Topological Optimization of a Polyfunctional End-Effector Used in Palletizing Applications

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***Abstract*—In the industrial engineering domain, the manufacturing flexible cells represent a system having the ability to adapt to the new requirements of the global market, with minimal costs. The specific features of such a manufacturing flexible cell are the following: The modularity of cell integrated systems; The possibility of long-term work without the intervention of human operators; Although the initial costs are high, these could be amortized over time. In the present paper the authors developed a flexible cell destined to palletizing operations for prismatic objects. Besides the design of constitutive elements, a topological optimization for the virtual prototype of the vacuumatic end effector has been performed in parallel.**

***Keywords*—topological optimization, articulated arm robots, industrial palletizing cell, robot working cycle**

I. Introduction

To conceive such a robotized palletizing cell, the study starts from an end effector prototype able to manipulate the objects which are to be arranged by volume in an orderly manner on the pallet. To exploit at maximum performance the robot integrated in the fabrication cell several criteria should be checked. A first criterion is linked to the mass the effector could manipulate in the most unfavorable work configuration. In the actual analysis, this situation is encountered when the characteristic point attached to the robot effector is situated at the furthest distance from the coordination system attached to the robot base. This point represents in fact the Tool Center Point (TCP). A second criterion is linked to the strength structure stiffness. In this context appropriate materials with minimal costs and relatively high rigidity should be selected. Usually, in industrial applications the Aluminum is frequently used, due to its elastic properties giving to the structure a suitable behavior for robotic applications. For the checking of the strength structure and the achievement of a topological optimization, a similar working cycle corresponding to an equivalent one obtained in off-line simulation.

II. Description of the Virtual Prototype of the End-Effector

For the design of an end-effector compatible with the robot flange it is necessary to identify the weight of the objects to be handled by the specified robot. This one should be selected in function of the two criteria presented in introduction. Since the presented application is based on the palletizing of prismatic objects the authors selected a robot with two closed kinematics chains permitting to keep the flange parallel to the ground during a working cycle.

Moura and Silva [1] focused on palletizing, an important constituent of handling functions since it connects production to transport. Fig. 1 presented the current research plan.

RESEARCH PLAN

Prototyping a robotic cell for palletizing operations	Topology optimization	Obtained results
1. Virtual end-effector prototyping; 2. CAD modeling of the constituent elements; -Belt Conveyors ; -Chain conveyors; -Technological equipment of the robot; -Mounting support for the ABB-industrial robot -Pallet dispencer; 3. Industrial cell layout design; 4. Defining the role that an industrial robot has in proposed automation cell; 5. Offline simulation proceed to obtain robot movement cyclograms;	1. The import of the robot movement cyclograms obtained from the ABB-robot programming software. 2. Use of Rigid body dynamics module for the evaluation of inertial forces acting on the analyzed element (end-effector wall); 3. Static analysis on the end-effector using inertial forces during the working cycle;	1. The general optimization criterion used is that of the density percentage; 2. For the initial structure a maximum displacement value of 0.4581 [mm] was obtained. The maximum value of von Mises equivalent stress was 6.9445 [MPa]. 3. For the initial structure a maximum displacement value of 0.4678 [mm] was obtained. The maximum value of von Mises equivalent stress was 7.3985 [MPa].

Conclusions

1. Rigid body dynamics (RBD) includes the study of displacement during operation considering all rigid components. The purpose of this analysis is to determine the velocities, accelerations, system energy, forces and moments in kinematic couples during the function.
2. Rigid body dynamics (RBD) is useful to the designer to identify critical moments in the operation of an assembly and to make specific checks at certain moments, without running a transient analysis, which takes a very long time. The RBD analysis takes into account the forces, moments of inertia, as well as the centers of gravity of the components.
3. Weight and material reduction: Topological optimization can help identify and eliminate unnecessary or redundant areas of a structure, resulting in a significant reduction in weight and the amount of material used. This can be particularly beneficial in the aerospace and automotive industries, where weight is a major concern for system efficiency and performance.
4. Improving structural performance: By eliminating unnecessary materials and redistributing loads optimally, topological optimization can significantly improve the performance of structures in terms of strength, stiffness and resistance to deformation. This can lead to a longer useful life of the products and a reduction in maintenance and repair costs.
5. Organic design and innovation: Topological optimization enables the generation of complex and organic shapes that might be difficult to conceive or achieve through traditional design and engineering methods. This approach can open new opportunities in terms of innovation in design and architecture, allowing the creation of more efficient and aesthetic structures.

