International Journal of Industrial Electronics and Electrical Engineering, ISSN(p): 2347-6982, ISSN(e): 2349-204X
Volume-9, Issue-3, Mar.-2021, http://ijieee.org.in

MASS COMPLIANCE OF A NOVEL CURVILINEAR-JAW ROBOTIC GRIPPER WITH OPTIMALITY CRITERIA USING TOPOLOGY OPTIMIZATION

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Abstract - Currently, the robotic grippers are gaining admiration with numerous design modulations in its jaws. These grippers are used in all domains of industrial applications. The objective of the present work is to attain size minimization and mass compliance of an indigenously developed robotic gripper having two fingers that are broadly used in industrial robots. Thisnovel contigutive robotic gripper is developed for direct adhesion contact in order to meet the technical challenges of force closure of the grasp. The motto here is to chop off undesirable mass of the prototype gripper keeping the strength unchanged. The material retention percentage is defined for the prototype gripper using customized topology optimization so as to improve its overall envelope.

Keywords - Topology, Optimization, Compliance, Mass, Design, Robotic Gripper, Articulated Jaw

I. INTRODUCTION

Design modulation and customization of robotic grippers are gaining popularity in global perspective due to its effectiveness in variety of end-applications. However, in many of the new designs prototyping poses considerable challenge because of the external envelope of the gripper and its self-weight. The objective of the present research is to reduce the tare-weight of a novel curvilinear-jaw robotic gripper keeping the strength unaffected by imbibing topology optimization niche. More weight means additional cost of manufacturing for no motive. Thus, size minimization and mass compliance of a novel robotic jaw gripper are the two goals of this work.

Topology optimization method permits users to attain ensemble specifications of robotic systems where supports and loads are positioned a-priori. Under such a situation, designer can pin-point the best shape / contour of the very robotic component.This absolute design freedom makes topology optimization a powerful design tool in many areas, including robotic systems.

Enhancing features of parts through topology optimization, deprived of applying manufacturing constraints, results in organic design. This is because the material will self-define the through-path from the load to the restraint, ensuring the most effective shape mathematically. The present study describes the syntax of the customized topology optimization routine as well as use of optimization module of commercially available Finite Element Analysis (FEA) software, with specific reference to the prototype design of the robotic jaw gripper. The solver optimizes for maximum stiffness, deformation, Eigen frequencies and many other parameters. This has been accomplished by defining a design space from which the solver can eradicate material until the most optimal shape is realized.

The overall external dimensions of our prototype gripper are 145 mm x 54 mm x 42 mm, which signals the small-scale of the envelope that we are dealing with. The designed gripper has a payload capacity of 1.4 kg (approx.) and being a contigutive-typegripper, it can pick up objects that are cylindrical and spherical in nature more effectively. In fact, the two important aspects of robotic grasp, namely, ‘form closure’ and ‘force closure’ have been implemented in the customized design of the jaws of our gripper. Since we have addedcomplementary design metrics of contiguity, the ‘form closure’ of the final grasp has attained superior realization.

As part of fundamental research, topology optimization of continuous linear elastic two-dimensional structures was attempted using optimality criteria, wherein material was also selected as 2-D [1]. Fracture-free stability of the final structure was ensured through structural nodal analysis under plane state of stress in this work. The incorporation of FEA in topology optimization problem has led to use of parametric design variables in order to achieve the objective function [2]. The optimum values of the design parameters were computed therein using topology algorithm. On the other hand, one of the most popular models of multi-objective genetic algorithm, namely, Constructive Solid Geometry-based Topology Optimization Method (CSG-TOM) was used for 2D topology optimization of compliant mechanisms and was extended for 3D cases as well [3]. The primary enthusiasm of the proposed approach was to develop and improve CSG-TOM to include different test problems that could be handled by the present popular techniques of topology optimization.

With the advent of various analytical approaches for topology optimization, researchers have concentrated on component-level optimization modules also. Tamta& Saxena [4] carried out the topology optimization work on three design-models, viz. i] hook, ii] corbel and iii] electric mast, by adopting customized program. It was reported that the optimality criteria approach used in this research converged very fast in comparison to other topology optimization methods. Similar to the previous work, four types of brackets were topologically optimized for loading conditions, assuming plane state of stress in each bracket [5]. The optimal shapes (in form of optimal distribution of material) of those brackets were determined for given loads and boundary conditions. The optimality criterion of volume reduction was found effective in this study because the initial rectangular structured design space was converged finally to truss like structure.

