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Computer Integrated Design of a Torsional Spring for an Exoskeleton Module

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1 INTRODUCTION

Robotic exoskeletons are artificial mechanisms worn externally to the human body acting parallel to the limbs with the goal of extending, complementing, restoring or improving human functions and capacities. The biggest challenges of its designs are coupling it to the human being in a way that there are no hyperstatic or mounting forces, maintaining it on the desired relative position to the human limb throughout its workload, to implement a control that allows the exoskeleton to cooperate with the humans and minimize its mass and your energy consumption. In addition, the development of robotic exoskeletons is still a field in maturity. Problems such as wheel alignment of human and robotic joints are still the targets of several studies, without and apparent convergence of solutions. The main functions of a robotic exoskeleton are: (i) increase physical capacities; (ii) neuromotor rehabilitation, (iii) teleoperation, (iv) study of the human motor control, (v) motor education and (vi) neuromuscular improvements. (Andrey Bugarin Woiski Miranda 2015)

The use of robotic devices in the rehabilitation process of neurologically damaged patients, for example, is rapidly increasing due to the significance of functional exercises to push motor cortex and perfect motor recovery. Post-stroke patients' recovery was boosted with robot-assisted therapy. Comparing traditional rehabilitation processes and robotic therapy, the advantages of using external robotic accessories lay as the possibility to evaluate and measure patient progress constantly through objective data and to customize the treatment in accordance with the patient's commitment. (Wilian M. dos Santos 2014)

At the Biomechatronics Laboratory of the Polytechnic School of the University of São Paulo, a 3 degrees of freedom flat bilateral exoskeleton was fabricated, assembled and its control is on the development phase. There is always a great difficulty on the control of upper limb prostheses due to the number of joints that may be manipulated, the ability of simultaneously and accurately control each motion of these joints, and the relationship between forces and movements. The interaction between human beings and exoskeletons can be passive, active-assisted or active-resisted movements, in order that this combination of activities can be reached through the implementation of impedance control, which allows the adjustment of theirs interaction efforts (Wilian M. dos Santos 2014). This modulation of impedance may reduce power consumption, minimization of trajectory error in the presence of perturbations and smooth movements. The muscles intrinsically modulate impedance of joints based on position and speed, while allowing humans to vary that impedance depending on the task. Impedance may be divided into three components that affect the interaction of force and movement: stiffness, viscosity, and inertia. (Sensinger, ff Weir 2008)

The stiffness of the impedance control can be a compliant element as a series elastic actuator (SEA). Its importance lays on reducing the dynamic effects of existing backlashes in the gearbox, cogging torque in the motor and friction. This elastic element serves as an accurate torque source, as a low cost torque sensor and as a compliant interface between human and robot, which protects the user from sudden shocks and improves the gears backdrivability. Since the SEA defines the maximal large torque bandwidth and force fidelity of the actuator, its design is of vital importance for a human friendly exoskeleton. (Lagoda et al.)

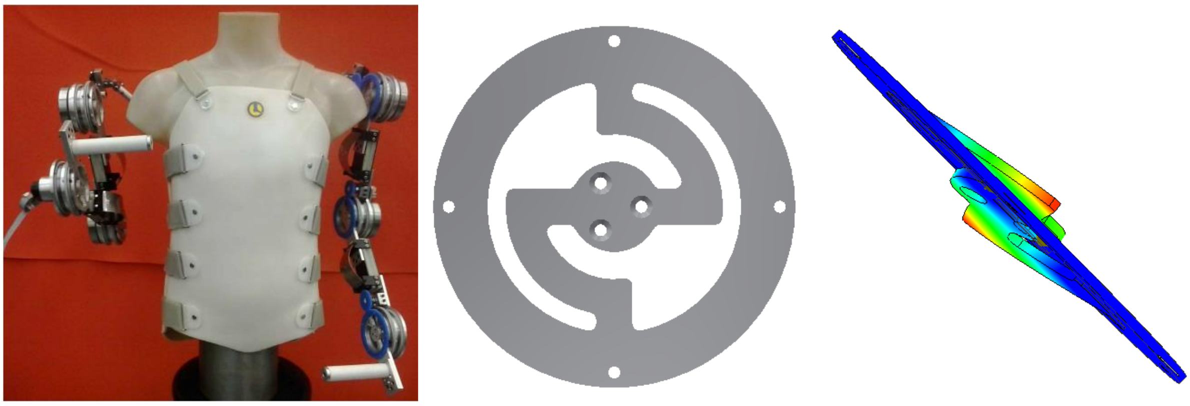
For the scope of this work, a rotary SEA will be designed and manufactured, intending to fulfill the requirements for the exoskeleton of the Biomechatronics Laboratory exoskeleton. For its development, this work intend to use the topology optimization method (TOM) as a way to find the best fitting design, considering the characteristics that the torsional spring should have. The TOM combines the finite element method (FEM) with mathematical formulations for optimization, with the intention to find the best material distribution in a space delimited by boundaries. The inner space of these boundaries is discretized on finite elements so it may be possible to analyze its mechanical behavior and then material can be displaced and distributed so the best behavior of the structure is found. The benefit of TOM is its capability to provide the best mechanical component layout. Thus, this method can be applied during the conceptual phase of a project, as it works as a synthesis of mechanical structures. (Stump 2006)

None of the researched SEAs were obtained through a topology optimization method (TOM). This work is a new approach for its development, because elastic profiles are quite different from rigid or flexible structures, which are already known as a result from TOM. To optimize structures in a way they can become springs or elastic elements is an unexplored field. To achieve this goal, the software FEniCS will be used, intending to develop an algorithm from the beginning Finite Element Analysis (FEA) and then imposing the buckling condition of an elastic element for any magnitude of loads.

The second chapter describes the importance of coupling such a SEA between the actuator and the load, since this element is vital for the development of impedance control and user-friendly robots, and fundaments how the TOM will be applied to this case. Then, in the third chapter, the features of the SEA will be defined through the development of a requirement list, describing what the TOM cannot change, as mounting holes, material and width, and a machining process will be chosen. After all, the results from TOM, machining and performance tests will be presented, comparing them with the desired requirements previously defined.

2 STATE OF ART

At the Biomechatronics Laboratory of the Department of Mechatronics Engineering and Automation Systems (PMR) by the Polithecnic School of the University of São Paulo (POLI-USP), a 3 degrees of freedom flat bilateral exoskeleton was developed, assembled and has already a designed torsional spring (Andrey Bugarin Woiski Miranda 2015). The exoskeleton is shown in Figure 1. The current SEA from PMR has a random stiffness, which was designed solely to couple the actuator with the loads. For this reason, it’s behavior lays far from what is desired. Another research on progress studies it’s behavior and look for the definition of machining material and it’s properties. Since articles as (Lagoda et al.; Stienen et al.; Carpino et al. 2012) report an unexpected difference between the expected stiffness and the simulated ones, an assumption that can be done is an inaccurate definition of the materials properties (Young Module and Poisson ratio). In order to achieve more accurate results, the material features will be measured through traction tests, in order that the simulations have a closer to reality meaning.



(a) (b) (c)

Figure 1 – (a) 3 degrees of freedom flat bilateral exoskeleton (Andrey Bugarin Woiski Miranda 2015) ; (b) Current SEA assembled to the exoskeleton ; (c) undesired displacements

When submitted to a torque load in the inner circle and fastened in the outer mounting holes, a finite element analysis shows there is a displacement out of the springs plan, as it is shown in Figure 2. This kind of displacement is undesirable, since it may generate internal compressions in the actuation module, when assembled.

2.1 IMPEDANCE CONTROL

Robotics actuation is a challenging task, demanding high torque and low speed, large peak power output for short periods and precise feedback sensing. In the scope of robot interaction, a new concern emerges: the inherent safety of the actuation mechanism and its compatibility with unpredictable and unstructured environments. High impedance position controlled actuators is typical of most industrial robot arms. Difficult tasks such as walking are even more challenging, where collisions with the ground by the rigid limb, particularly on uneven or unknown surfaces. In unknown, unstructured human environments, low impedance force controlled actuation improves safety and system controllability. Low impedance actuation means that the actuators controls force (or torque) to the load, rather than commanding the load's position (or angle). (Gordon Wyeth 2006)

Impedance control is a branch of position control, or in general terms, motion control. In impedance control, the user defines the desired position and desired impedance, where the impedance is the relationship between position perturbations and resultant force. The desired position and impedance are driven to the controller, which calculates a torque based on the coveted impedance and the difference between the actual position of the limb segment and the desired position. The actuator generates the calculated torque, and the position of the limb segment is driven back to the controller, as illustrated in Fig, 1. (Sensinger, Weir)

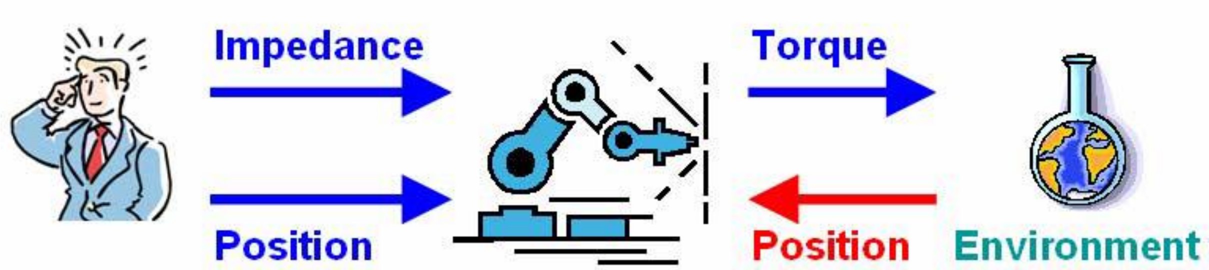


Figure 2 – Impedance control (Sensinger, Weir)