Fig. 1. Research plan.

Fig. 2 depicted the ABB IRB660/180-3.15 with a payload of 180 kg, with a maximum range radius of 3.15 m. In the same figure, a part of the working cycle which the robot performs in the palletizing cycle is presented.

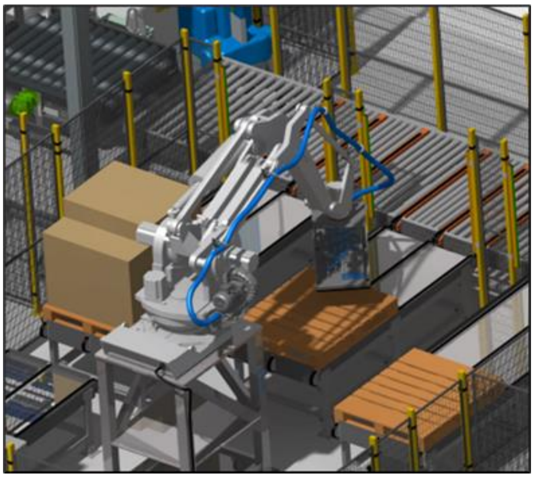


Fig. 2. ABB IRB660/180-3.15 palletizing robot.

The strength structure of the end-effector is made of Aluminum metal sheets connected through fixing elements having at the same time the role of structure stiffeners.

Fig. 3 depicted the overall model of the end-effector structure.

Fig. 3. Overall model of the structure.

To evaluate the total mass of the end-effector it is necessary to integrate the standardized vacuumatic components selected based on the mass of manipulated objects.

The final virtual prototype of the end effector is depicted in Fig. 4.

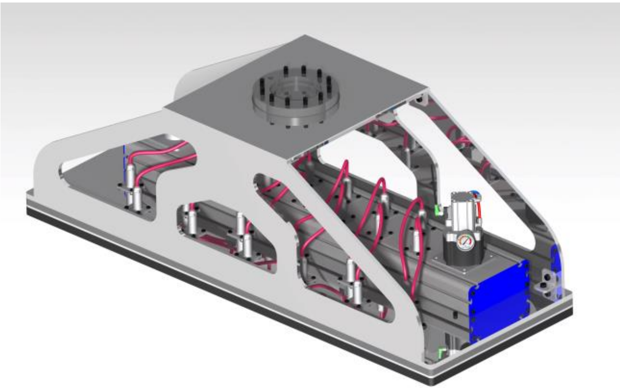


Fig. 4. Final assembly of the virtual prototype.

III. Design of the Palletizing Cell

In all palletizing flexible cells, there are transport systems as well as transfer systems of the raw materials or of packed objects to be placed on the pallets. The transfer systems are represented by different types of conveyors (belt, chain, and roller conveyors).

The transfer systems are represented by industrial robots. The final assembly of a virtual prototype is depicted in Fig. 5.

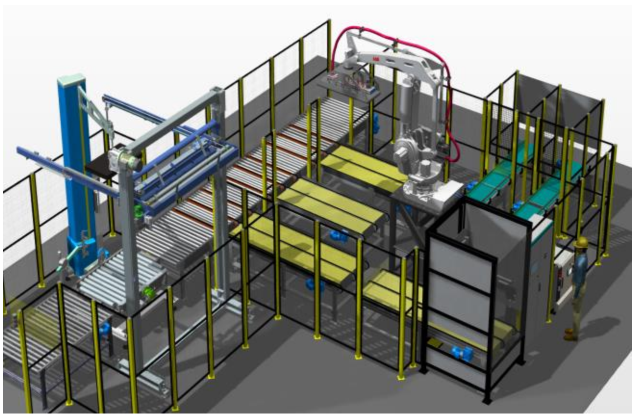


Fig. 5. Final assembly of the virtual prototype.

