Conceptual Design Framework for Developing a Cylindrical Robot Manipulator for Material Handling in Zimbabwean Small to Medium Enterprises: A Finite Element Approach

Rujeko Masike, Talon Garikayi, and Godfrey Tigere

***Abstract*—**In many small to medium engineering companies in Zimbabwe the need for material handling devices has become a necessity. There is lack of machinery that could increase production rate, improve product quality and reduce manufacturing costs while maintaining safe working environments. Material handling is a bottle neck during production due to lack of proper equipment and plant layout thus this research seeks to improve the material handling system through the conceptual design of a framework for the application of a cylindrical robot. There are many robots in the market that will improve material handling effectively. The purpose of this paper is to present a framework that has a structured approach for developing cylindrical robots based on finite element analysis methods that will be used by small and medium engineering enterprises (SMEs).This will enable the SMEs in developing nations to maintain competitive prices on products with minimal work accidents. The research explores the current literature and design approaches used to develop cylindrical robots. The paper also provides detailed methodologies to be used for structural analysis, component simulation and performance evaluation of the machine through finite element analysis (FEA). The framework provides suitable guidelines for designers to make appropriate decisions from the initial design stage to the commercialization of the design. The authors conclude that the preliminary framework be applied to formalize design steps for sim ilar material handling machinery implementation in the SME sector.

***Keywords*—**Cylindrical robot, Finite Element Analysis, Framework, Material handling

I. Introduction

MATERIAL handling is a bottle neck during production due to lack of proper equipment and plant layout [1]. It has been the most overlooked aspect in most process flow designs hence material handling in industries in developing nations is usually done by human beings. Areas which have always needed attention are the material handling of heavy loads in manufacturing set ups of most engineering companies, material handling in hazardous areas like high temperature operations, material handling in sensitive areas like pharmacology and the food industry etc.Hence this calls for the introduction of new machineries such as robots.

This paper presents a framework for the development of a cylindrical robot. As experienced currently, most robots are designed in standard sizes for specific demands. This means that for each production variation the designers have to develop a new machine. This procedure is considered costly and takes time. The new machine design concepts are mostly copied from similar type of designs and only one or two parameters are changed.

The creation of design concepts isbased on the knowledge that the designers have accumulated through years of design experience [2]. It is therefore the objective of this paper to propose a conceptual framework to assist engineers or designers from the concept selection stage to the final concept evaluation stage. To address this problem, AUTODESK INVENTOR® was used to carry out design validation and hence propose a framework which can be followed.

For the purposes of this paper, the material handling of heavy loads in a manufacturing set up of SME engineering companies was looked at. These loads include raw materials in the form of steel bars to be processed in precision machining workshops, injection or blow moulds in a plastic products manufacturing set up, serviced engines in an automotive workshop, moving finished hammer mills in a SME machinery assembly plant and various other engineering situations and environments. These heavy loads need to be picked from different points to other locations in a manufacturing set up. The picking and placing is to be done in an efficient way which facilitates minimisation of transportation time and in a safe way which greatly reduces accidents records in organisations.

A. Statement of the problem

The Material handling of heavy loads has been cited as the major contribution stage for slow production rate and increased occupational injuries. Currently most SMEs use manual human labour and or mechanical and manual

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hydraulic lifting mechanisms which are not safe to the user, require a high degree of human energy input, take more time to accomplish a task and has limited number of degrees of movement.

After having done numerous material handling projects, the researchers saw there was a need to come up with a conceptual design framework for easy implementation of robotic designs for material handling in the SMEs engineering sector.

II. Background

A. Concept development

Concept development is the process of generating ideas based on existing concepts; these concepts are generated through the memories constructed by the designer's interaction with the environment [3]. In this paper, a brief description of most important literature on the topic of robot arm implementation is presented.

Various design frameworks exist in the industry and academia in general. Therefore understanding the methods used on these frameworks is vital in combining their strengths for them to be more effective. From diverse literature sources, two different types of frameworks commonly used to develop machineries and machines components were identified, namely:

- Design recovery framework
- Agent framework

Different design techniques have been developed in the past, amongst them is a process called design recovery framework. This type of framework consists of three different levels namely: functional, structural and data resolution. Jill et al. [4] conducted a study on the design recovery framework for mechanical components. From the study a multi-level roadmap to all functional, structural and data information to be accumulated for different levels was achieved. Design recovery framework was developed to drive collaboration across the different design domains in order to improve the design reconstruction process. Cao et al.[5] conducted a study using a well know agent-based framework for guiding conceptual design of mechanical products. From the study a hybrid hierarchical agent architecture that is responsible for creating and improving design alternatives was proposed. The framework developed in this paper is a combination of all above techniques, combining their strengths and trying to reduce their weaknesses.