There are generally three variables in impedance control: a static stiffness, a dynamic viscosity and an inertial term. Stiffness improves the precision, stability, and bandwidth of position-control. Increasing stiffness lowers necessary actuator motion in response to load variations and raises the resonant frequency of the motor inertia and interface compliance. The use of gearing also causes an increase in reflected inertia so that shock loads cause very high stress on the teeth of the output gear, possibly resulting in failure. This increased reflected inertia and the typically high backdrive friction of high ratio gear trains can also cause damage to the robot or environment when unexpected contact occurs. (Gill A. Pratt et al. 1995)

Increasing compliance is desirable owing to the fact that not only it increases force fidelity in the controllable frequency bandwidth, allowing for near-zero impedance, but also limits the impedance of the actuator to the stiffness of the spring at frequencies above the controllable bandwidth. This spring-impedance limiting permits the inclusion of high impedance dynamics before the spring, with no effect on the overall output impedance of the system. However, the inclusion of compliance debilitates the performance of the actuator by decreasing the frequency saturation enveloped for given torques. (Sensinger, Weir)

A Series Elastic Actuator (SEA) deliberately introduces compliance via a spring between the motor-gearbox and the load, and so has intrinsic low impedance. Reducing interface stiffness by inserting series elasticity can resolve many problems. The first benefit of the series elasticity is to low-pass filter shock loads, thus greatly reducing peak output gear forces. Although this also low-pass filters the actuator's output, we believe this is a place for an engineering trade-off, not the traditional "stiffer is better" minimization. The proper amount of interface elasticity can substantially increases shock tolerance while maintaining adequate small motion bandwidth for natural tasks like locomotion and manipulation. Series elasticity also turns the force control problem into a position control problem, greatly improving force accuracy. In a series elastic actuator, output force is proportional to the position difference across the series elasticity multiplied by its spring constant. (Gill A. Pratt et al. 1995) The spring's deformation is measured with a position, distance or angular sensor, which is used for a feedback, that generates a torque controlled actuator with inherently low output impedance. (Sensinger, Weir)

Because position is much more easy to control accurately through a gear train than force, the force errors usually caused by friction and torque ripple are reduced. Friction and backlash are usually a trade-off in gear train design. Series elasticity allows this trade-off to be driven much further towards high friction and low backlash, resulting in better position control at the gear train's output and thus better force control at the load. Importantly, high friction, low backlash gear trains can also be made inexpensively. Increased series elasticity also makes stable force control more easy to achieve. (Gill A. Pratt et al. 1995)

These kind of Serial Elastic Actuator, used as a compliance element for a more soft and user-friendly robot, as also to implement the discussed impedance control problematics are vastly researched. None of them has ever used topology optimization as a method to reach a suitable profile.

(a) (b) (c)

Figure 3 – (a) Series Elastic Actuator with a 88 Nm/rad stiffness (Stienen et al.)
(b) Series Elastic Actuator with a 219 Nm/rad stiffness (Lagoda et al.)
(c) Series Elastic Actuator with a 98 Nm/rad stiffness (Carpino et al. 2012)

2.2 TOPOLOGY OPTIMIZATION

2.2.1 Introduction

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Essentially, the Topology Optimization (TO) consist in a search for a material distribution in the interior of a project domain by adding or subtracting material in each spot inside it, in order to maximize an objective function (for example, maximizing its stiffness or minimizing its volume), and at the same time satisfying given restrictions. (Stump 2006) The following figure X.x illustrates a TO process in a classic example of stiffness maximization of a structure with weight restriction. In this case, taking the symmetry for reasons of computational economy, just half of the whole beam shall be calculated. (Cícero Ribeiro Lima 2006)

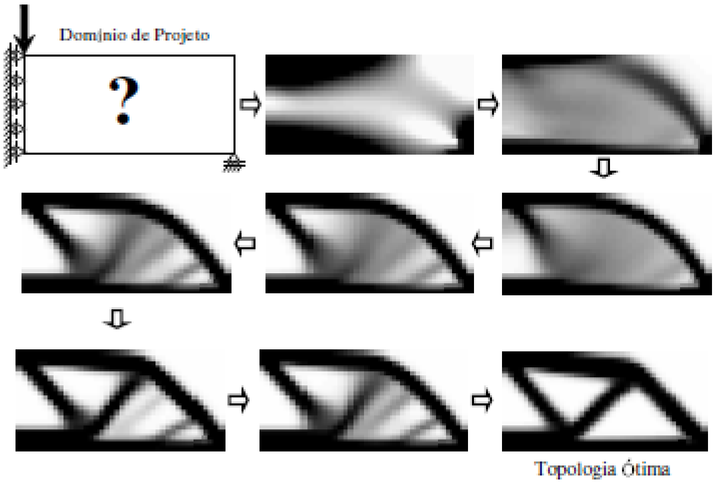

Figure 4 – Example of topology optimization of a loaded structure (Cícero Ribeiro Lima 2006)

Topology optimization does not require any previously information about the desired topology, which is obtained iteratively from an initial distribution of material. (Stump 2006) Combining numerical analysis methods, preferably the finite element analysis, with optimization algorithms, the Topology Optimization Method shows itself as a powerful method to solve optimization problems. (Cícero Ribeiro Lima 2006)

The generic formulation of an optimization problem can be described as the minimization of an objective function when restrictions are given describing conditions, which the solution must obey. This formulation is shown in equation XX,

$$\underset{\rho(x^T)\,\in\,]0,1]\ \in R^{+}}{\text{Minimize}} \quad F(\rho,u)$$

$$\text{s.t.:} \quad \delta\Pi_p(\rho,u,\delta u) = 0, \forall\, \delta u$$

$$\frac{V\left(\rho(x^T)\right)}{V_0} - \bar{V} \le 0$$

$$r_{min} \le r^{*}(\Omega_d^T)$$

where $F(\rho,u)$ is the objective function to be minimized. The project restrictions are given in the weak form formulation of the solid space $\delta\Pi_p$, in the volume function $\bar{V}$ and in the minimum element by r_{min} for controlling the complexity of the topology.

The TOM is based on two concepts: Extended Fix Domain and Material Model, which will be detailed on the following topics.

2.2.2 Extended fix domain

The extended fix domain consists on a domain with a fixed geometry, limited by the supporting spots of the whole structure and by the locals in which the loads are applied. This domain will then contain the unknown structure. The main goal of the TO is to determine which are the empty or solid spots and their connectivity in order that their distribution gives the best properties in the extended fix domain. With a numerical implementation, this domain shall be discretized through finite elements, that means the modeled finite elements aren't modified, solely its material distribution. (Stump 2006)

2.2.3 Material Models

The empty or solid definition inside the domain grounds the material model concept. An equation that defines this compound in a micro-scale of two or more materials, in which one of them is the material "empty" and another one is the "solid", allowing intermediary stages (Stump 2006). Basically, the topology can be described by a discrete function χ(x), defined for each x of the domain Ω, as the following formulation:

$$\chi(x) = \begin{cases} 1 \;\; se \;\; x \in \Omega \\ 0 \;\; \text{se} \;\; x \in \Omega \setminus \Omega_{\text{D}} \end{cases}$$

where OmegaD represents the region of the domain Omega with material. Considering it as an isotropic material, it can be written as:

$$\mathbf{C}(x) = \chi(x) \; \mathbf{C}_0$$

where Co is a tensor that represents the constitution of the material. In other words, the discrete function χ(x) specifies if the spot (x) of the domain is completely fulfilled with the corresponding material (solid) or it's an empty space (hole), without intermediary stages. (Cícero Ribeiro Lima 2002)

This discrete parametrization of the Eq. X.x (C(x)), however, generates a undesired conditioning in the numeric solution of the problem, owing to the abrupt change (0 or 1), and doesn't ensure a solution to the TO. Taking this into consideration, allowing the variables assume also intermediate values between 0 and 1, namely defining a continuous function for the material model. (Cícero Ribeiro Lima 2002). These intermediary stage don't have a physical meaning, they're only a mathematical formulation to unstring the solution achievement.

There's a homogenization method based on microstructures, or cells, formed by a blend of two homogeny materials. This is a complex and robust material modeling capable of describing effective properties of a homogenized material. However, there is a cost involved to define in each unitary cell how the materials are distributed. Owing to this cost, another method, the density method, shows itself as preferable to optimize topologies, since it's easier to implement and uses solely one additional variable to the project: the material relative density in each spot of the project domain. (Cícero Ribeiro Lima 2002)

The density method, or Simple Isotropic Material with Penalization (SIMP) consists of a mathematical equation, which defines the value of density in each spot of the domain (OMEGA) according to a function of the material properties, simulating a microstructure. Such a function can be described as the following expression:

$$\mathbf{C}(x) = \rho(x)\ \mathbf{C}_0$$

where ro(x) represents the density distribution (continuous), 0 <= ro(x) <= 1 and x E OMEGA. In order that the material density in each spot of the domain can vary from "zero" to "one", in other words from absence of material to fully presence of it. (Cícero Ribeiro Lima 2002)

The physical meaning of this concept is not right. However, in an engineering point of view, the continuous function representing levels of density, ables the TOM to reach a solution, where its composition is made almost entirely of holes and the base material. Namely, the result may have properties that can be reached when fabricating the optimized geometry. Meanwhile, some intermediary densities may remain as a solution (gray scales). The gray scales have no real meaning, therefore it must be somehow avoided. For this reason, penalties for the intermediary values are defined represented as in the following equation:

$$\mathbf{C}(x) = \rho(x)^p\ \mathbf{C}_0$$

The factor p represents the penalty, which reduces the intermediary values in the final result. Co is the isotropic tensor, which depends on the elasticity module of the base material (Eo) and on the Poisson ration (v). The elasticity module varies according to the density in each spot of the domain, while v doesn't. (Cícero Ribeiro Lima 2002)

2.2.5 Topology Optimization for an elastic component

In this thesis, an optimized topology for a torsional Series Elastic Actuator will be searched in order to impose to it a specific stiffness. Such a problem is not trivial as it may seem. Topology optimization of solid structures determines features such as number, location and shape of holes and their connectivity inside a specific domain and many of fundamental issues of this field are the designing methods for minimum compliance (maximum global stiffness). However, maximizing or minimizing stiffness is not the aimed goal. (REFERENCIA BENDSOE E SIGMUND). Therefore, as the purpose of this work is to achieve a specific stiffness when distributing material inside the domain, this method is not appropriate to solve this problem.