Chapman [6] described optimization of beam & cantilevered cross-section as well as plate topologies, by augmenting new methods for the efficient use of FEA in a genetic algorithm-based search. In fact, he proved that the motivation for using genetic algorithm to perform structural topology optimization is not an enhanced ability to find exact optima or an increase in computational speed, but advancement in simplicity and generality. The results for the topology optimization of beam structures, performed by the ANSYS® - based optimality criterion, were validated by Solid Isotropic Material with Penalization (SIMP) method [7]. SIMP is a novel scheme based on penalty calculation that was benchmarked with Bi-directional Evolutionary Structural Optimization (BESO) method in the treatise. As part of the system-level optimization, step by step procedure to use the optimization tool for weight optimization of a front suspension upper control arm of commercial heavy truck was reported by Anand &Misra [8]. Another such study was conducted on a rear lower control arm component where the structural requirements on that component involves pre-tension, plastic hardening material behavior and fatigue problems that were treated during the optimization process [9]. Author has shown that by including peak loads from the chassis rig cycle (robustness check) to the topology optimization task, it is possible to improve fatigue life, besides reduction of effective stress.Topology optimization of real-life systems often go with multiple objective functions. A multi-objective optimization approach was introduced by Kim [10], towards designing a special gripper for a wearable robot. A six-bar linkage incorporating a toggle mechanism was employed to reduce the overall weight of the gripper while maximizing the gripping force. An optimum design was selected from the Pareto front, which satisfies the requirements of both coupler path and drive torque.

Though topology optimization of design parameters of finite-sized robotic gripper systems has been well-researched hitherto, not much work has been reported for miniaturized grippers. With miniaturization of the hardware, topology optimization too needs orientation. In all practical cases, iterative process becomes the rule-base for such optimization modules. In our work, we have focused on three aspects of topology optimization, namely: design iteration, load balancing and harnessing of system compliance. These three paradigms remained as major open problems till date in the domain of topology optimization of size-restricted robotic gripper systems.

The paper is composed in six sections. An overview on the principles of structural optimization used for the prototype gripper is addressed in the next section. Section III describes the details of the topology optimization module, backed up by mathematical model. Section IVaddresses the real-time implementation of the developed topology optimization module. Results of the optimization routine are reported in section V. Finally, section VI concludes the paper.

II. STRUCTURAL OPTIMIZATION OF THE PROTOTYPE ROBOTIC GRIPPER: AN OVERVIEW

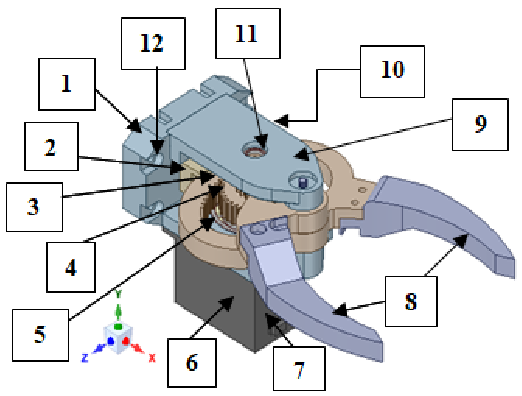
Mathematically, the lemma of structural optimization is based on the evaluation of the ‘objective function’ of the proposed design of the robotic gripper. The ‘objective function’ being multi-dimensional, we need to adhere to minimization attribute for getting the ‘topology optimized’ design values of the prototype robotic gripper. The analytical expression for the topology optimization is shown in eqn. (1) below:

$$subjected\ to \begin{cases} \boldsymbol{obj\_fn} \\ \qquad f(x, y(x)) \\ \begin{matrix} min \\ x \end{matrix} \begin{cases} i]\ design\ constraints\ on\ x \\ ii]\ state\ constraint\ on\ y(x) \\ iii]\ equilibrium\ constraint \end{cases} \\ \qquad \{iteration\} \end{cases} \quad \text{…..(1)}$$

Equation 1 reveals two important aspects of topology optimization process, namely: a] minimization of ‘design variables’ {x} and b] finite number of iterations that will be permitted. Fundamentally, the process of minimization of objective function (‘obj_fn’) is dependent upon the success of both of these two indices. Now, the aspect of minimization of design variables is branched into three domains, which are predominant in case of the prototype gripper system. The first and foremost among these domains is various design constraints on the design variable(s) of the robotic gripper system, such as tare weight of the gripper and its external envelope. The second aspect is state constraints on the state variable(s), 'y(x)' of the gripper system. This factor is instrumental in defining the boundary conditions for the structural and /or modal analysis of the robotic gripper system, besides taking care of the external stimulants, e.g. payload of the gripper or mountingpre-torque for the robotic assembly in the work-place. The third factor, namely, 'equilibrium constraint' deals with the intrinsic properties of the robotic gripper unit, such as material parameters and system compliance.