B. Material Handling

The researchers analyzed the various applications of robots in order to find out the most suitable robotic application that addresses the need defined in the topic. In current applications robots are mainly used in the following fields:-Material handling, Casting, Welding, Spray painting, Assembly, Machining, Inspection, Nuclear Fields, Rehabilitation, etc.Material handling robots are further classified into:

- Machine loading and unloading
- Material transfer.

This application makes use of the robot's capability to transport objects. By fitting the robot with an appropriate end-effector (e.g., gripper), the robot can grasp the object that needs to be moved. The robot may be mounted either stationary on the floor or on a transverse unit, enabling it to move from one workstation to another. The robot can also be ceiling mounted. The primary benefits of using robots for material handling are reduction of direct labor costs and removal of humans from tasks that may be hazardous, tedious, or fatiguing. Also, the use of robots for moving fragile objects results in less damage to parts during handling [6]. Robots that are used for material handling can interface with other material handling equipment such as containers, conveyors, guided vehicles, monorails, automated storage/retrieval systems, and carousels easily.

C. Modeling and Final Element Analysis

The limitations of the human mind are such that it cannot grasp the behavior of its complex surroundings and creations in one operation. Thus the process of subdividing all systems into their individual components or 'elements', whose behavior is readily understood, and then rebuilding the original system from such components to study its behavior is a natural way in which the engineer, the scientist, or even the economist proceeds [7]. The finite element method, or finite element analysis, is a computational technique used to obtain approximate solutions of boundary value problems in engineering. Boundary value problems are also called field problems. The field is the domain of interest and most often represents a physical structure i.e. the robot manipulator. The field variables were the dependent variables of interest governed by the differential equation. The boundary conditions were the specified values of the field variables (or related variables such as derivatives) on the boundaries of the field.

The main objective was to predict the complicated behavior of cylindrical robot joints. A 3D nonlinear finite element model for half of the entire connection was generated using the AUTODESK ® finite element software package. Welded joints were modeled to investigate the effect of dynamic loading on the load-displacement relationship and the moment rotation relationship under axial tensile loads, shear loads, and combined axial tensile loads plus shear loads. The main goal was to find a solution that approximates the exact solution through structural analysis of the manipulator. The manipulator structure was subdivided into smaller sections through meshing, in each interval proper simple functions were chosen to approximate the true function. The numerical result was an approximation to the exact solution. The accuracy of the numerical result depended largely on the number of sub-divisions and approximate function.

In a conventional finite element analysis, material properties, dimensions and applied loads are usually defined as deterministic quantities. This simplifying assumption however, is not true in practical applications. Using statistics in engineering problems enables us to consider the effects of the input variables dispersion on the output parameters in an analysis. This provides a powerful tool for better decision making for more reliable design [8]. In this paper, a probabilistic based design is presented which evaluates the sensitivity of a mechanical model to random input variables. The robot elements are analyzed for stress-strain behavior using commercially available finite element software. Young's modulus, applied pressure and dimensions are considered as random variables with Gaussian distribution and their effects on maximum stress and displacement is evaluated. Hence the concept that these are steps which can formulate the basis to be followed for optimizing new designs, verifying the fitness of existing facilities, predictive performance and evaluating new concepts. The steps are clearly elaborated in Fig 1 below.

II. Conceptual Framework For Implementation Of Robot Arm

Design geometry is a lot more complex, and the accuracy requirement is a lot higher. The designers need to understand the physical behaviors of a complex object (strength, heat transfer capability, fluid flow, etc.), to predict the performance and behavior of the design, to calculate the safety margin and to identify the weakness of the design accurately and to identify the optimal design with confidence

A. Model Design

The robot was designed based on existing robot models. A system comprising of different elements was designed and assembled. The system design was based on: reach arm design, load carrying platform design, welded joint design, column shaft design, column shaft key design, bearing selection, column bearing housing plates design, design of driving lead screw, design of rack and pinion for arm reach, radial motion gear design, pinion gear design,and motor selection.

Factors considered for the detailed design of machine components were:

i) Type of forces and stresses caused by the loads

ii) Statics, Kinematics and dynamics of the machine elements in operation

iii) Selection of materials

iv) Form and size of the parts

v) Frictional resistance and lubrication

vi) Ergonomic considerations

vii) Maintenance requirements

viii) Economic implications

The robot was made of mainly high grade high carbon steel (EN45). The robot reach arm is designed to grip pay loads of up to 1 500kg which can be as far as 1,5m away from the column and will rotate through 150^0. For the purpose of analysis the authors considered the reach arm design and analysis only, however the complete structure was analysed as an INVENTOR® model.