Minimum compliance approaches minimizing stiffness of a beam, for example, would take material out of the beam in order to reduce its transversal section and so reducing its stiffness. However, with this analysis, to achieve a very low stiffness the transversal section would need to be extremely slender, being very fragile and facing up buckling. Therefore, the linear elasticity would not prevail no more. Instead, an unpredicted nonlinear behavior would take place. In Figure XXX this kind of approach is illustrated, showing the decrease of the beams transversal section.

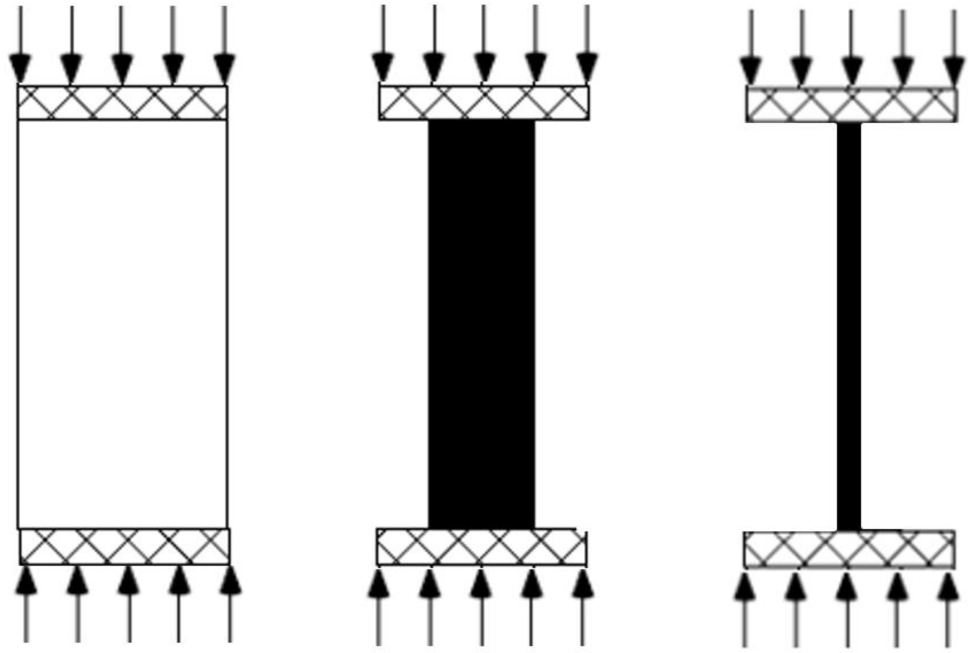

FIG XXX Minimum compliance – minimizing stiffness

Another method that may be a way to find an optimized solution is looking for buckling modes, since buckling gives out big displacements, despite of non-linear. A topology that is intended to buckle may have a more similar to a spring geometry, like spirals, whirls, etc. This method grounds on finding buckling modes for a desired profile analyzing eigenvalues and eigenvectors of the structures and then distributing material in a way they buckle with very small loads, keeping the firsts modes very low. The problem of this approach may lay on the "non-linearity stage" of buckling (after instability has been reached), where displacement and forces restrictions are very difficult to be fulfilled. (REFERENCIA RICARDO)

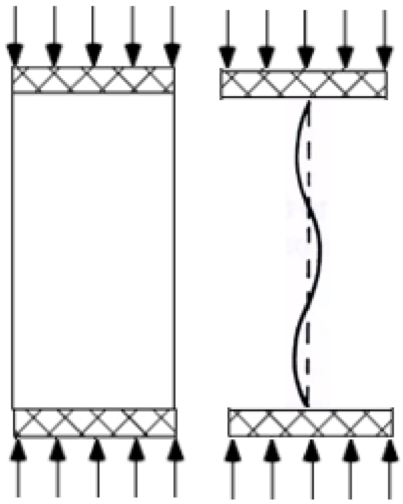

Figure XX – Buckling flexibility example

Substantially what gives the spring a specific stiffness is the exact displacements for determined applied loads. Regulating the proportion of this displacements and loads, a stiffness is reached. In literature and in (REFERENCIA RICARDO) compliant mechanisms approach bases on intentionally being flexible, so the mechanism can transform input and output movements with monolithic structures. Its concept is based in mechanical and/or geometric coefficients that relates the transformation from these inputs to output movements. However, a big complexity is involved when taking into consideration big displacements.

In the study from (REFERENCIA RICARDO), a new formulation for solving in TOM was proposed in which restrictions that involve non-linear buckling can converge to a optimized distribution of material. This work was developed in the Multiphysics Systems Optimization Laboratory inside the Polytechnic School of the University of Sao Paulo and its approach is the most suitable method to reach the desired topology.

2.2.4.1 Synthesis of Compliant Mechanisms via Topology Optimization Method

A compliant mechanism is designed to work under the limit of elasticity of its compounding material. Therefore, its flexibility is used to transform the incoming energy (W_{in}) by the input ($\partial\Omega_{in}^{T}$) into displacement or forces by the output ($\partial\Omega_{out}^{T}$), as shown in Figure XX. These structures may have one or more inputs and outputs, depending solely from project requirements. (REFERENCIA RICARDO)

As a matter of effect, for this work it will be considered that the system is conservative and almost static. That is, the incoming energy is equal the sum of the outcoming work plus the intern energy, shown in equation XXXX

$$W_{in} = W_{out} + U$$

$$W_{in} = f_{in} * u_{in}$$

$$W_{out} = f_{out} * u_{out}$$

where f_{out} and f_{in} are forces actuating in the output door and in the input door of the compliant mechanism ($\partial\Omega^T_{out}$ and $\partial\Omega^T_{in}$) and U is a reference to the intern energy stored by the mechanism. That means the mechanism can be designed over the relationship between forces in the input and output or over coefficients of mechanical efficiency. (REFERENCIA RICARDO)

However, this work that fundaments this approach don't include elements or variables of rotation and translation as springs and trusses. Therefore there is an evident limitation, because the internal connection inside the topology are constituted based on beams and hinges. Those are compounded by continuous elements, which are responsible by giving mechanism its flexibility along the project domain ($\partial\Omega^T$).

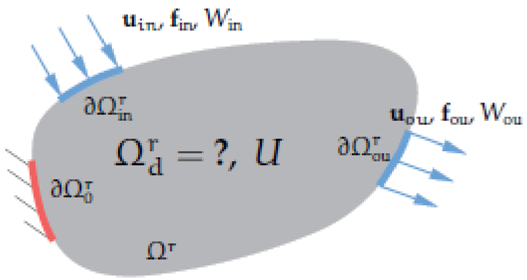

FIGURA XX Project domain representation of a compliant mechanism

The results presented in this work will be based on the synthesis of compliant mechanisms, in which the compliant components buckles linearly, since the non-linear analysis would take a lot more time and effort to implement. It is important to outline this implementation was done by Ricardo Doll Lahuerta, since he is the author of this whole analysis and implementing such an approach goes way far from the goals of this thesis.

3 PRODUCT DEVELOPMENT

According to (G. Pahl et al. 2007), today's conditions for product design and development demand careful planning of:

- required activities for the proposed project
- timing and scheduling of these activities
- project and product costs

The main working steps defined for reaching at the end an optimized SEA design are (a weekly division of these activities are shown in Attachment 1):

- Literature Research
- Requirements Definition
- Design, FEM Analysis and Optimization
- Manufacture
- Tests and Validation
- Documentation

After planning and clarifying the considered main tasks, it is time to move on for the building up of a requirements list, with features of a conceptual design and specification of main solutions. One possibility of supporting rivaling tasks is leaving the idea of traditional product development and using an algorithm-based product development method (A5_A1), in order to define which are these requirements, optimize the topology and plane the manufacturing process. With this approach it will be feasible to create a variety of possible solutions based on the identified products primary specifications and requirements.