Fig. 6 described the palletizing cell assembled in Catia V5. The off-line programming and simulation are realized in ABB Robot Studio.

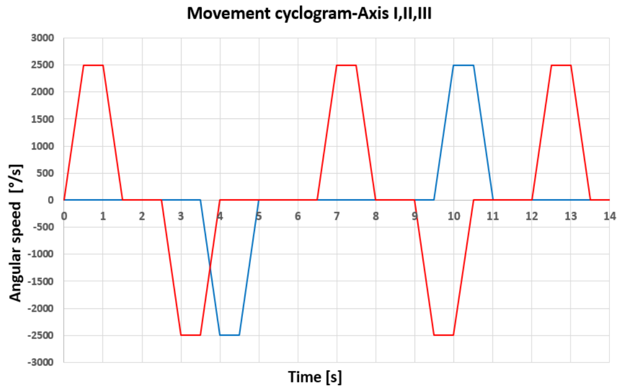


Fig. 6. Working cycle defined for the analysis in rigid body dynamics.

Through off-line simulation of the palletizing cell one can identify through the robot virtual controller the most unfavorable working cycle.

IV. Coupled Analysis

In mechanical design it is essential to carry out the verification stages using the finite element method because in this way certain prototype design or conception mistakes are avoided.

Since the manipulated load carried by the robot in the most unfavorable position is quite large (exceeding 130 kg) the aim of this paper is to reduce the mass of the end effector as much as possible so as not to endanger the safety in exploitation. The topology optimization concept was introduced as an innovative and powerful approach to structural design, many steps being taken in several directions and, consequently one can nowadays affirm that topology optimization is a mature discipline that has led to conceptual and practical improvements [2].

The mass reduction could be performed through topological optimization based on the working cycle defined in Fig. 6. The virtual prototype of the analyzed structure is imported in Ansys Workbench as STEP format. He *et al.* [3] dedicated to palletizing process, the end effector carrying load undergoes acceleration and deceleration process; therefore, inertia force should be considered in the static analysis. In Ref. [4], the stiffness optimization problem is investigated for structures with geometrical nonlinearities. In Ref. [5], a design domain with given load and support conditions is discretized into N finite elements. The objective was to find an optimal material distribution in the design domain that, subject to some given constraints, minimizes an objective function.

Over the last decade, substantial efforts of fundamental research have been devoted to the development of efficient and reliable procedures for solution to find the best possible topology or layout for given design objectives and constraints at a very early stage of the design process [6].

As is any analysis with finite elements, the imported geometry is simplified, since a great number of elements should be added on the interested domain such as the strength structure of the end effector.

After obtaining the reactions in the center of gravity attached to the element which will be topologically optimized, the authors realized a uniform meshing with elements whose dimensions have been globally controlled (6 mm). The meshing elements are first order elements (with four nodes on each element).

To obtain a realistic transfer of the efforts, a refined meshing was realized in the vicinity of the holes. In the performed analysis, the meshing elements are QUAD 4, with the following advantages: this element type decreases the number of elements and reduces the structural stiffness. For the evaluation of the meshing elements, the global quality criterion called "element quality" is used.

In Fig. 7, one can observe the majority presence of QUAD 4 meshing elements. According to the quality criterion, the quality of meshing elements tends to a value close to 1 (0.85). The perfect meshing elements have a mean value equal to 1.