Topology optimization of mechanical systems is computationally expensive and a successful optimization routine, by and large, pre-defines the total number of design iterations that are permissible. In case of robotic systems, permissiblenumber of iterations gets piggy-backed with another critical paradigm, which is manufacturability. In our case, the prototype robotic gripper is poised to get constrained by the issue of manufacturability of certain small-sized components that overrules design optimization. Hence, number of iterations does play a significant role in the structural optimization of the prototype robotic gripper. We will be able to appreciate the usefulness of the iteration number in the subsequent portions of this section, dealing with the aspects of mechanical design of our gripper.

The ensemble of topology optimization, especially its iterations, largely depends upon the intrinsic features and complexity of manufacturing. Thus, it is important to scrutinize the spatial view of the prototype curvilinear-jaw robotic gripper to get an idea about the level of complexity (i.e. design & set variables) and extent of optimization (i.e. iteration number). Figure 1 illustrates the 3D isometric Computer Aided Design (CAD) view of our prototype robotic gripper with its major constituent parts indexed.



Index: **1**: Jaw Base; **2:** Linear Brass Bushing; **3:** Internal Gear Module; **4:** Hardened Internal Gears; **5:** External Gear Modules; **6:** Lower Plate; **7:** Servomotor; **8:** Curvilinear Jaws; **9:** Jaw-fixing Bolts; **10:** Upper Plate; **11:** Bearings; **12:** Location of Base-fixing Bolts

Fig. 1: 3D Isometric View of the Prototype Curvilinear-Jaw Robotic Gripper

As illustrated in fig. 1, the ensemble topology of the prototype gripper is comprised of 11 heterogeneous structural elements. The extent of optimization will ensure design variations of each of these 11 structural elements.

The optimization technique, customized for the prototype robotic gripper, involves importing the CAD model in the compatible format and performing the finite element analysis as well as some de-featuring of unwanted features. After interpreting the results so obtained, the objective function and constraints are defined, as required for the real-time run of the robotic gripper system. The core routine of topology optimization is performed then after. Once the topology optimization code (customized software) provides the optimized model after completing the finite number of iterations, the stress analysis and modal analysis are performed again. The final design model of the prototype robotic gripper is said to be ready if satisfactory results are accomplished at the termination of the optimization iterations. Else, the model has to be re-optimized to meet the required objectives. The overall flow chart of the topology optimization routine used in the present study is presented in fig. 2.

It may be stated that the flow chart of fig 2 is essentially generic and our topology optimization routine is equipped to handle design optimization of other robotic assemblies too. The fundamentals of the routine and lemma will remain unaltered, although the coding has been customized for our robotic gripper system.

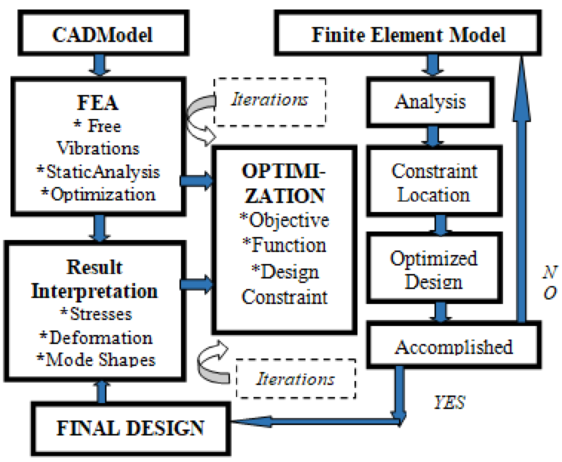


Fig. 2: The Flow Chart of the Topology Optimization Invoked

III. TOPOLOGY OPTIMIZATION OF THE PROTOTYPE GRIPPER

A. *Optimality Criteria*

Topology Optimization problem benchmarks a performance function, subjected to equilibrium equations and the constraints, piggy-backed with minimization of the material. Numerous methods, based on density function, were proposed under topology optimization, which resulted in models with supplementary design variables. While optimizing material layout within a given design space, Topology optimization (TO) attains the goal of maximizing the performance of the system for a given set of loads, boundary conditions and constraints. Thus, TO is different from shape optimization and size optimization as final design can mature to any shape within the design space, in lieu of performing FEA with predefined configurations. The functional objectives of topology optimization of the robotic gripper system in the present study are two-folds, viz.: a] to minimize compliance (and thereby maximize stiffness) and b] to maximize natural frequency of vibration. These two functional objectives lead to working objectives, namely, minimization of volume of the gripper ('shape') and also, its mass. Hence, the ensemble response constraints for the robotic gripper become mass, volume, global stress (Von-Mises), displacement and natural frequency of vibration.

