Abstract- This paper presents a novel simulation tool for structural analysis of a delta robot using SOLID EDGE and ANSYS 11 that allows optimization of the robot’s mechanical structure as regards to materials, geometry and manufacture costs. To develop this simulation tool, a three-dimensional model of the delta robot was obtained through SOLID EDGE, and trajectory analysis was carried out, resulting in selection of critical trajectory between several possible movements. Finally, dynamic structural analysis of the robot was run on Flexible Dynamic ANSYS 11, taking into account the dynamic forces of inertia intervening in the model, as well as stress analysis along the selected critical trajectory.

I. INTRODUCTION

In general, the design process of an industrial robot is determined by specific operation features called for by application needs. Some operation specifications are: maximum work space, top speed of final effector, positioning accuracy, structure weight, useful life, materials used, and production costs. Once operation specifications are defined, the design process of an industrial robot falls in the following stages: kinematic optimization, trajectories analysis, dynamic optimization, and control system design. Kinematic optimization aims to select mechanical structure and length of each one of its links or segments. Trajectories analysis defines possible “critical trajectories”. It is in these trajectories that the robot’s mechanical structure is subject to maximum stress. Dynamic optimization uses dynamic structural analysis in defining the strains, stresses, and deformations that affect the structure, so as to optimize materials, geometry, and mass of each mechanical structure component, and to commercially select the robot’s actuators. Control system design takes into account the system’s dynamics, and it allows the effector to meet specific operation requirements in terms of precision, speed and movement smoothness [1].

The main objective of this document is the analysis of trajectories and dynamic optimization of a delta-type parallel robot, based on dynamic structural analysis [2]. This analysis enables optimization of the robot as to materials, geometry, mass, and selection of actuators. The result is more economic and efficient structures that will meet desired operation specifications.
The DELTA robot consists of a moving platform (2) connected to a fixed base (1) through three parallel kinematic chains (3-4). Each chain contains a rotational joint activated by actuators (5) in the base platform. The motion is transmitted to the mobile platform through parallelograms formed by links and spherical joints.

This project utilizes as the basis for the simulation model the dimensions and operation features of Delta IRB 340 FlexPicker robot (Fig. 3). This international-standard industrial robot is made by ABB.

A. Flexible Dynamic Simulation Model

The tool Flexible Dynamic de ANSYS 11.0 allows definition of the loads intervening in the dynamic analysis of the simulation model. In the case of the delta robot, the loads are the angular displacements of the three motors and the force of gravity.

The complete simulation model and the ANSYS 11.0 dynamic structure setting are shown in Fig. 4. Angular movements are shown by means of arrows turning around each motor and the force of gravity is represented by its direction.

III. TRAJECTORIES ANALYSIS

Trajectories analysis involves the study of different types of critical movements that the final effector of the delta robot is required to develop, and selection of critical trajectory through maximum stress analysis. This trajectory will serve as the basis for structural analysis of the delta robot and optimization of its mechanical structure.

Trajectories analysis was conducted taking into consideration the specifications of the maker of Delta IRB 340 FlexPicker robot.

- Workspace: (1130 mm) in diameter.
- Top speed: (10 m/s).

Trajectories for the delta robot were developed using a trajectory planner based on polynomials 616 [4], with a speed of (2 m/s).

A. Selection of Critical Trajectory

Three possible critical trajectories were taken for this study. They were loaded on Flexible Dynamic of ANSYS 11.0, in order to find the trajectory that will produce the maximum stress on the robot’s mechanical structure. For every movement analyzed, Fig. 5, 6, and 7, the workspace utilized corresponds to that of a cylinder with a 500 mm of diameter and 250 mm of height. Effector speed is (2 m/s).
Figures 8, 9 and 10 show the stress involved in each movement of the test.

As observable from results shown above, movement 1 brought about maximum stress of (18.39 Mpa), movement 2 brought about maximum stress of (16.73 Mpa) and in turn, movement 3 brought about maximum stress of (25.271 Mpa). Given the maximum level of movement 3, movement 3 is selected as the simulation model’s critical trajectory.

Figure 11 shows a sequence of the movements produced by the robot in the development of the critical trajectory selected. It shows the different positions adopted by the robot’s mechanical structure along the development of the trajectory.
IV. STRUCTURAL ANALYSIS AND OPTIMIZATION OF THE MECHANICAL STRUCTURE

This section presents the methodology followed in conducting the structural analysis of the Delta robot using a top speed of (10 m/s). This methodology uses the critical trajectory selected and the simulation model developed on ANSYS 11.0. Maximum stress and the safety factor are used as the evaluation criteria of the mechanical structure. The critical-piece selection process was initially carried out in the simulation model. This simplifies structural analysis and allows work on the piece that undergoes the most stress. Then, the construction material of the mechanical structure is selected. Finally, the mass of the piece undergoing the most stress, and made from previously selected material, is optimized.

A. Selection of Materials

In the design methodology proposed, selection of materials will be conducted by varying the construction material of the critical piece and by means of stress analysis, so as to find the type of material that most efficiently meets operation specifications. For this analysis, aluminum and structural steel are used as study materials.

Figures 12 and 13 show the mechanical characteristics of the arm made of aluminum and structural steel. It is observable that the arm made of aluminum has a mass of (4,5397 kg), whereas the arm made of steel has a mass of (12,865 kg).

B. Aluminum Vs. Structural Steel

Figures 12 and 13 show that geometry of the simulation model is the same for both materials, with a volume of 1.6389E6 mm³. However, masses vary due to difference in the densities of the materials.

