Optimization of HYDROìD Robot Foot
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Abstract—This paper presents a design of a new deformable active foot for HYDROìD robot. First the foot is modeled using the theory of sandwich panel. Second the design parameters of the sandwich structure undergoes optimization process using genetic algorithm to get the optimum weight which verifies the mechanical and antropometric constraints. Third, the finite element method is used to obtain the stress and deformation of the optimum design waling of the robot. Meanwhile, the impacts at the heel is studied and a solution is proposed using the property of rubber material, to calculate the energy absorbed by foot at the heel strike. Finally, the new design is carried out using CATIA software and the first prototype is manufactured.

Keywords—Active foot, Sandwich Material, Optimization, Genetic Algorithm, Lagrangian Method, HYDROìD.

I. NOMENCLATURE
L: Sandwich material length in m.
w: Sandwich material width in m.
c: core thickness in m.
t: skin thickness in m.
h: sandwich material thickness in m.
\(M_{(max)}\): Maximum moment applied at the sandwich panel in N.m.
F: Force applied at the sandwich panel in N.m.
\(\alpha\): inclination angle of the foot with respect to the ground in \(^\circ\).
\(x_{cg}\): distance from the center of the weight to the heel extremity in m.
\(E_s\): skin elastic modulus in GPa.
\(E_c\): core elastic modulus in GPa.
\(G_s\): core shear modulus in GPa.
\(\nu\): core aspect ratio.
\(W_p\): total weight of the panel in kg.
\(E_f\): Effective young modulus of the sandwich panel in GPa.
\(\rho_s\): skin density in \(\frac{kg}{m^3}\).
\(\rho_c\): core density in \(\frac{kg}{m^3}\).
\(I_s\): second moment of area of the sandwich panel in m\(^4\).
\(I_f\): second moment of area of the skin layer in m\(^4\).
\(\sigma_{f_{max}}\): maximum bending stress at the skin layer in MPa.
\(\tau\): maximum shear stress at the core layer in MPa.
\(\sigma_c\): acceptable bending strength of the skin in MPa.
\(\tau_c\): acceptable shear strength of the core in MPa.
\(D\): flexural rigidity of the sandwich panel in N/m\(^2\).
\(E_k\): kinetic energy in J.

\(E_{pot}\): absorbed energy during impact in J.
\(\delta_{comp}\): compression deformation of the heel during impact in m.
\(M_e\): effective foot mass during impact in kg.
\(v_1\): impact velocity of the foot in m/s.

II. INTRODUCTION

Although, the foot is defined as the lower extremity of the leg that is in direct contact with the ground, this isn’t sufficient to well define the functionality of this part. In other words, humanoid robot foot is responsible for the stability of the robot body during locomotion activities, such as walking, running or jumping. Moreover, it should be capable to bear the whole stresses due to the ground reaction forces. Add to this, the robot foot should absorb the shocks during gait cycle at the level of the heel and the toe, which decreases the energy consumption of the ankle actuator. All of this induces the research for the optimal foot design parameters and energy consumption.

Present humanoid robot foot are either rigid plate feet (Charli [1], Nao [2], Igus [3]), flexible foot (Robian [4], H6 and H7 [5]) or active foot (HYDROìD and Webian 2R [6]). The rigid foot is made up of one part, without any capability of movement between the toe or the heel and the mid-part. For example, Charli has plate aluminum to represents its foot, while Nao and Igus has used one rigid plastic foot. This provokes a high loss of energy due to the trajectory that the foot will do during walking if it is plate foot. In the other hand, the flexible and the active feet allow the motion between the mid-part and the toe using a torsional spring and an actuator respectively. Robian, as an example of a flexible foot, has five flexible rubber contact points (two at the heel and three at the toe) between its foot and the ground [4]. However, 2 contact points are not enough to show an efficient energy absorption at the heel level. In other hand, Wabian 2R [6] has used an active joint at the toe. This only decreases or even eliminates the impacts at the toe, without taking into considerations the impacts at the heel. This makes it necessary to design a new lightweight foot, which reduces the energy consumption, with a viscoelastic deformable heel, which will be applied on HYDROìD robot foot.