It is worth mentioning here that in the present study, our TO module is not multi-objective in true sense. We are just segregating the ultimate 'working' objective into two functional objectives to begin with. However, these two functional objectives are inter-linked in physical parameterization. The multi-objective TO will appear in cases of compliant robotic gripper systems, which we are excluding for the time being. We can now propose the mathematical lemma of our TO-module, as an extension of eqn (1) that has been realized through gradient-based mathematical programming techniques. The lemma is as follows:

$$\begin{aligned} &\textit{Minimize: } \Phi(x), \\ &\textit{such that}, \ h(x) = 0 \\ &\textit{and}, \quad g(x) \leq 0 \end{aligned} \qquad \ldots\ldots(2)$$

where, 'x' is the design variable that can describe the competing design candidates; $\Phi(\xi)$ is the ultimate 'working 'objective function; h(x) is the equality constraint (boundary condition of FEA) and g(x) are the inequality constraints, which impose specific requirements on the design variable 'x'. It may be noted that in our case of prototype robotic gripper wewill have multiple g(x). We have customized $\Phi(\xi)$ with two-fold strictures, viz. ShapeOptimization and Mass Optimization. The ensemble optimization of the prototype gripper can be realized by combining the topology optimization (TO) module with static/modal analysis module. The constraint location, exclude regions, mass retaining percentage and other parameters are defined here, which thereafter results into improved shape of the prototype gripper. We have also used topology density tracker in order to visualize the evolution of shape during solution phase. As part of the TO module, the primary stress analysis results are plotted back for the new improved design using a novel design validation system.

The present study aims at reducing the compliance of the prototype robotic gripper system through the built-in optimization capability of commercially available package. The optimal material distribution is subject to outline of initial design space and constraints (loads and boundary conditions). Thus, compliance is equivalent to strain energy, which yields higher stiffness when minimized. Minimization of compliance means minimization of work done, which results into lesser amount of energy stored in the gripper system leading to a rigid ensemble gripper unit.

B. Mathematical Model of the Topology Optimization Used

Topology Optimization (TO) becomes active by providing a solution file of the erstwhile static analysis of the prototype robotic gripper. As part of TO, we need to functionalize its settings like: minimum number of iterations, convergence accuracy and the solver type. On completion of the static analysis, the maiden step in executing TO begins by comprehending the load design objectives. The later step is essentially the objectives of the optimization i.e. to minimize the bulkiness of the part while upholding stress and deflection within quantified values. We define specified domains (i.e. optimization region) in TO module where we need to select two paradigms, viz.: [i] the bodies that are to be optimized and [ii] the excluded region for the faces (i.e. bodies to remain unaffected). We have set the optimization type to 'density-based lattice optimization', which is nothing but simply reduction of mass of the robotic gripper system. We have kept the objective of TO as default, i.e. to minimize the compliance of the gripper ensemble, with respect to both static as well as modal analysis. Our customized TO module is hitherto attributed with the elimination of undesirable material from the gripper body but the final form rest on the initial density of mesh used for the FEA. Our niche objective functions are accessible to optimize the shape and size of the prototype robotic gripper system, wherein 20% material removal is done taking into consideration of ease of manufacturing.

In-line with the proposition of eqn. (2), we can extend the lemma of our objective function as:

$$\Phi_i(x) = \Phi_i\{\Gamma_{shape}, \Omega_{mass}\} = \Phi_i\{f(\alpha, \beta), \langle\rho\rangle\} \qquad \ldots\ldots(3)$$

where, i: iteration number of the TO-module; $\Phi_\iota(\xi)$: ultimate working objective function; Γ_{shape}: 'shape function' sub-set of the objective function; Ω_{mass}: 'mass function' sub-set of the objective function; f: functional form of the shape function; α: ensemble length of the prototype gripper system; β: ensemble breadth of the prototype gripper system;

<ρ>: density vector of the materials of manufacturing of the gripper sub-systems.

Equation (3) is the backbone of our development of the TO-module, which will lead to the following transcendental equation for the objective function:

$$\Phi_i(x)=\oint_V \Phi_i\left[\{f(u(\delta))\},\langle\rho\rangle\right]dV \qquad \text{........(4)}$$

where, V: volume fraction of the gripper system at the $i^{th.}$ iteration of the objective function; dV: infinitesimal volume of the FE-mesh under consideration at the $i^{th.}$ iteration; u(δ): generic length function of the gripper system at the $i^{th.}$ iteration. Naturally, the surface integral of eqn. (4) is deducible via FEA and the outcome will get subsumed in the customized code of the TO-module.