3.1 ALGORITHM BASED PRODUCT AND PROCESS DEVELOPMENT

This integrated approach focuses on defining and designing products and their processes, requiring concurrent and early determination of product properties as well as process parameters, integrating the impact of all design decisions on the product and technical processes into a development process (CHP 9). This concept can be visualized in Figure X. It is a scientific approach which combines state of art product development methodologies, such as VDI 2221, with application of mathematical algorithms in its conceptual steps. (2015_A4_Automated Interface XML to 3D CAD)

As a result of this methodology, a variety of discrete CAD models describing possible solutions is generated, from which the most suitable one can be chosen. This algorithm-based approach doesn't depends on individual knowledge and experience and should ideally generate complete and palpable solutions systematically. For the problem formulation, a set of requirements and boundary conditions are transformed into outer desired properties, which describe relations of the product to its environment. On the other hand, inner properties describe the products design and feature relations, which can be defined through graph-based analysis, mathematical procedures and constructive interrelations concerning the products topology. A set of mathematically and functionally optimized CAD-model are obtained and thereafter the best fitting geometry is chosen and passed on for production. (A5_A1)

This whole process when applied on the industry in a real market product development enable more options to be analyzed in less time, leading to higher quality for less design cost. It also enables higher levels of simultaneous engineering and the engineers to develop their design concept in an automated and computer aided way (A5_A1) expecting from it optimal product and process solutions that fulfill the acquired product and process requirements (CHP 9).

The final torsional spring do not intend to be a commercial product and the main goal of this thesis is to find an optimized topology for an elastic component, therefore just a part of this methodology is suitable to the project. To guide the development of our SEA, the core steps and goals of the Algorithm-Based Product and Process Development were followed, considering its suitability for the project. It's important to keep in mind, that the SEA development is not as complex as the whole development of a new product. The complexity and innovation of developing this SEA lays on the mathematical algorithms for the topology optimization and not exactly on the concept of what is a SEA, its usage or its functions.

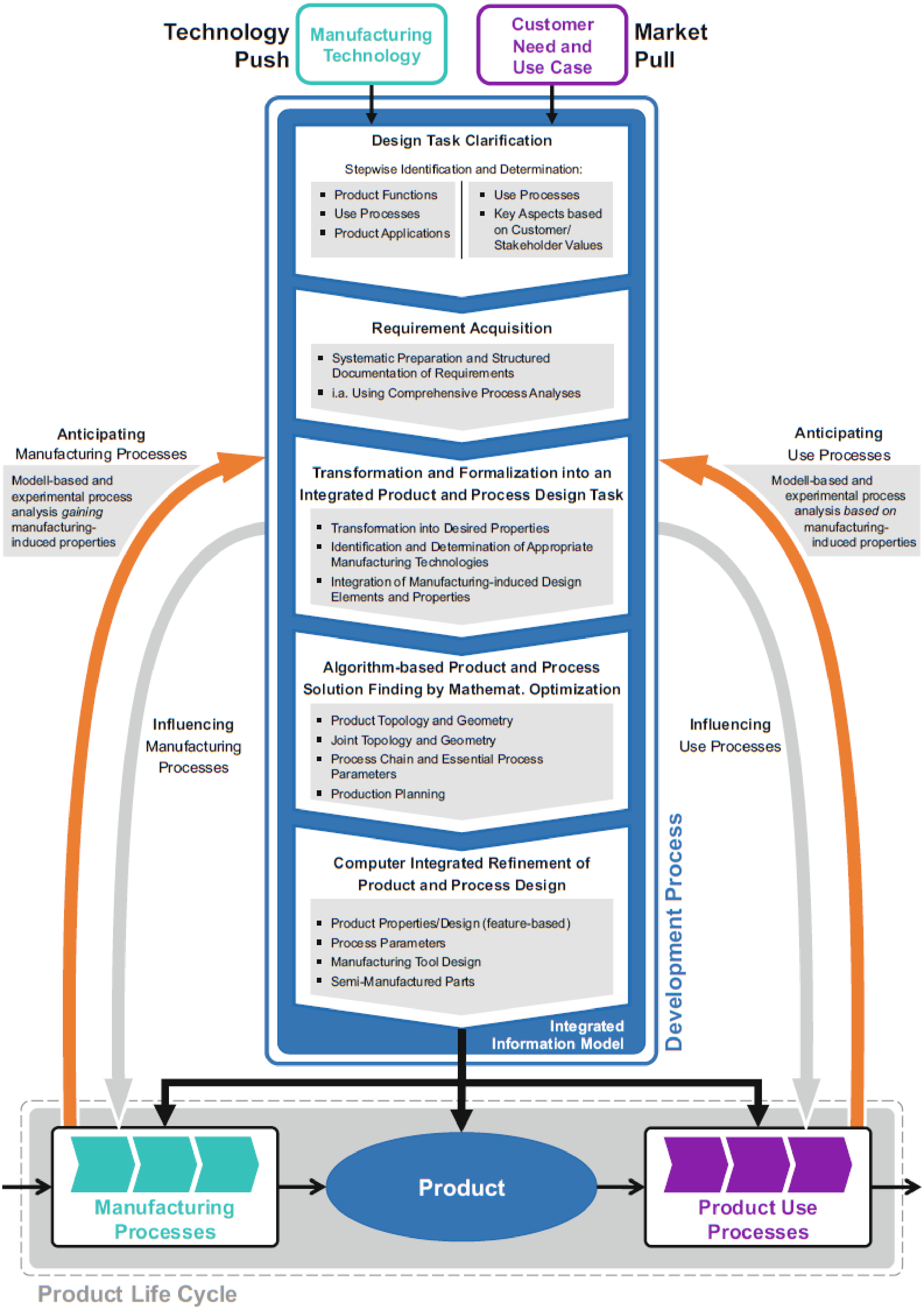

Figure X – Integrated Algorithm-Based Product and Process Development FONTE

3.1.1 Design task clarification and requirement acquisition

As chosen first step of the development, this is a conceptual phase, where product functions, use processes, and product applications are identified and determined, so that requirements of the product, manufacturing and use processes are acquired, based on anticipated knowledge. Product and process requirements are then prepared and structured for the subsequent steps.

The development of the SEAs goes through all development approaches of this method. Beginning with the “design task clarification and requirement acquisition”, the following descriptions are important for the next steps.

A) The SEA must be a torsional coupling between the actuators and the exoskeleton’s limbs.
   - Dimensions must be suitable to the current exoskeletons and motors mechanical designs
     - Coupling holes
     - Outer diameter
     - Width

B) It must work as a torque sensor (encoder and strain gages translating rotation and stresses into torques) – The strain gages usage is still under concern, since the stress range inside the spring is unknown (as so its linearity
   - Geometry must be enough for mounting a strain gage in its inner profile (where tensions can be measured)
   - Maximal acceptable torques
   - Stiffness
   - Maximal displacements and torsions (must be suitable to the encoder coupling)

C) The SEAs must work bi-directionally, since torques and actuations happen in both directions for all limbs (extensions and contractions)

D) Its material must perform well in schock-loads, fatigue and stressed conditions

E) Its resonance frequency shall be bigger as the control system actuation clock

F) In order to keep a machinable geometry, the SEAs end design must be a 2D extruded profile

3.1.2 Transformation into and formalization of an integrated product and process design task

In this phase, the collected requirements are formally processed as desired properties, appropriate manufacturing technologies are identified and determined, considering geometric and material properties of the chosen manufacturing technology, taking into consideration geometric and material properties of the chosen manufacturing technology. This step shall deliver as result a formalized integrated product and process design task. Such task must be documented as objective functions, design constraints and design variables for mathematical optimization purposes.

Since its complete geometry is unknown at this step, it’s difficult to affirm which is the best way of manufacturing the spring. However, based on previously designed SEAs found in literature and they corresponding geometries (REFERENCIAS DE MOLAS), some methods may be elected as possible appropriate machining.This is the case of wire drilling, 3D prototyping in metal, laser cutting, water jet and CNC machining, since they may be able to machine such a metal workpiece. The most appropriate type of machining can be chosen only after knowing the exactly SEAs profile and material. However, a previous analysis of each manufacture processes can be done, intending to gather their advantages, disadvantages and their availability.

3.1.2.1 Desired Properties

A) The SEA must be a torsional coupling between actuators and the exoskeleton's limbs (its dimensions must be compatible to the current mechanical design)
   - Coupling holes
     - According to mechanical design (REFERENCIA DO ANEXO)
   - Outer diameter
     - 100 mm
   - Width
     - 4 mm

B) It must work as a torque sensor (reading displacements from an encoder and stresses from strain gauges)
   - Geometry must be enough for mounting a strain gauge in its inner profile (where tensions can be measured)
     - The 4mm width was defined according to a quickly review of strain gauges suitability, based on the available products from (REFERENCIA DO DOC DE STRAIN GAUGES), but since the inner profile will be defined by the topology optimization, and hence, the stress interval inside swirl, the statement if and which strain gauges could be placed inside de spring can be known only after the results are reached
   - Maximal acceptable torques
     - 40 Nm, according to (REFERENCIA ANDREY BUGARIN)
   - Stiffness
     - Since the definition of the desired stiffness in such a project depends on desired dynamics calculation for the impedance control, and such determination stays out of scope of this project, a range of stiffness was selected based on SEAs projected for exoskeletons in (REFERENCIAS DE SEAs COM RIGIDEZES LEGAIS), allowing the choice of the best SEAs design when obtained a stiffness in the range [100Nm/rad ; 350Nm/rad]
   - Maximal displacements and torsions (must be suitable to the encoder coupling)
     - Maximal acceptable torsions [0.114rad ; 0.4rad] or [6.5° ; 22.9°]
       - Since the gear coupled to the MA3 (Miniature Absolute Magnetic Shaft Encoder) mounted next to the spring has a reduction ratio of 2.5:1 and a 10 bits resolution (REFERENCIA DO ENCODER), the grad resolution read by the encoder lays on 0,00245rad, what accrues a torque resolution range of [0.245Nm;0.859Nm], depending on the SEAs stiffness. It's important to highlight, this range doesn't reach the minimum resolution of torque measurements of 0.1 Nm for wearable robotics applications ***(REFERENCIA STIENEN, A., HEKMAN, E., ter Braak, H., Aalsma, A., van der Helm, F., and van der Kooij, H., 2010. "Design of a rotational hydroelastic actuator for a powered exoskeleton for upper limb rehabilitation". IEEE Transactions on Biomedical Engineering. 57 (3). pp. 728 – 735)***.