Current HYDROìD robot foot is a rigid plate foot with small flexibility and with active toe. It is made from aluminum and it weighs 0.95 kg. The target foot is lightweight with integrated deformable heel and optimized parameters. These parameters consist of the dimensions, the mechanical properties and the weight. This is carried by using the proper optimization algorithms and mathematical approach. As an optimization algorithm, genetic algorithms is used to carry out the optimization process [7].

In the other hand, the classical method for fabricating sandwich material has two main disadvantages. The first one
is the necessity to fabricate metallic molds using machining. The second one is the complex setup which can be either by vacuum or by thermo-compression on the hydraulic press with heated metallic plate. This provokes high cost and long time of fabrication. This leads to the use of 3D-printing of composite material as the fabrication method.

This paper is divided into six sections excluding the introduction. In sec III, the foot is modeled using sandwich material theory, where all the parameters are identified. Then, the optimization process is carried out using the defined model of the foot. This is performed in section IV, where the results are obtained and verified using genetic algorithm optimization method. Meanwhile, a 3D-model is used in section V to obtain the static and the dynamic response of the foot during walking. Thereafter, a heel model is used in section VI to study the impacts at the foot, in order to design a viscoelastic heel. These results are used to re-design the current HYDROiD foot, using 3D-printing of composites, which is explained in section VII. Finally, section VIII gives the conclusion of the work.

III. Foot Modeling Using Sandwich Panel Theory

To define its design parameters, HYDROiD robot foot is considered as a sandwich panel exposed to a force $F$ at a distance from its heel. Sandwich panels are well known for their high bending strength and stiffness and acceptable impact strength. They are anti-corrosive with high durability. The sandwich panel consists of two skin and one core intermediate layers. Usually, the skin is a composite reinforced polymers and the core is a stiff material. The main parameters of the sandwich panel are: its length $L$, width $w$, thickness $h$, core thickness $c$, skin thickness $t$ and the core aspect ratio $\nu$ (Fig 1).

![Fig. 1. Modeling of HYDROiD robot foot using sandwich theory.](image)

The failure takes place in the skin when the maximum axial stress, either tension or compression, reaches the yield strength of the skin material. For example, when $\sigma_{f_{\text{max}}}$, the maximum bending stress, reaches the yield strength of the skin $\sigma_{fy}$, the panel skin fails.

In the other hand, the core is supposed to fail when the maximum shear stress $\tau_{\text{max}}$ reaches the shear strength of the core material $\tau_c$.

During walking, the foot is supposed to be supported beam counter the ground and subjected to bending moments which come from the ground reaction force applied at a distance $x_{cg}$ from the center of weight to the heel extremity. As a result, normal and friction forces appear at the level of the heel during heel strike (Fig2-A), and at the level of the toe during terminal stance (heel off) (Fig2-B) [21]. Using Newton law, the maximum moment applied at the foot at the contact point with the ground is expressed in case A and B in Eq. 1 and Eq. 2 respectively:

$$M_{\text{max}} = F\cos\alpha x_{cg1}$$ (1)

$$M_{\text{max}} = F\cos\alpha (L-x_{cg2})$$ (2)

In the other hand, the maximum bending stress is calculated, in both cases A and B, using the classic formula of a beam under simple bending:

$$\sigma_{f_{\text{max}}} = \frac{F\cos\alpha x_{cg1} h}{2I}$$ (3)

$$\sigma_{f_{\text{max}}} = \frac{F\cos\alpha (L-x_{cg2}) h}{2I}$$ (4)

However, Allen [12] has suggested a modified equation to take into account the shear deflection effect of the core, which can be expressed as follows, for both cases A and B respectively:
\[
\sigma_f = \frac{F \cos \alpha (x_{eq1})}{2} \left( \frac{h}{I_f} + \frac{t}{I_f \theta} \right) 
\]

Where \( I_f \) is the second moment of area of the skin layer, \( x_{eq1} \) is the distance from the center of weight to the heel extremity for the first case, \( x_{eq2} \) is the distance from the center of weight to the heel extremity for the second case, \( \alpha \) is the angle of contact of the foot with the ground and \( \theta \) is a correction factor used to take into account the effect of the shear deflection in the core of the sandwich panel. It is expressed using Eq.7:

\[
\theta = \frac{L}{\nu h} \sqrt{\frac{G_c \nu}{2 E_c t} (1 + \frac{3 h^2}{t^2})} 
\]