Let us now take an insight to the equality constraint, h(x) of eqn. (2). The TO-module of the prototype robotic gripper essentially aims at the internal & external force balance under run-time sequences of grasp. We have two external force functions of the gripper system, so far as the real-time grasp as well as its stability is concerned. In order to compensate the external force function, we have five internal force functions. The external force functions of the gripper system are: i] payload & ii] tare-weight. These force functions are uni-directional co-planar force vectors as per the standard kinematics of the prototype gripper. Besides, these forcing functions are static loads that act through a specific 'point' in the plane ('point-loading'). In contrary, the internal force functions of the gripper system are: i] reaction force at the fixed end of the gripper / attachment to the robot wrist; ii] force due to the torsion produced while grasp is in process; iii] gear-meshing force including backlash; iv] slip force at the jaws (during grasp) and v] contigutive force during grasp. Hence, we can formulate the expanded expression of h(x) as below:

$$h_i(x)=\left(W_p+\rho_{av}.V_{gripper}.g\right)-\left\{F_R+\frac{\tau_{gripper}}{L_{gripper}}+\eta.F_{gear/}+F_{slip}+\lambda.F_{grasp}\right\}_i=0 \qquad \text{........(5)}$$

where, $h_i(x)$: equality constraint of the TO at $i^{th.}$ iteration; i: iteration number; W_P: payload to be gripped; ρ_{av}: average density of the gripper; $V_{gripper}$: ensemble volume of the gripper; g: acceleration due to gravity; F_R: reaction force at the fixed end of the gripper / attachment to the robot wrist; $\tau_{gripper}$: torsion produced while grasp is in progress; $L_{gripper}$: length of the gripper in plane (horizontal distance between the jaw-tip & fixed-end of the gripper); F_{gear}: gear meshing force; F_{slip}: slip force at the jaws (during grasp); F_{grasp}: contigutive force during grasp; η, λ: appropriate factors for the respective force-components. It may be noted that the force expressions inside first bracket signify external force functions and those inside the second bracket are the internal force function components at the $i^{th.}$ iteration.

It is also obvious that external force functions will remain unaltered throughout the iterative process, but internal force components can vary from one iteration to the other.

Let us investigate the situation with the inequality constraints now. At the outset, we may take a note that g(x) is valid for all FE-segments, be it tetrahedral or hexahedral. In our case, g(x) is largely a function of material density and infinitesimal volumes of the FE-elements together. However, g(x) in our case is linear and not a joint-function. Mathematically, we can express these infinitesimal volumes and masses thereof as shown below:

$$g_v(\rho)_i=\sum_{j=1}^{j=n}\rho_j(\delta v)_j \qquad \text{....(6)}$$

where, $g_v/(\rho)_i$: infinitesimal mass of the topology optimized section of the gripper at $i^{th.}$ iteration; i: iteration number of the TO-module; ρ_j: density of the material of the $j^{th.}$ segment

of the topology optimized section of the gripper; δv_j : infinitesimal volume of the $j^{th.}$ segment of the topology optimized section of the gripper.

We can now extend the proposition of eqn. (6) to formulate the analytical paradigm of g(x) for the first two levels of iterations as under:

$$g(x)_{i=1}=\sum_{j=1}^{j=n1}\left[\oint_v \rho_j.dv_j\right]-\rho_{av}.V_0\le 0 \qquad \text{......(7a)}$$

$$g(x)_{i=2}=\sum_{j=1}^{j=n2}\left[\oint_v \rho_j.dv_j\right]-\sum_{j=1}^{j=n1}\left[\oint_v \rho_j.dv_j\right]\le 0 \qquad \text{...(7b)}$$

where, $g(x)_{i=1}$: inequality constraint of the TO-module at first level of iteration; $g(x)_{i=2}$: inequality constraint of the TO-module at second level of iteration; i: iteration number of the TO-module; j: number of FE-segments of the prototype gripper that are involved in the optimization process; n1: total number of FE-segments of the gripper that are involved in the first level of iteration; n2: total number of FE-segments of the gripper that are involved in the second level of iteration ρ_j : material density of the $j^{th.}$ FE-segment that is involved in the optimization process; dv_j : infinitesimal volume of the $j^{th.}$ FE-segment during de-featuring process that is involved in the TO-module; ρ_{av} :average value of the density of the ensemble gripper prior to de-featuring process; V_0 : volume of the gripper system prior to de-featuring as well as optimization process.

Based on the syntax of eqn. (7b), we can deduce the generalized form of the iterative method of evaluating g(x) as per the following lemma:

$$g(x)_{i=k}=\sum_{j=1}^{j=nk}\left[\oint_v \rho_j.dv_j\right]-\sum_{j=1}^{j=n(k-1)}\left[\oint_v \rho_j.dv_j\right]\le 0 \qquad \text{...(8)}$$

where, 'k' signifies the generalized iteration level of the TO-process. Accordingly, total number of FE-segments that are involved at the $k^{th.}$ level of iteration is 'nk' and that at the preceding iteration level is 'n(k-1)'. Rests of the symbols have same nomenclature, as detailed under eqns. (7a) & (7b). Thus, the numerical evaluation of g(x) is iterative and the subtleness of the iteration-levels signifies the accuracy of the TO-process as a whole. The iterative process for the evaluation of g(x) will continue till the last iteration and the mathematical condition for the closure of the iterative process will be denoted by the following lemma as necessary and sufficient condition:

$$g\,(x)_{i=i_{\max}} \Rightarrow \sum_{j=1}^{j=ni_{\max}} \left[\oint_v \rho_j .dv_j\right] \geq \sum_{j=1}^{j=n(i_{\max}-1)} \left[\oint_v \rho_j .dv_j\right] \quad .....(9)$$