C) The SEAs must work bi-directionally, since torques happen in both directions for all limbs (extensions and contractions)
   - The spring must have the same stiffness, or at least similar ones, for torsions in both directions.

D) Its material must perform well in schock-loads, fatigue and stressed conditions
   - Chromium Vanadium Steel, according to (REFERENCIA Matheus), is the best suitable material for this kind of application.
     - Labeled Young's Module: Eo = 200 GPa (REFERENCIA)
     - Labeled Poisson Module: nu = 0,3 (REFERENCIA)
   - For the purpose of this thesis, an assumption was made about the different results between simulated profiles and manufactured profiles in (REFERENCIAS DE MOLAS COM SIM DIFERENT DE REAL). Since the material properties are different depending on how they were manufactured and treated afterwards, its meaningful to suppose that using labeled instead of measured properties may result in a difference between simulations and reality. Therefore it's reasonable to carry out a traction test over the bought steel plate. ***Results are presented in section XXXXX***

E) In order to keep a machinable geometry, the SEAs profile must be 2D, in order to keep the same design in its whole width. Otherwise, only a 3D metal prototyping manufacture would be possible
   - 2D analysis for the Topology Optimization Method

3.1.2.2 Appropriate Manufacturing Technologies

Machining is a universe of possibilities with different losses and gains for each method and process. This section intend to create an overview of the possible machining process capable of machining slender and complex profiles, while the material properties are not affected, considering its availability of usage. Methods as 3D metal printing could be an excellent candidate for this work. However, the necessary machinery is not available yet in the university and is extremely expensive.

Eletrical Discharge Machining

Electrical Discharge Machining (EDM) is an advanced machining technique capable of a precise, detailed cut, that were once out of reach with traditional machining. Essentially, an electrical discharge is created between a copper or graffiti mask and the workpiece. This discharge melts down the workpiece surface with the smallest distance to the mask. Therefore, the mask profile extracts material from the workpiece in very small steps, while a dielectric fluid removes the particles. It has become a crucial part of tool making especially for prototype and production work and has the ability to repeatedly and consistently complete parts with minute tolerances. EDM machining is the ideal solution for manufacturing parts with unique cuts, angles, tolerances and materials (since they are electrically conductive). **(http://www.header.com/capabilities/edm)**

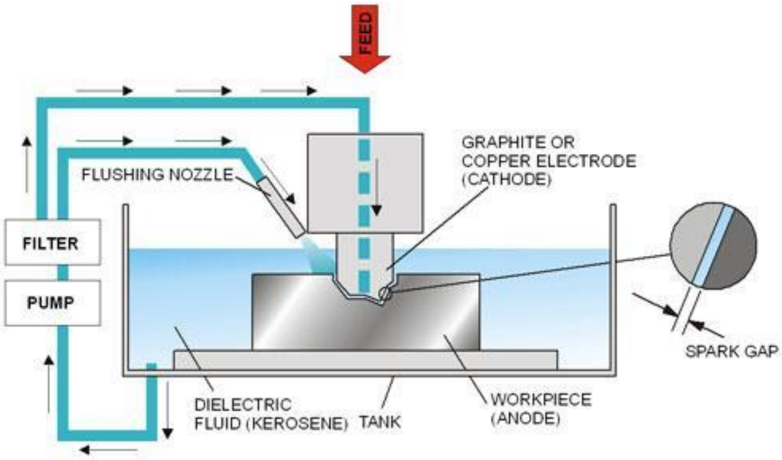

Figure X – EDM schematic

The variant Wire EDM process is another approach that creates an electrical discharge between the wire and the workpiece. The shortest distance between a single strand of wire, usually brass, and the workpiece is sparked. **(http://www.header.com/capabilities/edm)** The discharged area is heated to extremely high temperature, so that the surface is melted and removed. The removed particles are flushed away by the flowing dielectric fluids. The wire EDM process can cut daedal components and is widely used to pattern tool steel for die manufacturing. However, high temperatures are created during the process and that must be carefully pondered. **The melting temperature of the workpiece material is an important parameter for this process rather than strength or hardness**. **(http://www.nitc.ac.in/dept/me/jagadeesha/mev303/OVERVIEW_OF_NTM_PROCESSES.pdf)**

Advantages of EDM:

(http://www.header.com/capabilities/edm) (http://www.nitc.ac.in/dept/me/jagadeesha/mev303/OVERVIEW_OF_NTM_PROCESSES.pdf)

- Complex shapes
- Extremely hard materials can be machined with very close tolerances.
- Slender shapes can be obtained where conventional cutting tools may damage the part from excess cutting tool pressure
- Delicate sections and fragile/brittle components can be machined without perceivable distortion, since there is no direct contact between tool and workpiece
- Good surface finish can be obtained
- Very fine holes can be attained
- Tapered holes may be produced
- Complex internal shapes can be machined

Limitations of EDM:

- Slow rate of material removal.
- Rough surface finish when at higher rates of material removal
- The additional time and cost used for creating electrodes for ram/sinker EDM.
- Reproducing sharp corners on the workpiece is difficult due to electrode wear.

- "Overcut" and unwanted erosion may occur
- Excessive tool wear occurs during machining.
- Electrically non-conductive materials can be machined only with specific set-up of the process

Waterjet Cutting

Waterjet technology uses the principle of pressurizing water to extremely high pressures, and allowing the water to escape through a very small opening called “orifice” or “jewel”. Water jet cutting uses the beam of water exiting the orifice to cut soft materials. This method is not suitable for cutting hard materials. The inlet water is typically pressurised between 1300 – 4000 bars. This high pressure is forced through a tiny hole in the jewel, which is typically 0.18 to 0.4 mm in diameter. (**http://www.nitc.ac.in/dept/me/jagadeesha/mev303/OVERVIEW_OF_NTM_PROCESSES.pdf**) A waterjet is a versatile and flexible machining tool. A wide variety of material can be cut efficiently and cost-effectively and a wide variety of geometries are achievable. However, the workpiece can not be thick enough to deflect or even interrupt the waterjet. (**https://www.webcitation.org/5nWaNTDGA)**

The generated heat by the waterjet is absorbed by the water and carried into the catch tank. The material itself experiences almost no change in temperature during machining. The result is that there is no heat affected zone on the material. During piercing 5 cm thick steel, temperatures may get as high as 50° C, but otherwise machining is done at room temperature. . The absence of a heat affected zone means you can machine without hardening the material, generating poisonous fumes, recasting, or warping. **(http://waterjets.org/archive/about-waterjets/overview-of-waterjets/)** Since no heat is applied on the materials, cut edges are clean with minimal burr. Problems such as cracked edge defects, crystalisation, hardening, reduced wealdability and machinability are reduced in this process. (**http://www.nitc.ac.in/dept/me/jagadeesha/mev303/OVERVIEW_OF_NTM_PROCESSES.pdf)**

Abrasive Water Jet Cutting

An extended version of water jet cutting is the Abrasive waterjet cutting; in which the water jet is spelled with abrasive particles such as silicon carbide or aluminium oxide in order to increase the material removal rate. Almost any type of material ranging from hard brittle to extremely soft materials can be cut by this process. It is particularly suitable for heat sensitive materials that cannot be machined by processes that produce heat while machining. In this process, high velocity water exiting the jewel creates a vacuum which sucks abrasive from the abrasive line, which mixes with the water in the mixing tube to form a high velocity beam of abrasives, as can be seen in Figure X and X. **(http://www.nitc.ac.in/dept/me/jagadeesha/mev303/OVERVIEW_OF_NTM_PROCESSES.pdf)**

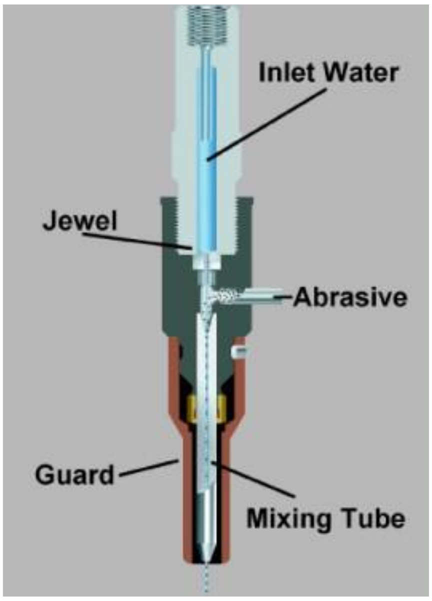

Figure X – Abrasive Waterjet Cutting nozzle

(http://www.nitc.ac.in/dept/me/jagadeesha/mev303/OVERVIEW_OF_NTM_PROCESSES.pdf)

Figure X – Abrasive Waterjet in progress (http://www.dtiexact.com/waterjet-cutting.html)

Advantages of water jet cutting

(https://www.webcitation.org/5nWaNTDGA)

(**http://www.nitc.ac.in/dept/me/jagadeesha/mev303/OVERVIEW_OF_NTM_PROCESSES.pdf)**

• Does not produce any dust or particles

• Environmental impact is relatively low, since there is almost no removed material, discarded water can be recycled and does not produce any dust or particles that are harmful if inhaled

• Uniformity of material not important

• Relatively low cost

• Can manufacture wide workpieces, since they fit in the machine and are correctly fastened

• Low cutting forces on workpieces

• Limited tooling requirements

• No heat affected zone

• No cutter induced metal contamination

• Eliminates thermal distortion

• No slag or cutting dross

• Precise, multi plane cutting of contours, shapes, and bevels of any angle

Limitations of abrasive water jet cutting

(**http://www.nitc.ac.in/dept/me/jagadeesha/mev303/OVERVIEW_OF_NTM_PROCESSES.pdf)**

• One of the main disadvantages of water jet cutting is that a limited number of materials can be cut economically

• Thick parts cannot be cut by this process economically and accurately

• Taper is also a problem with water jet cutting in very thick materials. Taper occurs when the jet exits the part at different angle than it enters the workpiece and cause dimensional inaccuracy.