Where \( G_c \) is the shear modulus of the core and \( E_f \) is the young modulus of the skin. In other hand, \( c \) and \( t \) can be expressed as function of \( h \). By introducing the core aspect ratio \( \nu \), \( c \) and \( t \) are written as follows:

\[
c = \nu h 
\]
\[
t = \frac{(1 - \nu) h}{2} 
\]

Now Replacing Eq.8 and Eq.9 into Eq.5, 6 and 7, the following relations can be expressed as follows:

\[
\sigma_f = \frac{F \cos \alpha (x_{eq1})}{2} \left( \frac{h}{I_f} + \frac{t}{I_f \theta} \right) 
\]

\[
\sigma_f = \frac{F \cos \alpha (L - x_{eq2})}{2} \left( \frac{h}{I_f} + \frac{t}{I_f \theta} \right) 
\]

\[
\theta = \frac{L}{\nu h} \sqrt{\frac{G_c \nu}{2 E_c t} (1 + \frac{12}{(1 - \nu)^2})} 
\]

In other hand, the weight of the sandwich panel is calculated in the term of the core volume aspect ratio and the panel thickness. Eq.13 gives the weight of the panel:

\[
W_p = w h L (\nu \rho_c + (1 - \nu) \rho_s) 
\]

Where \( W_p \) is the weight of the panel, \( \rho_c \) is the core density and \( \rho_s \) is the skin density. A.F. Johnson [13] has defined the notation of the effective bending modulus of sandwich panel, using some algebraic manipulation. \( E_f \) is expressed function of the skin modulus \( E_s \), core modulus \( E_c \) and the core aspect ratio \( \nu \). (Eq. 14)

\[
E_f = \nu^3 E_c + (1 - \nu^3) E_s 
\]

Finally, the flexural rigidity of the sandwich panel \( D \) is calculated using the effective bending modulus \( E_f \), as function of the panel thickness \( h \). (Eq. 15)

\[
D = \frac{w h^3 E_f}{12} 
\]

### IV. Optimization Process

In general, optimization is the process of finding the optimal value (minimum or maximum) or condition for an objective function, governed by constraints [15]. The target of the optimization in the design problem is to achieve the most desired design parameters, in relation with governing criteria and constraints. More specific to the sandwich panels, the optimum design is the design with the lowest weight to the highest rigidity, and which respects the limits of tensile strength of the skin and the shear strength of the core. According to this proposition, the optimization process is carried out.

#### A. Definition of Optimization Parameters

Before starting the optimization process, it is necessary to define the objective function of the optimization procedure. This is by defining the main target which is to get the minimal weight of the panel \( W_p \). Thus the objective function \( F_{obj} \) is defined as the weight(Eq. 16) and the target is to minimize \( F_{obj} \). The second indispensable need is to define the constraints functions. This is by defining the conditions that should be verified for the accepted solutions. In the studied case, the maximum bending stress \( \sigma_f \) should be always lower than the acceptable bending strength of the sandwich skin \( \tau_c \) and the maximum shear stress \( \tau_s \) should be lower than the acceptable shear strength of the core \( \tau_{max} \). These two conditions are defined using two ratios \( f_1 \) and \( f_2 \), which are respectively the ratio of the maximum bending stress to the bending strength of the skin, and the ratio of the maximum shear stress to the shear strength of the core (Eq. 17 and 19).

\[
F_{obj} = W_p(h, \nu) 
\]

While,

\[
f_1 = \frac{\sigma_f}{\tau_c} < 1 \]

\[
f_2 = \frac{\tau_{max}}{\tau_s} < 1 
\]

Another condition related to the practical sandwich material design is defined by H.G. Allen[13] in the following relation:

\[
f_3 = \frac{100 E_c c^2}{6 E_s t (c + t)^2} < 1 
\]