It is to be noted that in all the previous formulations, i.e. eqns. (6) to (9), the legend, 'δv_j' or 'dv_j' (under integral) signifies *de-featured volume* of the particular FE-segment. This is very important proposition of our TO-module wherein each level of iteration is based on the successive de-featuring of the geometry / topology of the gripper system.

Let us now take a re-look at the physics behind the design of the prototype gripper via TO-route. We have deliberated that the topology optimization for the present case is equivalent to minimization of system compliance and maximization of natural frequency of vibration of the gripper system. We can expand the formulae of the system compliance and natural frequency of vibration for the gripper assembly as shown below:

$$C_s(s \prec k)_i = \left[\frac{\delta_k}{F_k}\right]_i^s = \left[\frac{\delta_k^{\ 2}}{W_k^v}\right]_i^s \quad ......(10)$$

$$\omega_s(s \prec k)_i = \left[\sqrt{\frac{\left(\dfrac{1}{C_s(s \prec k)}\right)}{m_s(s \prec k)}}\right]_i^s = \left[\sqrt{\frac{W_k^v}{m_s.\delta_k^2}}\right]_i^s \quad ....(11)$$

where, $C_s\,(s\neg k)_i$: compliance of the $k^{th.}$ FE-segment at $i^{th.}$ level of iteration of the TO-module; $\omega_s\,(s\neg k)_i$: natural frequency of vibration of the $k^{th.}$ FE-segment at $i^{th.}$ level of iteration of the TO-module; s: segment of the FEA (comprising hexahedral and/or tetrahedral elements); δ_k : deflection of the $k^{th.}$ FE-segment at $i^{th.}$ level of iteration; F_k : Force of interaction pertaining to the $k^{th.}$ FE-segment at $i^{th.}$ level of iteration; $m_s(s\neg k)_i$: mass of the $k^{th.}$ FE-segment at $i^{th.}$ level of iteration; W_k^v : virtual work done by the $k^{th.}$ FE-segment at $i^{th.}$ level of iteration.

Now, by the fundamental principle of our TO-module, i.e. minimization of compliance or maximization of natural frequency, we will get the analogy of maximization of 'W_k^v'. We will take a look at the physical insight of this virtual work at a specific iteration-level, with reference to the formulation of 'h(x)' in eqn. (5). We can demarcate two types of forcing functions that are analogous to 'internal forcing functions' and 'external forcing functions' of eqn. (5). These forcing functions are now grouped on the basis of the 'action' on the FE-segments. It may be noted that all constituents of internal forcing functions are essentially distributed over the FE-segments and each one of those forcing functions is responsible for a finite amount of 'displacement' of the FE-segments, whatever infinitesimal the magnitude becomes. These distributive forcing functions are co-planar vectors and hence displacements generated thereof are also vectors in the same plane. Thus, the virtual work done by the FE-segments due to the actuation of these distributive forcing functions is additive. On the other hand, the effect of the external forcing functions on the FE-segments is tractive by nature that can be computed as force per unit area of the FE-segments.

IV. REAL-TIME IMPLEMENTATION OF THE DEVELOPED TOPOLOGY OPTIMIZATION MODULE

We have incorporated 'density tracker' in TO-outcome that can be used to envisage the optimization in real-time. The outcome of the customized 'density tracker' is in the form of STL file, which can be exported for CAD operation and validation. By virtue of 'density tracker', the STL file and CAD model are transferred to the validation system of the TO-module. Editing operations are then performed on the model and finally the same is converted to solid model from the erstwhile STL format. Then after, we open the so-called TO-generated 'geometry' of the prototype gripper in FE-pre-processor and performs alteration and essential modification. The optimized model of the robotic gripper, so generated, was then allowed to be meshed again for analysis (with load & boundary conditions being applied afresh). The 'optimized' model was solved again and it was validated so as to ensure that the design objective has been met. Nonetheless, we needed to overcome the issue of identifying local maxima and local minima in the TO-optimized design for manufacturing. We have used Lagrange Multiplier for this in a customized fashion. The method is very useful as it allows the optimization to be solved without explicit parameterization in terms of the constraints. In our case, the load constraints are very vital (refer eqn. 5) and the subtleness of the forcing function can alter the result. Hence, we have used Lagrange Multiplier technique in order to have the gradients of local minima linear. Based on the linearization of the gradient of the load constraint, we have used Lagrange Multiplier method for the volume constraint as well. The local minima for the volume constraint have become effective in restricting the ensemble mass of the prototype gripper system to a significant extent.