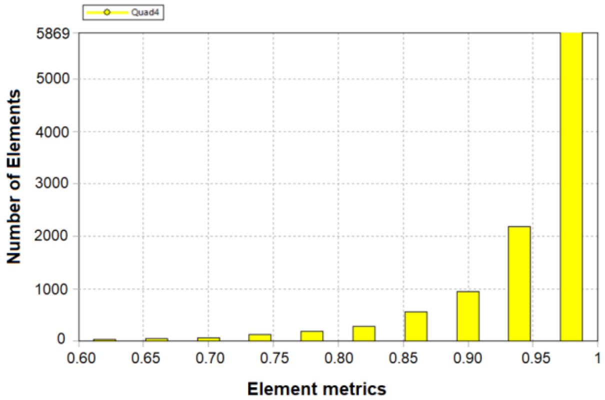


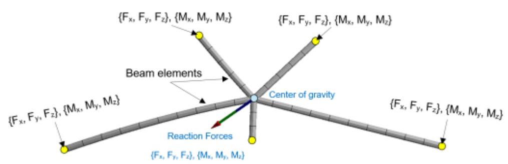
Fig. 7. Geometry meshing and elements quality criterion.

Another preprocessing step in the analysis is to define the support conditions, as well as the loadings acting on the analyzed element. In our case, to take over the degrees of freedom, the screw holes are used as a fixed support. To adequately define all the forces acting on the structure during the robot working cycle, the following problem is solved for a beam system (Fig. 8(a)).

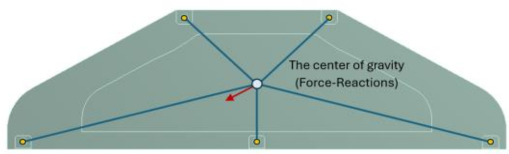
From dynamic analysis one can extract the forces at the level of the fixed supports. Knowing the forces in the fixed supports, the reactions in the center of gravity of the analyzed plate could be determined.

The output data from the dynamic analysis is used as input data for the static analysis.

From the dynamic analysis, the inertial and gravity forces that act on the structure during the movement of the robot have the following values: $F_x = -45.95$ N, $F_y = -30.2$ N, $F_z = -39.04$ N, whereas $M_x = -1{,}118 \cdot 105$ Nmm, $M_y = 1.76 \cdot 105$ Nmm, $M_z = 1231{,}7$ Nmm.



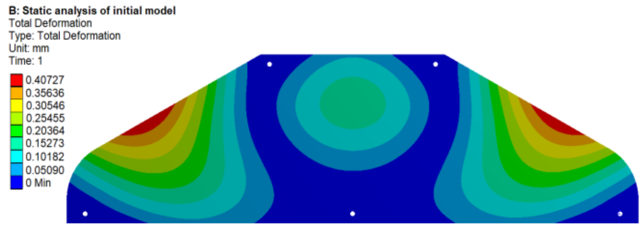
(a)



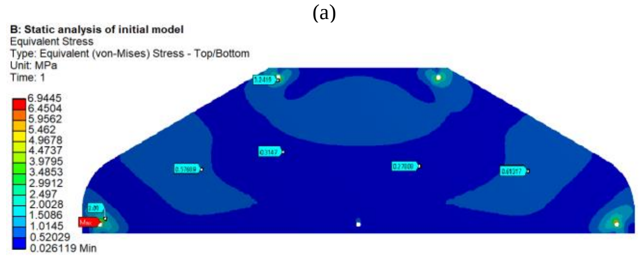
(b)

Fig. 8. Boundary conditions, (a) Concentration of equivalent forces in the center of gravity, (b) Model of analysis of the reaction forces in the center of gravity.

The output data from the dynamic analysis is used as input data for the static analysis. By establishing the support conditions and applying the previously evaluated forces and moments (Fig. 8(b)), data on the stress distribution according to the von Mises criterion are obtained, as well as the values of the structure displacements. The data obtained in the static analysis will be essential for the topological optimization of the geometry. In Fig. 9(a), a maximum displacement value of 0.45818 mm is shown, whereas in Fig. 9(b), a maximum von Mises stress of 6.94 MPa occurred.