Using the equations in sec III, \( F_{obj} \) is function of the sandwich material parameters,i.e, the length \( L \), the width \( w \), the thickness \( h \), the core aspect ratio \( \nu \), the skin density \( \rho_s \) and the core density \( \rho_c \) (Eq. 13). In other hand, the two constraints function \( f_1 \) and \( f_2 \) are function of the previously mentioned parameters in addition to the load \( F \), the angle of contact \( \alpha \), the core young modulus \( E_c \), the skin young modulus \( E_s \), the core shear modulus \( G_c \) and the width of the panel \( w \) (Eqs. 20 and 21).

\[
f_1 = \frac{F \cos \alpha (x_{eq1})}{2 \sigma_s} \left( \frac{1}{I_f} + \frac{1}{2 I_f \theta} \right) 
\]
\[ f_2 = \frac{F}{2wh\tau_c} \] (21)

In the other hand, the available materials that can be 3D-printed are carbon fiber reinforced epoxy, glass reinforced epoxy or kevlar reinforced epoxy, with pre-specified fiber aspect ratio by the provider company [14], for the skin and nylon 66 for the core. Thus, the core and skin properties aspect ratio by the provider company [14], for the skin and printed are carbon fiber reinforced epoxy, glass reinforced nylon 66 for the core. Thus, the core and skin properties aspect ratio by the provider company [14], for the skin and printed are carbon fiber reinforced epoxy, glass reinforced nylon 66 for the core. Consequently, the only two variables in the optimization process are the thickness \( h \) and the core aspect ratio \( \nu \). All the other known values are given in table I.

**TABLE I. VALUES OF THE KNOWN OPTIMIZATION PARAMETERS.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>General</th>
<th>Nylon</th>
<th>CFC</th>
<th>GFC</th>
<th>Kevlar</th>
<th>Rubber</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_s ) (GPa)</td>
<td>0.94</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( E_c ) (GPa)</td>
<td>0.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( G_c ) (GPa)</td>
<td>1050</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \rho_c ) (kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \rho_s ) (kg/m(^3))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( x_{cg1} ) (cm)</td>
<td>10</td>
<td>1500</td>
<td>1460</td>
<td>2100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( F ) (N)</td>
<td>3000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( L ) (cm)</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( W ) (cm)</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \sigma_s ) (MPa)</td>
<td></td>
<td>700</td>
<td>260</td>
<td>300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma_c ) (MPa)</td>
<td></td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \alpha ) (°)</td>
<td></td>
<td>45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \sigma_{rubber} ) (MPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \epsilon_{rubber} ) (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE II. PARAMETERS OF THE PANEL.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>CFC</th>
<th>GFC</th>
<th>Kevlar</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h^* )</td>
<td>mm</td>
<td>15</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>( \nu^* )</td>
<td>—</td>
<td>0.71</td>
<td>0.4</td>
<td>0.57</td>
</tr>
<tr>
<td>( W_p^* )</td>
<td>g</td>
<td>460</td>
<td>781</td>
<td>542</td>
</tr>
</tbody>
</table>

B. Optimization Using Genetic Algorithm

Genetic algorithms are a category of optimization algorithms, used to find an optimal solution, the minimum or the maximum, of an objective function. It is considered as one branch of what is called evolutionary computations. These algorithms are more efficient than random and exhaustive search algorithms. They allow to solve multi-objective optimization problem with the lack of linearity, continuity and derivatives. These algorithms are used in many optimization issues such as control [9] and design problems [10].

Genetic algorithms are employed to carry out optimization on an objective function subjected to constraints. The chromosome is defined as vector \( V \) of the two genes \( h \) and \( \nu \). The upper and lower bounds of the variables are well defined, respecting the anthropometric data for normal foot height for \( h \) and the normal chosen aspect ratio \( \nu \) for sandwich panels. In addition, the genetic algorithm (GA) parameters such as: the population size \( Pop_{size} \), the crossover probability \( P_c \), the mutation probability \( P_m \) and maximum generations number \( Ngen_{max} \) are defined. In other hand, an improved (GA) reported by Yokota et al [17] is used in the optimization process. That is, for the constraint function \( f_i \) an incremental value \( \Delta_i \) is defined. Consequently, a new modified objective function \( F_{objmod} \) is used including incremental value, and the solution chromosome \( V^* \) is assigned using the argument function \( argmin \) which means, it is the chromosome which gives the minimal value of \( F_{objmod} \). The following notations clarify the algorithm.

