocity, low vibration and regular contact force. The three hook-shaped arc segment became active only when Tribot climb over the step. In the other case a complete circular surface is possible.

Increasing the friction force, leads to a reduction in the speed of the robot, while at the same time improving its precision in maintaining trajectory, as shown in the graph (fig. 7).

### 3 Topological optimization

Weight is a major factor in the performance and agility of a robot, which is why reducing it is a key objective. Weight must be reduced without compromising resistance to dynamic loads and the appropriate stiffness of the individual components and machine as a whole. Good design is achieved here by structural optimization tools. In particular, we used the geometrical methods of SKO (Soft Kill Option) [11, 12 and 13] which facilitates topological optimization with FEM used in engineering design. A numerical tool divided the structure into components and then split the desired components into finite geometrical sections, defining the material property of each finite element. A FEM algorithm identifies areas of high stress, and shows the simulated effects of adding or removing material.

Topology optimization is an established tool for optimizing engineering components, for which linear analysis is sufficient to describe the performance of the component and where optimal strength, frequency, or stiffness are the objectives. In contrast to other methods, the SKO method is driven by the stresses in the proposal. This is the case for most cast parts in the robot chassis. Here, topology optimization helps find he optimal features of a component, such as the optimal cross-section or, for ribs the optimal number and shape.

We restricted ourselves to issues where strength (stress) or maximum stiffness is desired. Usually, strength is the problem in practice, but there are indications that the results for both objectives are the same or at least similar.

We used a tool for uniform strength even if the stiffness objective has yet to be verified. Usually topology optimization uses the homogenization or Simple Isotropic Material with Penalization (SIMP) approach. Here, the
structure is described in terms of elements with high density or stiffness, whereas elements with low stiffness values (void elements) correspond to void areas. This produces very flexible optimization where very simple initial designs can evolve into very complex structures. Often the price for this flexibility is that, after optimization, design proposals cannot be used directly. With the SKO method, we created a feasible design as close as possible to the proposal.

3.1 Optimization of Tribot axle chassis with Soft Kill Option method

Using the SKO method and using structural ABS it was possible to make the robot chassis components lightweight but still strong enough to withstand stress. In fig. 8 is showed the front axle chassis CAD model.

![Fig. 8 Initial geometry for front axle chassis.](image)

The front and rear chassis of the robot are U-shaped and they were discretized with 17750 Tet 10 element and 35736 node. Loads are applied in correspondence of hole to simulate the wheels force and the payload; fixed constraints are used in the middle of structure (fig. 9).

Using this FEM model it was possible to estimate the maximum Von Misses equivalent strength in the original structure (fig. 10).

![Fig. 9 FEM model of front axle chassis.](image)

![Fig. 10 Maximum strength values on front axle chassis.](image)

In the SKO method, robot components are gauged by investigating which sections of each component can be reduced in weight to maximize dynamic response. The main issue is determining the ribs within the U-shaped structure. As a typical example fig. 11 shows the design space of an axle chassis and the proposal obtained with the topology optimization program SKO.

![Fig. 11 Initial optimization geometry for front axle chassis.](image)

It is not difficult to identify the optimal cross-section, but the proposal is not sufficiently detailed to determine the optimal arrangement of the ribs inside.

This leads to results which depend significantly on component size. The smaller the component, the clearer the details can be resolved. This leads to an effect where the structure shrinks away and vanishes from the proposal, if it becomes smaller than the mesh size. This again changes the stress distribution of the current structure and, driven by the growth rule, evolves into the optimum design without details smaller than the element size. We can consider this effect as a kind of constraint, which enables the user to allow only details in the magnitude of interest.

Here, an auxiliary model (fig. 12) can be used to optimize the rib shape. The idea of this model is that only the edges of the ribs are usually highly loaded, and that this area determines the optimal shape. Consequently, it should be sufficient to only apply topology optimization to the edge areas. Using this idea, a model of the cross-section alone is created. This is closed on the open side by a layer of shells (layer 1), which has the same grid point arrangement as the elements at the bottom of the cross-section.
This shell layer simulates the edge areas of the ribs where topology optimization was applied. Additionally, the coupling of the rib edges to the bottom of the cross-section is simulated by connecting every grid point of the shell layer to the corresponding grid point of the cross-section bottom with a rigid bar element. Finally, a shell layer (layer 2) is added to the bottom to also couple the rotational degrees of freedom. Usually, topological optimization of the auxiliary model leads to a chassis-like structure in the shell layer, which reflects optimal rib arrangement.

Figure 13 shows the results for the robot axle chassis optimized. Eight rib can be derived from the proposal with the small volume fraction, whereas the other proposal gives an indication for two additional ribs. Because of internal obstruction constraints, only four for each side of these ribs could be included in the final model. In the top two rigid beams stiffen the entire structure by making complete the topological optimization.

4 Result’s analysis

The analysis of the final design shows that the stresses are not critical, and that the axle fulfils all the requirements.

The optimization task of finding the optimal thickness of the ribs can be done with minimum effort using the auxiliary model. For strength issues however, a solid model is required to compute the stresses with the desired accuracy. For a complicated geometry neither algorithm is able to create the shape variations for rib thickness.

Mesh deformations can occur very quickly for local shape variations, such as the variation in rib thickness. So a re meshing procedure is necessary after any change. The stress in final optimized front axle chassis is show in fig. 14.

Only small areas can reach the critical stress and Von Mises equivalent strength has little value and big security coefficients. In fig. 15 a we can see the displacement in original front axle chassis long z axis. The maximum displacement is over 2 mm and there are an high risk of interference between electronic cards. Obviously the total magnitude (fig. 15 b) is more elevate and the maximum value is about 5,5 mm.

In fig. 16 is reported the total magnitude displacement in front axle chassis after the optimization process. The maximum value is only 1 mm and the component has an optimal stiffness.
5 Conclusions

The main focus concerned the mechanical specifications of the robot motion mechanism, with the aim of proposing new mechanical configurations to optimize its performance. In particular, we proposed a new mechanism and new shape for the wheels.

This research addresses the problem of determining the optimal topology which maximizes the rigidity of bodies subject to local stress. Some solutions were obtained using SKO optimization methodology to optimize the modular structure of the robot. By using the methodology of rapid prototyping (RP) the solutions were assessed quickly and particularly lightweight and reliable modular structures were built.

A highly detailed dynamic FEM model of the Tribot robot component was built and a multibody and FEM simulation were used to study dynamic characteristics of motion. Several simulations were performed to investigate the response of the system under different working conditions. By acquiring position, velocity, force and torque data from the model, the maximum payload of the robot was estimated and its ability to climb over obstacles was assessed.

At the end of the optimization process using the SKO method Tribot is 25 percent lighter yet 20 percent more stable.

References