Stress analysis on Flexible Dynamic Ansys 11.0 shows maximum stress of (42.643 Mpa) and (18.59 Mpa) for steel and aluminum arms, respectively, (Fig. 14). It is shown that for dynamic cases where the force of inertia is a factor, higher mass levels or higher mechanical (static) properties will constitute no guarantee of higher mechanical resistance in a dynamic analysis, the following theory: In a dynamic machine, adding weight (mass) to moving parts could have the opposite effect, reducing the safety of the machine, its permissible speed, and its payload capacity. This arises from the fact that part of the load that generates stress on moving parts is the consequence of the inertia laws foreseen in Newton’s second law, F=m.a. Given that acceleration of moving parts is determined by their kinematic design and their operation speed, adding mass to moving parts will increase the loads from inertia on those same parts or pieces, unless their kinematic acceleration is reduced by slowing down operation. Even though the mass added might increase resistance of the pieces, such benefit would be reduced or cancelled by resulting increases from the force of inertia “becoming the victims of their own mass”.

![Fig. 12. Mechanical characteristics of the arm made of aluminum](image1)

![Fig. 13. Mechanical characteristics of the arm made of structural steel](image2)

![Fig. 14. Graphs (Stress (Mpa) vs. Time(s)):](image3)
The previous analysis, and the fact that the movement speed considered for the analysis is (10 m/s), lead to the conclusion that the larger the mass in motion, the larger the par (pair), involving a larger, costlier motor, which makes aluminum the material with the best performance for the delta robot, and the one chosen for the project, as well as the basis for the following optimization step.

C. Optimization of Mass

Optimization of mass is finding the adequate mass for a piece, taking as the design evaluation criterion the safety factor for a specific number of work cycles.

Delta IRB 340 FlexPicker (ABB) robot was previously taken as the reference, and it can conduct an average 150 picks per minute, or 788400000 work cycles along 10 years. For the proposed simulation model, a 700- million work cycle in 10 years and a safety factor (SF) of 1 have been used.

1. Simulation models with different masses

Mass optimization is an iterative process. The iterative process starts out with a determined mass, and the maximum stress and safety factor are pinpointed. If the safety factor exceeds desired levels, mass is eliminated, and the safety factor is pinpointed once more. This process is repeated until the desired safety factor is reached.

Figure 15 shows the stress undergone by the aluminum arm when the critical trajectory is followed. In this first model, the total mass of the arm (4,5397 Kg.) is taken. Given that strain is too low and the safety factor exceeds 15, further iteration and reduction of mass were necessary. As an example, Figures 16 and 17 shown two iteration models where mass has been reduced. The total number of iteration models used was 8.

The relation between mass variation and safety factor, as well as mass variation and strain obtained in each step of the iterative process are shown in Figures 18 and 19. There is a minimal strain increase when the arm’s mass varies between (4.5 kg) and (1.7235 Kg). Below (1.7235 kg), a minimal mass reduction had a significant increase in strain. This agrees with the safety factor results, where models 1 through 5 represent a safety factor in excess of 15, and only ulterior models show significant safety factors. It can also be concluded that in order to optimize mass, it is necessary to reduce mass wherever the structure is over-dimensioned (zone of minimal strain), and add mass wherever it is necessary (zone of maximum strain).

For this case, in the first iteration it was found that the arms were over-dimensioned, given that the safety factor is > 15. This was the piece selected for the mass optimization iterative process. Theoretically, a machine that poses no risk for human life, like the Delta robot, is considered over-dimensioned if the safety factor exceeds 3. For the simulation model proposed, a safety factor = 1 has been selected.

As a conclusion, it can be stated that the model that met the design criteria (700 million cycles with a safety factor below 3) was model 8. For this model, the SF = 1.07.
D. Selection of Motors.

Figures 20 and 21 show the torques for the motors according to the initial model (without mass optimization), and according to the final model (with the minimal mass possible), respectively. These figures show the moments necessary in the motors to comply with the critical trajectory.

A maximum torque of (337 Nm) can be observed for the simulation model without optimization process, and a maximum torque of (165 Nm) for the optimized simulation model. These results show that the optimization methodology proposed for the robot obtains the torques necessary for each motor, guaranteeing compliance with the operation conditions initially thought up for the mechanical structure. Additionally, this tool allows commercial selection of the motors, showing on the implementation costs of the final prototype.

V. CONCLUSIONS

In this paper, a methodology for structural dynamic analysis of a parallel Delta robot using ANSYS 11 simulation software has been developed. The methodology allows optimization of the robot’s mechanical structure in terms of materials, geometry and manufacture costs. Therefore, this methodology allows selection of the best motor, with the lowest power consumption, the most efficiency in the weight-potency ratio, and thus lowers costs. Dynamic analysis allows visualization of the distribution of strain of each position along the entire trajectory, which makes this project novel and meaningful, because distribution of strain used to be possible for only one position of the whole trajectory.

Testing of the structure can be conducted under evaluation criteria that use maximum strain, useful life, safety factor, ease of construction, and service, among others. For the simulation model proposed in this project, the evaluation criterion used was the safety factor for a number of 700 million work cycles. Implementation costs were additionally taken into account.

Tasks proposed for the future include: extending structural analysis of serial-type and parallel robots of whatever degree of freedom, since the methodology developed for this delta robot is usable for whatever robot type.

VI. REFERENCES