In order to cross-check the validity, the solution of original and optimized model was equated. On the flip side, multiple iterations were performed to make the solution converge. Once this iterative solution process is done, we launched the design validation system to accomplish the final validation. Both un-optimized and optimized model were moved to the design validation system. This was carried out essentially to edit the optimized geometry, as the optimization tool has eradicated excess material from the model. As a final cosmetic makeover to the TO-outcome of the prototype robotic gripper, we performed minor editing to manipulate or smoothen the geometry accordingly.

V. RESULTS OF TOPOLOGY OPTIMIZATION

The topology optimization has helped to reduce the overall weight the gripper and it has improved overall mechanical design as well. Table 1 presents the final dimensions and material for manufacturing of the various constituents of the topology optimized prototype robotic gripper system.

Sl. No.	Description of the Component	External Dimension (mm)	Material for Manufacturing
1	Jaw Base	70 x 42 x 52	Aluminium
2	Linear Brass Bushing	20 x 12 x 10	Brass
3	Internal Gear Module	Diameter 25 x 8 thickness	Steel
4	Hardened Internal Gear	65 x 62 x 8	Steel
5	External Gear Module	36 x 36 x 8	Aluminium
6	Curvilinear jaw	70 x 28x 14	Aluminium
7	Upper Plate	60 x 30 x 8	Aluminium

Table 1: Final External Dimensions and Material for Manufacturing of the Components of the Topology Optimized Prototype Robotic Gripper

Let us now take a closer look over different components of the prototype gripper system, post topology optimization.Figure 3(a) shows the CAD model of the optimized jaw and fig. 3(b) shows the same for the original jaw. TO-iterations have incorporated number of groves and slots in the jaws so as to make the jaw light-weighed. Special attention has been paid for this iterative design of the grooves and slots of the jaws so as to machine those with ease. TO-module has made the jaw design perfect by reducing the weight of the jaws.

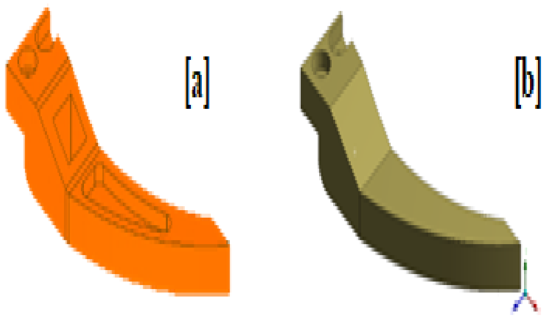


Fig. 3: Results of Topology Optimization of the Prototype Gripper via CAD Models (a) Optimized Jaw;(b) Original Jaw

All components made up of aluminum have been optimized not only for the design but also for manufacturing. Reduction of weight criteria for the upper plate has been fulfilled by providing more slots & recesses. However, gears have been left out in detailed optimization because of the limitations in manufacturing. Figures 4(a) and 4(b) illustrate the optimized and un-optimized CAD model of the external sector gear respectively. The curvilinear-shaped large recess of the optimized CAD may be referred, which is the outcome of multiple iterations on its design.

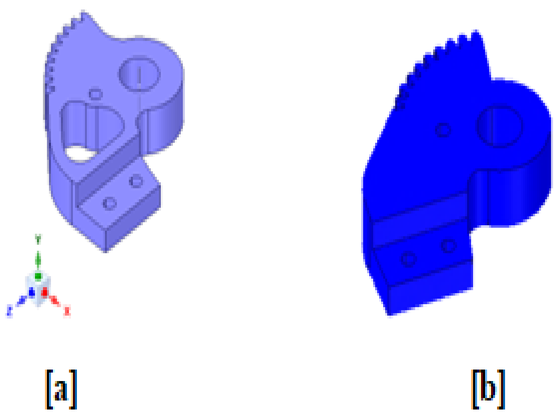


Fig. 4: Topology Optimization Result of the External Sector Gear of the Prototype Gripper: (a) Optimized; (b) Original

We may observe that most of the mass has been removed from the parts without affecting the functional requirements and load constraints. An assessment of the final tare weight of the gripper is made, as detailed in table 2. The mass of the ensemble gripper system is reduced by almost 20%. Due to customization of our iterative TO-module, manufacturing became easy as the grooves and slots were created in single setting of the machine tool. In fact, the design iterations for the grooves and slots in various components were created in such a manner so that those parts were not required to be moved for grooving or slotting separately along the length-wise direction of the gripper. This was a crucial judgment for the iteration in TO-module that resulted in the reduction of the manufacturing cost. The final optimized model of the prototype robotic gripper (post-iterations and design for manufacturing combined) is shown in fig 5.