\[ V = [h \ \nu] \]

\[ 8 \leq h \leq 15 \]

\[ 0.1 \leq \nu \leq 0.8 \]

\[ Pop_{size}=18, \ P_c=0.4, \ P_m=0.15 \]

\[ \Delta_i = \begin{cases} 1 - f_i, & \text{if } f_i \leq 1, \text{ for } i = 1..3 \\ 0, & \text{otherwise} \end{cases} \]

\[ \text{minimize } F_{objmod} = F_{obj}(1 - \frac{1}{3} \sum_{i=1}^{3} \Delta_i) \]

\[ V^* = argmin(F_{objmod}) \]

This algorithm is performed in Matlab optimization toolbox, using the above defined settings. The obtained results are summarized in table II.

**TABLE II. OPTIMIZED VALUES OF THE PANEL PARAMETERS.**

According to the results shown in table II, carbon fiber composite gives the minimum weight \( W_p^* \), the minimum thickness and the highest core aspect ratio \( \nu^* \). So, CFC is chosen to be the material of the foot middle part.
V. Finite Element Analysis: Static and Dynamic Response

In order to verify the parameters found in section IV, a static and a dynamic finite element analysis is carried out. So, a 3D model (Fig.3) is defined according to the obtained dimensions in the optimization process. First, this model undergoes a static load to define the stresses at each layer of the sandwich material. One this is verified, a dynamic study is performed according to the time graph of the ground reaction forces during normal walking. This study will depend on a data provided by a study on human normal walking [18].

Fig. 3. 3D-CAD Model of the optimized foot.

A. Static Response

The first study carried out on the static response of the foot. The design is divided into three layers: 2 skins and one intermediate core layer. Each skin layer has a thickness of 2.25 mm, while the core layer has thickness of 10.5 mm. These values are taken according to the optimum core ratio and thickness \((\nu^*\) and \(h^*\)) found in the previous subsection. Now, the FEA study is carried out supposing that the panel is fixed at one of its two ends and a uniformly distributed 2D-force of total magnitude \(F=3000\) N is applied at the upper skin face (Fig.4), where \(F\) is calculated as ground reaction force 105% of the weight multiplied by the security factor. Note that the applied materials are nylon for the core and CFC composites.

The upper skin face is subjected to the highest stress which is equivalent to 114 MPa, while the lower skin face is subjected to about 93 MPa (Fig.5). In the other hand, the nylon core is effected by about 13 MPa. These results verify that the foot will bear the applied stresses due the reaction impact forces of the ground, with a security factor of at least \(Fs=3\).

B. Dynamic Response

During walking, the gait cycle is divided into two phases: the stance and the swing phase. The swing phase represents the situation of the heel in the air with no contact with the ground. The stance phase takes place when the heel is in contact with the ground. Only during this phase, the impact takes place with a force of excitation of period of about 0.6 sec. This reaction force has a maximum amplitude of 105% of the robot weight [18]. Thus for HYDROID robot, the ground reaction force at the heel strike has a maximum amplitude of 1312.5 N. The variation of this force during time is represented in Fig.6 with security factor \(Fs=2.3\) (depending on the study at [18]).

The same set up in static response is carried out except with an excitation force equals to the ground reaction force. The data are imported to Solidworks software and the simulation is carried out to find the stress and the displacement responses of the sandwich panel. The excitation is repeated 3 times and the responses are monitored (Fig 7). The displacement response (Fig 7-A) shows a maximum displacement of 5.8 mm, which is equivalent to 2.5% elongation in the foot length. In the other hand, the stress response (Fig 7-B) shows a maximum stress of 114 MPa, which is about 3 times smaller than the tensile strength of the sandwich panel.

VI. Heel Impact Study

The walking activity of HYDROID robot consists of an important energy loses during heel strike. This is mainly due to the impact energy that is not absorbed by the heel pad due to the poor deformability of the heel structure. In general, the heel should have a damping and elastic characteristics in order to overcome the impacts. This is mainly available at the viscoelastic material such as rubber.