• Cannot drill flat bottom

• Cannot cut materials that degrades quickly with moisture

• Surface finish degrades at higher cut speeds which are frequently used for rough cutting

• The major disadvantages of abrasive water jet cutting are high capital cost and high noise levels during operation

CNC Machining

This process is a specific form of computer numerical controlled (CNC) machining and is similar to drilling and cutting. It's a machining process able to achieve many of the operations performed by both of them. Milling uses a rotating cylindrical cutting tool, as can be seen in Figure X, able to move along multiple axes and create a wide variety of shapes, slots and holes. The workpiece is often moved across the milling tool in different directions. (http://www.thomasnet.com/about/cnc-milling-51276103.html)

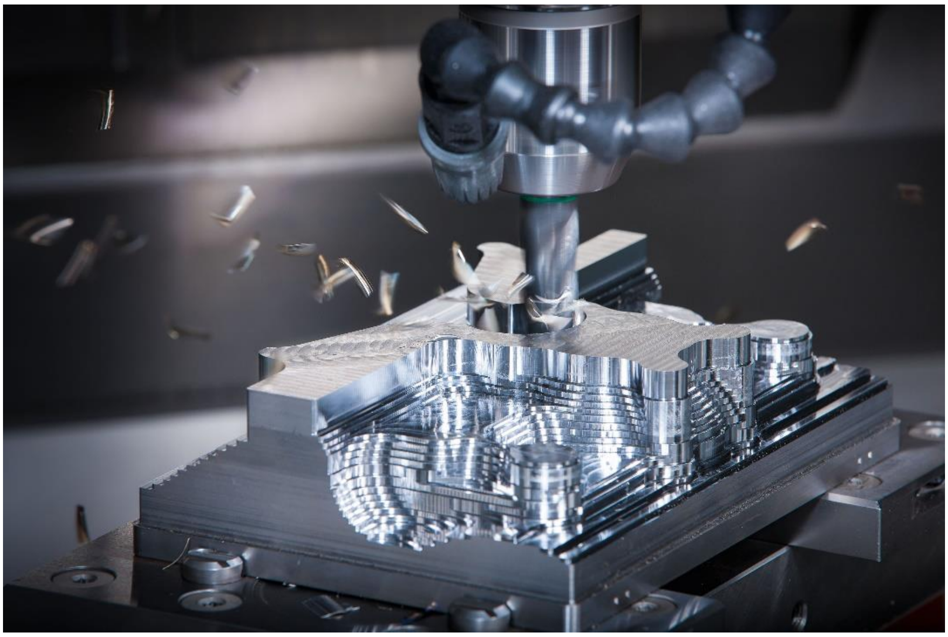

Figure X – CNC Milling in progress

CNC machining centers are used to produce a wide range of components and tooling costs are increasingly becoming more affordable. Large production runs requiring simples designs are better served by other methods, but CNC milling can accommodate lots of manufacturing needs, mainly prototyping and short-run production of complex parts to the fabrication of unique precision components. (http://www.thomasnet.com/about/cnc-milling-51276103.html)

Advantages of milling:

http://www.custompartnet.com/wu/milling

- Availability
- Costs
- Production rate

Limitations of milling:

http://www.custompartnet.com/wu/milling

- Tool contact generates heat over the workpiece surfaces
- Slender and brittle profiles may be difficult to machine, since contact may generate vibrations
- Precision depends a lot on the machine
- Surface finishing (roughness) may concentrate stresses on undesired spots
- Geometry limitations due to cutting tools geometries (for example, can't machine inside corners)
- Clamping raw material may be a difficult task
- Cutter may become dull if tool and parameters are chosen wrong

Laser Cutting

Laser cutting is a thermal process that utilizes a high-energy, coherent light beam to remove material by melting and vaporizing particles on the surface of a workpiece. It can be used to cut, drill, weld and mark. LBM is particularly suitable for making accurately placed holes. It's schematic is shown in figure X.
(http://www.nitc.ac.in/dept/me/jagadeesha/mev303/OVERVIEW_OF_NTM_PROCESSES.pdf)

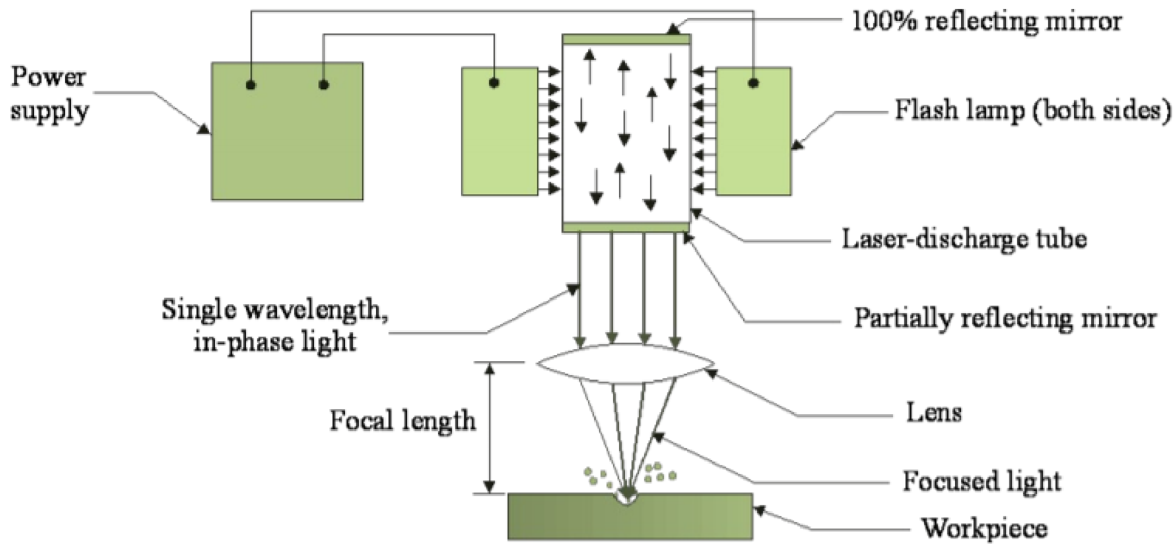

Figure X – Laser cutter schematic

Since the light must be focused at the workpiece surface, it's important to have a regular height. Otherwise the beam loses its power and precision. In this point of contact, the material is melted, changes into plasma and leaves the region. A gas jet (usually oxygen) can be used to ease this transformation and removal of material. It's a process suitable to hard materials machining and to produce hole geometries that can't be achieved with other methods.

(http://www.nitc.ac.in/dept/me/jagadeesha/mev303/OVERVIEW_OF_NTM_PROCESSES.pdf)

Advantages of laser cutting:

https://www.behance.net/gallery/32298803/Laser-Cutting-Advantages-And-Disadvantages

https://medium.com/@altpartsinc/advantages-disadvantages-of-laser-cutting-process-603da2e0da73

http://www.nitc.ac.in/dept/me/jagadeesha/mev303/OVERVIEW_OF_NTM_PROCESSES.pdf

- Can cut in any desired path

• Stressless, what allows very fragile materials to be laser cut without any support

• Cuts very hard and abrasive materials

• Cost effective and flexible process

• High accuracy

• No cutting lubricants required

• No tool wear

• Narrow heat effected zone, reducing possibility of material properties changes

• Easy placement of workpiece

Limitations of laser cutting:

• Uneconomic on high volumes compared to stamping

• Limitations on thickness due to taper

• Assist or cover gas required

• Expensive compared to other processes

https://medium.com/@altpartsinc/advantages-disadvantages-of-laser-cutting-process-603da2e0da73

https://www.behance.net/gallery/32298803/Laser-Cutting-Advantages-And-Disadvantages

http://www.nitc.ac.in/dept/me/jagadeesha/mev303/OVERVIEW_OF_NTM_PROCESSES.pdf

3.1.2.3 Manufacturing Process Definitions

The available material in the Biomechatronics laboratory is a Chromium-Vanadium Steel (AISI 6150) plate with dimensions 260 mm x 300 mm x 13 mm. The two most suitable technologies for machining this plate from beginning until a spring profile (considering that the Optimization result will lead the Topology into a similar result to the ones found in literature) is Water Jet Cutting and Electric Discharge Machining.