Parts / Assembly	Weight
Optimized Jaw (Fig. 3a)	0.02828 kg
Un-optimized Jaw (Fig. 3b)	0.03686 kg
Optimized External Gear (Fig 4a)	0.01119 kg
Un-optimized External Gear (Fig 4a)	0.01379 kg
Un-optimized Gripper Assembly	0.26808 kg
Optimized Gripper Assembly	0.24276 kg

Table 2: Assessment of the Mass of the Optimized Gripper

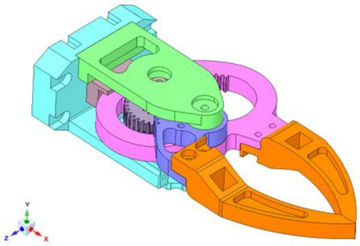


Fig. 5: Final Optimized Model of the Prototype Gripper

Figure 6 shows the photographic view of the curvilinear-jaw prototype 'test' robotic gripper in grasp action. The manufacturing of this 'test' gripper has been instrumental in various grasp analyses towards confirming the deployability of this novel gripper for material handling in industry.

Fig. 6: The Prototype Robotic 'Test' Gripper in Action

VI. CONCLUSIONS

Mass compliance and size attenuation of the prototype robotic gripper were achieved using our topology optimization module. Product aesthetics was improved by this novel methodology of topology optimization apart from saving of material and fabrication cost. The customized module of iterative topology optimization has resulted in design for manufacturing as well as physical realization of real-life hardware of a novel lightweight curvilinear-jaw robotic gripper. The successful prototyping of this curvilinear-jaw robotic gripper has been attributed to various real-life contigutive slip-free grasp of objects, both in stand-alone mode as well as integrated with robotic manipulator [for details, please refer to the following video-clips: (i) https://www.youtube.com/watch?v=048N9Xqsseg; (ii) https://www.youtube.com/watch?v=29gz3_Im6lg; (iii) https://youtu.be/29gz3_Im6lg; (iv) https://www.youtube.com/watch?v=E5G_veak8tU].

REFERENCE

[1] Kishan Anand and AnadiMisra, "Topology Optimization and Structural Analysis of Continuous Linear Elastic Structures Using Optimality Criterion Approach in ANSYS", International Journal of Innovative Research in Science, Engineering and Technology, vol. 4, issue 6, June 2015, ISSN (Online): 2319-8753, pp. 2347-6710.

[2] Adrian Ghiorghe, "Optimization Design for the Structure of a RRR type Industrial Robot", U.P.B (UniversitateaPolitehnicaBucuresti). Science Bulletin, Series D, vol. 72, issue. 4, 2010, ISSN 1454-2358, pp. 121-128.

[3] Anmol Pandey, Rituparna Datta and Bishakh Bhattacharya, "Topology Optimization of Compliant Structures and Mechanisms Using Constructive Solid Geometry for 2-D and 3-D Applications", Springer-Verlag, Berlin Heidelberg, 2015.

[4] Sudhanshu Tamta and Rakesh Saxena, "Topological Optimization of Continuum Structures Using Optimality Criterion in ANSYS", International Research Journal of Engineering and Technology (IRJET), e-ISSN: 2395 -0056, vol. 3, issue 7, July-2016, pp 1483-1488.

[5] Gunwant, D. and Misra, A,"Topology Optimization of Sheet Metal Brackets Using ANSYS", MIT International Journal of Mechanical Engineering, vol. 2, no. 2, Aug. 2012. pp 119-125.

[6] D. Chapman, "Structural Topology Optimization via the Genetic Algorithm", Thesis, M. S. Massachusetts Institute of Technology, U.S.A., 1994.

[7] KishanAnand andAnadiMisra, "Topology Optimization of Beam Supported at Ends and Elastic Plate with Central Elliptical Hole Using Optimality Criteria Approach in ANSYS", International Journal for Research In Emerging Science And Technology, vol.2, issue 5, May 2015, pp 241-247.

[8] Caner Demirdogen, Jim Ridge, Paul Pollock and Scott Anderson, "Weight Optimized Design of a Front Suspension Component for Commercial Heavy Trucks", Proceedings of the SAE Commercial Vehicle Engineering Congress and Exhibition Chicago, Illinois, U.S.A., October 26-28, 2004, pp 400-410.

[9] Robin Larsson, "Methodology for Topology and Shape Optimization: Application to a Rear Lower Control Arm", Master's Thesis in Applied Mechanics, Department of Applied Mechanics Chalmers University Of Technology,G¨oteborg, Sweden 2016.

[10] Kim, J. H. "Design and Optimization of a Robotic Gripper for the FEM Assembly Process of Vehicles", Mechanism and Machine Theory, Volume 129, ISSN: 0094-114X, 2018, pp 1-16.

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