The total mechanical energy \(E_{\text{mech}}\) induced during impact is the kinetic energy \(E_k\). The kinetics energy is function of the mass of the robot including the effective mass of the foot participating at the impact strike \(M_e\) and its impact velocity \(v_l\) (Eq. (22)), while the absorbed potential energy due to the flexibility of the heel structure is function of the ground reaction force and the compression deformation of the heel \(\delta_{\text{comp}}\) (Eq. (23)).

\[
E_k = \frac{M_e v_l^2}{2}
\]
The effective mass of the foot during walking is estimated by Kai et al [19] as 6.3% of the total body weight, which is equivalent to 8 kg for HYDROID robot which gives a total robot effective mass $M_e$ equals to 132 kg. In addition, the impact velocity is supposed to be equal to 0.53 m/s [19]. At the moment of the heel strike and before any deformation at the heel takes place, the mechanical energy is equal to the kinetic energy which is equivalent to 16 J. After strike, some of the induced kinetic energy is stored as strain energy due to the deformation of the heel.

The compression deformation of the heel during strike is calculated using finite element modeling of deformable and non-deformable heels (Fig. 8). The model supposes that the heel is exposed to a compression force against the ground. This force is equivalent to the ground reaction force $F$ (Fig 6). The resultant deformation data is collected and used to calculate the strain energy absorbed by the foot during heel stance (Fig.9). The results show that the deformable heel absorbs about 4 J per heel strike which is equivalent to 25% of the induced mechanical energy, while the non-deformable heel absorbs a relatively negligible amount of energy during walking (0.25

$$E_{pot} = \frac{1}{2} F \delta_{comp} \quad (23)$$
This new type of foot improves performance of the robot during locomotion and eliminates the disturbance and the vibrations due to shocks at the level of the foot actuator, which in turn improves the control of the system. Consequently, it is indispensable to provide the heel with a deformable rubber cover capable to absorb the impact energy.

![Deformable and non-deformable heels 3D-Model](image1)

**Fig. 8. Deformable and non-deformable heels 3D-Model**

![Stored potential and kinetic energy with and without deformable heel](image2)

**Fig. 9. Stored potential and kinetic energy with and without deformable heel**

### VII. HYDROiD Foot Mechanical Design

The current design of the HYDROiD foot is made of aluminum using subtracting manufacturing. It is an active foot and it has a total mass of 0.95 kg. Because it has no deformable heel, the impact still exists which worsens the normal contact force [20]. Fig10 shows the design of the actual foot.

The new design of the HYDROiD foot consist of 3 main parts: the heel, the mid-part and the toes. The mid-part is developed according to the results obtained in the optimization process. It has a length of 260 mm, a width of 0.1 mm and a thickness of 15 mm. It is 3D-printed from sandwich composite materials as has been specified. In the other hand, a 3D-printed part from a rubber-like material of 6 mm thickness covers the foot, with 2 MPa tensile strength and 76 shore A hardness, which would be capable to absorb 25% of the induced energy during impact. Finally, the toe is an active one with a rotational joint, which is important to improve the contact force of the foot with the ground.

![CAD view of the current HYDROiD foot](image3)

**Fig. 10. CAD view of the current HYDROiD foot.**

The new HYDROiD foot has many positive outcomes over other robots feet. First, it reduces the energy consumption due to its capability of absorbing heel shocks. Moreover, it has a lightweight (about 460 g) in relative to other similar sized feet which improves its performance during locomotion. Finally, it has better natural frequency and lower time response.

![Design of the new HYDROiD robot foot](image4)

**Fig. 11. Design of the new HYDROiD robot foot.**

### VIII. Conclusion

In this paper, a new optimized design of HYDROiD robot is discussed, which presents a solution for the impacts during walking. A 3D-model is developed using the sandwich material theory, with CFC composite as a skin and nylon as a core. Meanwhile, the sandwich parameters design are optimized using genetic algorithm to get the optimum weight and dimensions. In the other hand, a finite element analysis is carried on the model to deduce its static and dynamic response, to calculate the stress in the sandwich composite and the strain in the structure. Once the model is verified, a study is carried out to insert a deformable heel in the design from rubber material capable to absorb 25% of the induced kinetic energy, during heel impacts. Finally, the foot design is performed and compared with the current design.
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