The reasons for choosing Water Jet Cutting are:

Availability of machinery in the University

Relatively low cost

Low cutting forces on workpieces, not changing the material properties

No heat affected zone, since there is no contact between tool and workpiece

No cutter induced metal contamination

Eliminates thermal distortion

And the main reasons for choosing the EDM are:

Able to machine complex shapes

Extremely hard materials can be machined with very close tolerances

Slender shapes can be obtained where conventional cutting tools may damage the part from excess cutting tool pressure

Delicate sections and fragile/brittle components can be machined without perceivable distortion, since there is no direct contact between tool and workpiece

Good surface finish can be obtained

Complex internal shapes can be machined

The machining process can be made in more than one step, using advantages of both technologies. The Water Jet Cutting is intended to be used in the University to divide the plate into squares of 120 mm x 120 mm x 13 mm. A milling and a grinder shall be used to level the right width for the spring. A EDM could divide the 13 mm profile into two 4 mm width squares, but that is considered worst since it highly increases the costs and time of machinery, while milling and grinding waste material. With the square leveled to 4mm width, EDM will be used to cut the spring profile from this square. Lastly, drilling is used to machine the coupling holes of the spring.

3.1.3 Algorithm-based product and process solution finding using mathematical optimization

Specific algorithm-based mathematical optimization methods are in this phase applied intending to find the optimal solution for the proposed problem. These solutions presuppose equal consideration of products and processes. They not only addresses the product topology and geometry, but also take into consideration the manufacturing processes involved in its production.

According to the gathered requirements, the SEA may have different stiffness and different maximal torsions. That lead us to a path in which we have more than one possible result for their profile and their design, allowing the choice of the most compatible geometry and stiffness. Since the purpose of this thesis is not producing the spring which gives the best dynamic response, but reaching the spring topology trough an optimization method, a 300 Nm/rad stiffness is chosen, which results in a maximal displacement of 0.133 rad (or 7.62 degrees). This value lays inside the acceptable range and is considered a high value, which raises the possibility of been achieved. Defining very low stiffness as requirements may drive us to endless searches that may never be conclusive.

As a first step in the implementation of the TOM, it’s first required to define where material shall not be removed. Namely, a fixed topology part of design requirements. The SEAs torsion must happens between two rings, the external ring is coupled to the motor and the internal ring is coupled to the exoskeleton limb. These twos rings are defined as solid bodies and their topology won’t be modified in order to keep the mechanical coupling correct, as illustrated in Figure XX (red indicates full density and blue indicates empty densities). The diameter of the internal ring is 27.5 mm and the internal and external diameter of the outer ring are 83.0 mm and 100.0 mm, respectively. These dimensions are based on the previous mechanical design of the spring. (REFERENCIA ANDREY BUGARIN)

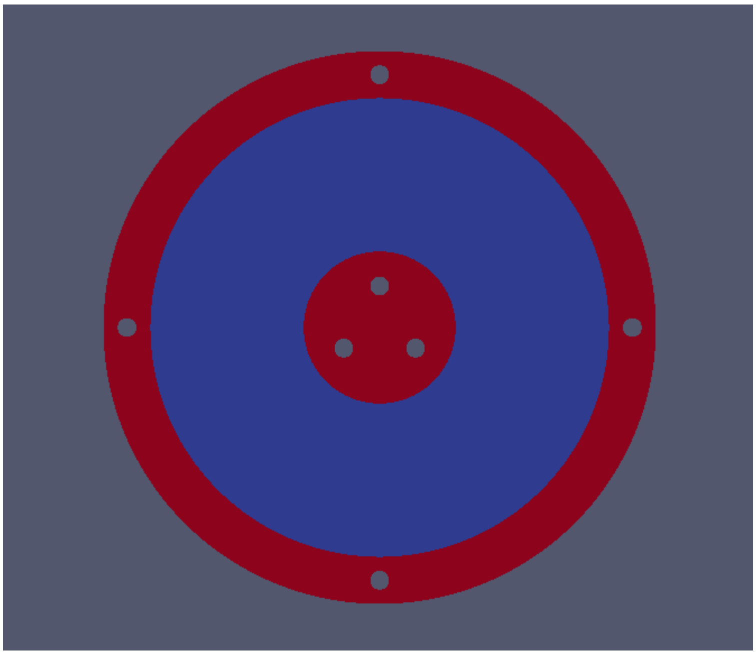

Figure XX – Outer and inner ring of pre-defined rigid elements

Boundary conditions are than defined. The inner ring is fixed so it doesn't rotate and four external tangential forces are applied on the four external holes, simulating the coupling contact with the motor which result in a torque transmission. Since the maximum actuating torque on the spring is 40 Nm and the distance from these holes to the centerpoint of the SEA is 45.75 mm, each applied force is 218.58 N.

Running the implemented algorithms from (REFERENCIA RICARDO LAHUERTA), none topology was achieved. After reaching the maximum number of iterations, no topology was found to fulfill all restrictions and minimize the objective function. An assumption to explain the not converging results is the extremely high modulus of elasticity of the steel. Reducing width could be a way to overcome this problem, but one of the project requirements is to fix strain gages in order to measure and transduce the actuating torque. This is not a parameter that may be changed willing to achieve a plausible topology. However, defining another material hoping the optimization converge and give us satisfactory result is also not coherent with the project requirements, since there is no steel with similar properties as the AISI 6150, but with a much different modulus of elasticity.

Thus, the initial idea and definitions of project requirements must be changed considering the losses and gains for the research and for the project.

- Changing the SEA width may be a solution for increasing the chances of convergence from the TO algorithm. With a width smaller than 4 mm, there is no guarantee that there will be an available strain gage able to be fixed in the SEA hinges in order to transduce stresses into torque, and the measurements will then be limited by the already insufficient encoders. An advantage of this modification is keeping the AISI 6150 steel as the SEA material, a very strength material, with high corrosion resistance, hardness, capability of bearing shock loads, high modulus of elasticity and tensile strength. These two last properties gives it particularly the best fitting properties when comparing to other kind of steels and materials. (https://www.techwalla.com/articles/properties-of-chrome-vanadium) Having a high tensile strength avoids it from breaking due to overloads and also gives it a very high lifetime when for example analyzing its fatigue limit. However, machining this material is not a simple task. Defining a width with which the elements are big enough to be precisely manufactured in such extreme processes as Water Jet Cutting and Electrical Discharge Machining is a challenging handling of variables.

- Considering changing material leads this SEA development to a way in which all advantages associated with the material properties may be lost, but manufacturing the spring may be easier, faster and cheaper, while keeping the fixing of strain gages. In the case where the AISI 6150 steel is changed into a more ductile material as aluminum or in an extreme assumption to some polymer, mechanical properties as bearing high shock loads, high stresses and infinite life under fatigue limit are lost. However, a wide variety of ductile materials can than be considered and the easiness of manufacturing than with rapid prototyping technics (considering the case of polymers) shows an interesting tradeoff, since a manufacture technic that assures certain material properties for the material is chosen.

TABELA COMPARANDO PROPRIEDADES MECANICAS DO ACO, ALUMINIO E DO POLÍMERO RGB525

	STEEL 6150	Aluminium 6160	RGD525
Elasticity Modulus	200 GPa	70 GPa	3.2 – 3.5 GPa
Tensile Strength			
Poisson ratio	0.33	0.33	0.34

ALUMINIUM TEST OF CONVERGENCE

Willing to analyze how different can the choice of the material change the optimized topology, the same optimization algorithm was ran considering the Aluminium alloy AISI 6061 as the possible candidate to be the spring material. It's known Aluminium is not the chosen material and is not a well suitable metal for using as spring material, but it's lower modulus of elasticity (69 GPa against the 200 GPa from the AISI 6150 steel) allow us to compare if the algorithm converges to an optimized profile. In fact, that is exactly what happens. Running the optimization algorithm for compliant mechanisms from (RICARDO LAHUERTA) with the material modulus of elasticity equals to 69 GPa, a converged result for the topology appears. However, as we may see in Figure X, there is a lot of gray scale in it.

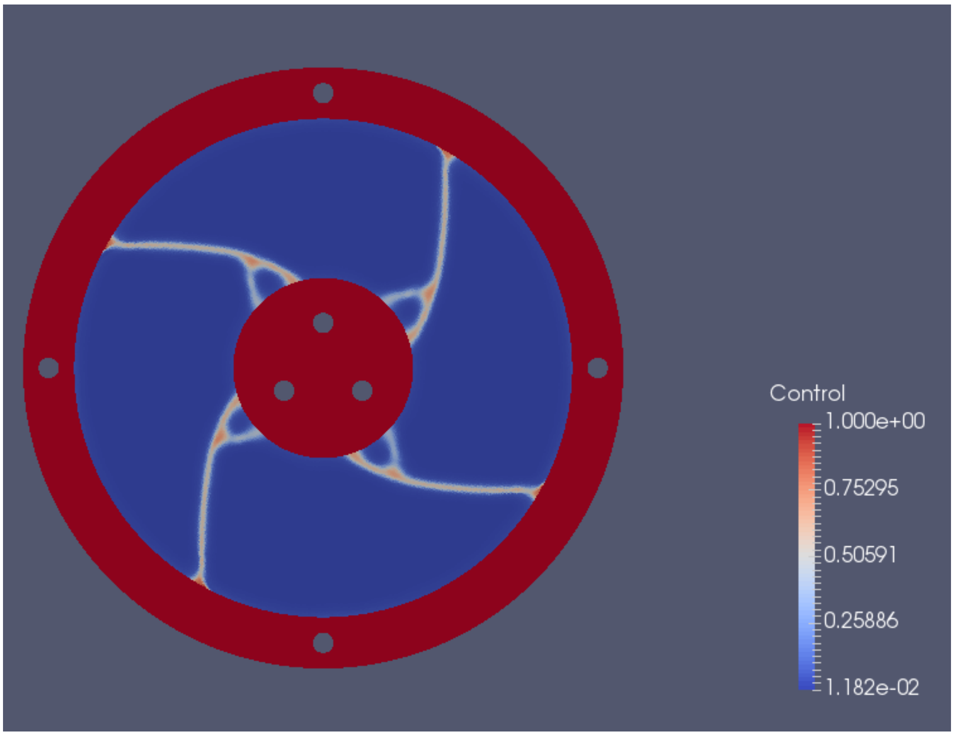

Figure XX – TOM result considering the AISI Aluminum 6160 alloy

This topology is not ideal and also shows a problem in convergence. However, it's result may be used as a basis for next steps. It's profile is similar to compliant mechanisms profiles, what indicates the algorithms approximates the topology to a desired distribution of densities. It's important to have in mind that implementing this topology is not as trivial as it may seen. The interval of densities of the members which creates a flexibility inside the spring is mostly between 0,3 and 0,8.