(a)



(b)

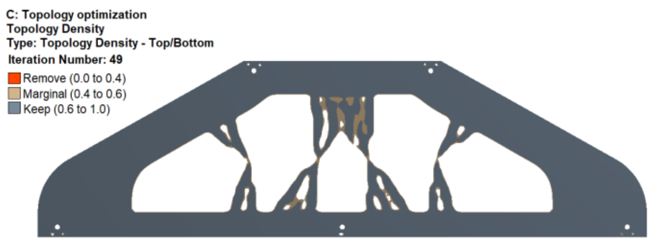
Fig. 9. Ansys results of initial element, (a) Structural displacements, (b) Equivalent von Mises stress distribution.

V. Results and Conclusion

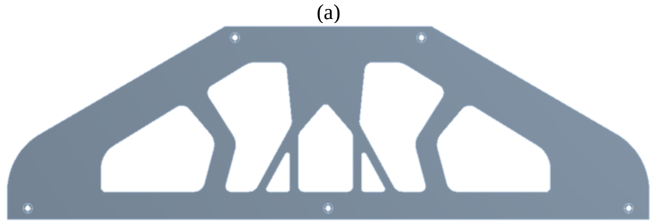
Fig. 10 showed the optimization performed by the ANSYS program solver. The main criterion considered during the optimization process was the mass criterion.

This topological optimization is achieved in the areas where the fixing elements do not occur. In these areas stress concentrators are present. Thus, the optimization will be performed in the areas where the equivalent von Mises stresses have low values (below 2 MPa) in this case.

This optimization is not uniform, the program removes in a very irregular way the elements corresponding to the criteria based on which the optimization is carried out.



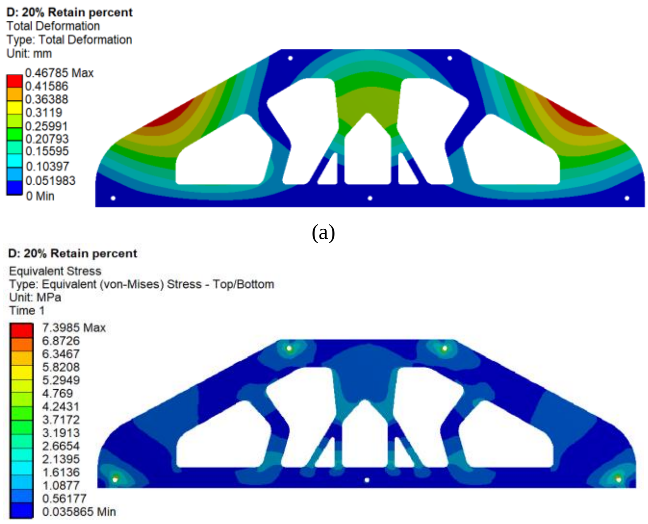
(a)



(b)

Fig. 10. Optimized elements, (a) ANSYS optimized structure with a percent of retain of 20%, (b) Optimized structure for manufacturing with the percent of retain of 20%.

After the topological optimization is carried out, the static analysis is resumed to compare the stresses and displacements in the optimized structure with those in the initial structure [4]. Fig. 11(a) depicted the total deformation of the optimized structure, whereas Fig. 11(b) plotted the von Mises stress distribution on the same structure.



(b)

Fig. 11. Ansys results, (a) Total deformation of the optimized structure, (b) Von Mises stress distribution on optimized structure.

Comparing the results from the static analysis of the initial structure with those obtained on the optimized structure, one. can observe a slight difference in the maximum equivalent stresses of 0.454 MPa under the conditions in which the mass of the structure was reduced by 3.2 kg. Considering that the end effector includes two structural elements of this type, the total mass will be reduced by 6.4 kg.

What should be emphasized is the fact that even the absolute displacement did not undergo substantial modifications. We could thus realize that the role of topological optimization is to remove material from areas that do not present stress concentrators without endangering the operational safety of the structure.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

M. Costea has performed the design of the automation cell and the definition of the movement cyclograms in order to determine the inertial forces acting on the structure. He realized the finite element modeling of the structural element. G. Jiga has performed the validation of the results obtained by the finite element method, he also took care of the creation of the article and its formulation. All authors had approved the final version.

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