RGD 525 TEST OF CONVERGENCE

A lower modulus of elasticity has presented better convergence in the used optimization algorithm, that may indicate that an even lower modulus can deliver better topologies. Keeping that in mind and available materials in the university, the PLASTIC XXXXXX and the 3D Printer YYYYYYY from the LAB ZZZZZZZZ, offer a reachable alternative to manufacture complex profiles with defined material properties. The available polymers to manufacture the spring with the Stratasys 3D Printer are listed in the ATTACHMENT XXXX and since the polymer RGD525 (which composition is not reveled by Stratasys) is the one with the highest Tensile Strength interval (70 – 80 MPa), it was selected as the best candidate to compose the spring. It also has the highest Modulus of Elasticity (3.2 – 3.5 GPa), but doesn't stay far away from the other polymers. Its Poisson's ratio was considered as 0.34 since this is the ratio of other similar polymers.

Changing from Aluminum alloy AISI 6061 to the RGD525 polymer, the optimization algorithm convergence has increased and reached a very reasonable topology.

FIGURA DA TOPOLOGIA DO RGD525

3.1.4 Computer Integrated Refinement of Product and Process Design

By this step, the topology and geometries are already obtained and the manufacturing process is already defined. However, topology optimization results are not always simple or easy to sketch in a Computer Aided Design software. Hence, refinements and adaptations applying computer integrated models, methods and tools are crucial to reach the product manufacturability with an integrated perspective (REFERENCIA CHAP 9).

The topology optimization results can be provided to CAD modeling, but with coarse and rough geometries that make the profile improper to manufacture and assembly. The obtained SEA may fulfill requirements as loads, constraints, displacements and stiffness, however it still needs to be adapted and refined to consider further requirements as design space, manufacturing processes and other restrictions. The result must be a fully parametrized 3D CAD model, which can have its performance simulated in a CAD-Finite-Element-Method (CAD-FEM). With a Finite-Element-Analysis (FEA) its intended to validate stresses and displacements of the final profile geometry, since refinements and adaptations changes the original optimized solution.

RGD525

DESIGN DA TOPOLOGIA

VALIDATION WITH ANSYS SIMULATIONS

3.2 MANUFACTURING

3.3 VALIDATION

4 CONCLUSIONS

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Attachment 1 – Scheduling and Planning

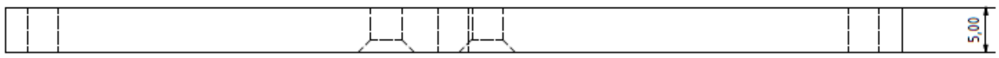
AGENDA 2017 - Computer Integrated Design and Manufacture of Torsional Spring for an Exoskeleton Module

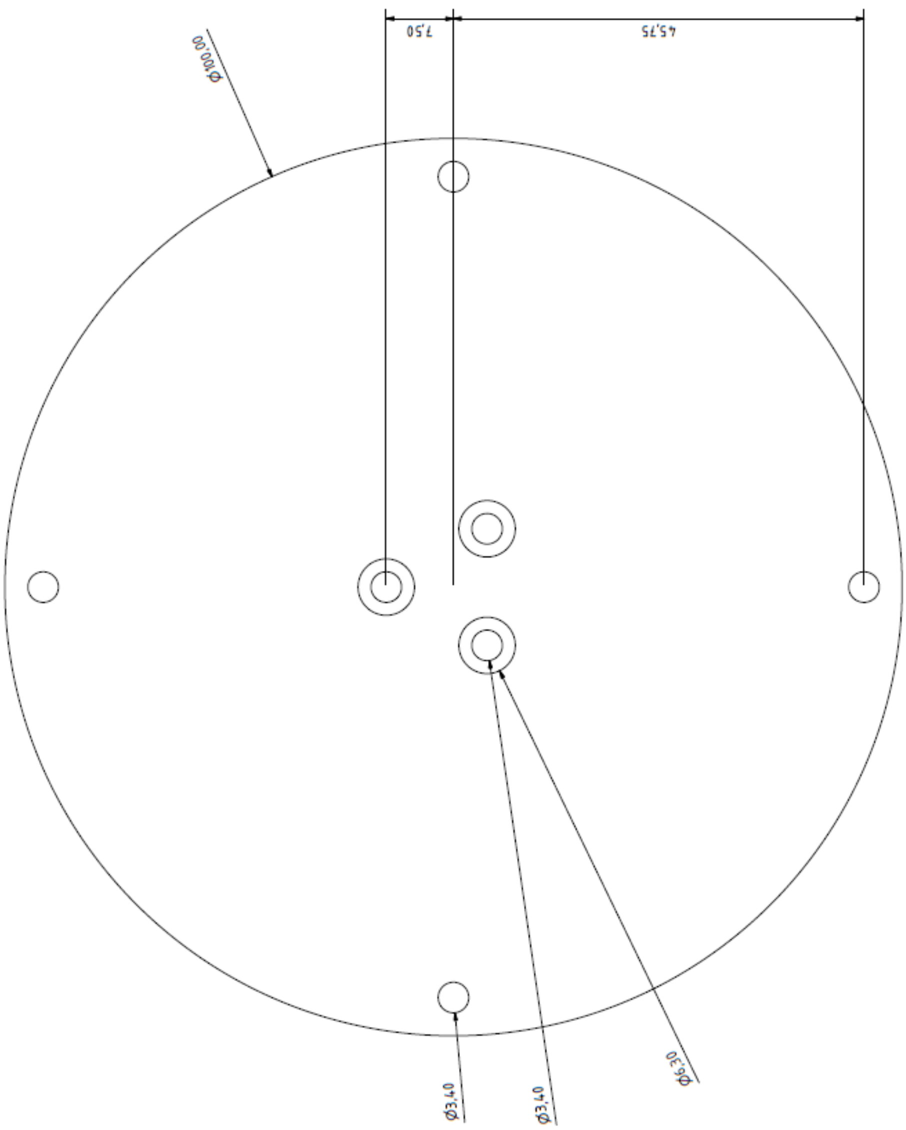
	10.04.2017 16.04.2017 **Week 1**	17.04.2017 23.04.2017 **Week 2**	24.04.2017 30.04.2017 **Week 3**	01.05.2017 07.05.2017 **Week 4**	08.05.2017 14.05.2017 **Week 5**	15.05.2017 21.05.2017 **Week 6**	22.05.2017 28.05.2017 **Week 7**	29.05.2017 04.06.2017 **Week 8**	05.06.2017 11.06.2017 **Week 9**	12.06.2017 18.06.2017 **Week 10**	19.06.2017 25.06.2017 **Week 11**	26.06.2017 02.07.2017 **Week 12**	03.07.2017 09.07.2017 **Week 13**	10.07.2017 16.07.2017 **Week 14**
Literature Research	■	■	■	■	■									
Requirements Definition		■	■	■	■	■	■							
Design						■	■	■	■	■	■	■	■	
FEM Analysis									■	■	■	■	■	■
Optimization											■	■	■	■
Manufacture														■
Tests														
Validation														
Documentation	■	■	■	■	■	■	■	■	■	■	■	■	■	■

	17.07.2017 23.07.2017 **Week 15**	24.07.2017 30.07.2017 **Week 16**	31.07.2017 06.08.2017 **Week 17**	07.08.2017 13.08.2017 **Week 18**	14.08.2017 20.08.2017 **Week 19**	21.08.2017 27.08.2017 **Week 20**	28.08.2017 03.09.2017 **Week 21**	04.09.2017 10.09.2017 **Week 22**	11.09.2017 17.09.2017 **Week 23**	18.09.2017 24.09.2017 **Week 24**	25.09.2017 01.10.2017 **Week 25**	02.10.2017 08.10.2017 **Week 26**	09.10.2017 15.10.2017 **Week 27**	16.10.2017 22.10.2017 **Week 28**
Literature Research														
Requirements Definition														
Design														
FEM Analysis														
Optimization														
Manufacture	■	■	■	■	■									
Tests						■	■	■	■	■	■	■		
Validation													■	■
Documentation	■	■	■	■	■	■	■	■	■	■	■	■	■	■

	23.10.2017 29.10.2017 **Week 29**	30.10.2017 05.11.2017 **Week 30**	06.11.2017 12.11.2017 **Week 31**	13.11.2017 19.11.2017 **Week 32**	20.11.2017 26.11.2017 **Week 33**	27.11.2017 03.12.2017 **Week 34**
Literature Research						
Requirements Definition						
Design						
FEM Analysis						
Optimization						
Manufacture						
Tests						
Validation	■					
Documentation	■	■	■	■	■	■

Attachment 2 – Geometry Requirements





Attachment 3 – MA3 Datasheet

Attachment 4 – Traction Tests

Attachment 5 – FEniCS codes