B. Finite Element Analysis

Experimental based testing was widely used as a means to analyze individual elements and the effects of steel strength under loading in mechanical engineering. In this case the use of FEA to study the manipulator elements was used. This section deals with determination of stresses in the robotic manipulator for material handling tested when subjected to 1 500kg load. A finite element program for analysis of meshed frames was developed and implemented in AUTODESK INVENTOR® environment. This developed program determines efficiently the combined state of stresses at any cross-section of a 3D frame. Crushing or cracking of the manipulator takes place when the strains lie outside the ultimate limit in the biaxial strain space. The static non-linear analysis was done to find out ultimate capacity, formation of first crack, initiation of diagonal crack and their distance from support.

C. Finite Element Analysis Design Framework

The modeling of the simulation started with geometric modeling of the elements of the robots to be analyzed. The elements were scaled depending on the requirement of the FEA software and accuracy needed for position control of the actual system. They were created in the part module and some were imported from other supporting software stored in formats such as ".ipt or .dwg," The entire model containing the part model data can also be imported into INVENTOR®. The robot manipulator model was created and modeled in INVENTOR® as a standard metric .ipt file as shown in Fig 2.

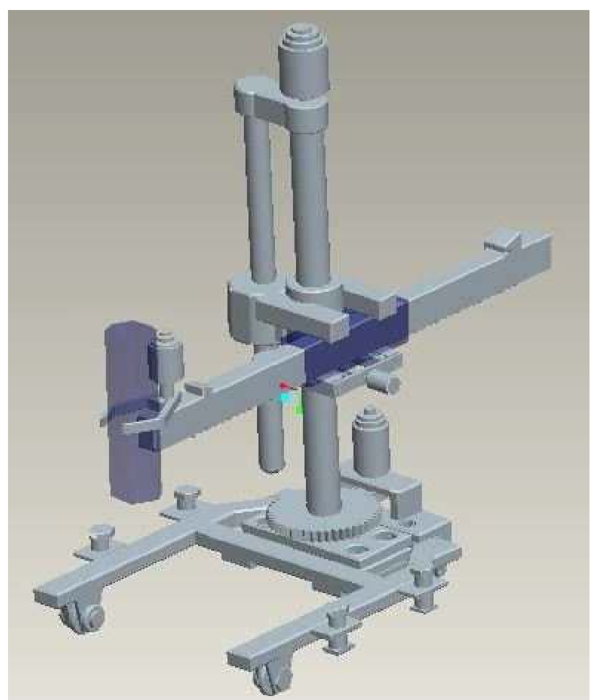

Fig. 2 The Robot Manipulator Model

Procedure for the FEA is as follows:

Preprocessing

- Define the geometric domain of the problem.
- Define the element type(s) to be used.
- Define the material properties of the elements.
- Define the geometric properties of the elements (length, area, and the like).

- Define the element connectivities (mesh the model).
- Define the physical constraints (boundary conditions).
- Define the loads.

Solution

- Compute the unknown values of the primary field variable(s)
- Computed values are then used by back substitution to compute additional, derived variables, such as reaction forces, element stresses, and heat flow.

Postprocessing

Postprocessor software contains sophisticated routines used for sorting, printing, and plotting selected results from a finite element solution.

D. Meshing Techniques

Generating meshes on parts was done in the mesh module. The results of the analysis depend on the quality of meshing. In the simulation performed in this research, the free meshing technique was used. Free meshing is unstructured, flexible and has a complex topology. Element shape plays a major role, it determines what shape the meshes are. Quad, tri, tetra and hexa are available mesh shapes in INVENTOR®. A conventional shell element was used to model the manipulator for simulation in this research. After creating meshes, a mesh part was created so that the same part could be used for different purposes.

The mesh part created acted as an independent part with the same mesh attributes of the original part.

i. Conventional shell model geometry was specified at the reference surface. Thickness was defined by section property structure body being modelled

ii. Full 3D continuum shell model was specified. Element thickness was defined by nodal geometry.

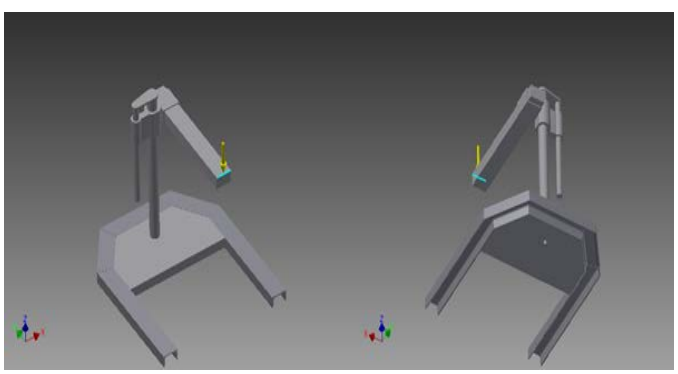

Fig. 3 The selected faces

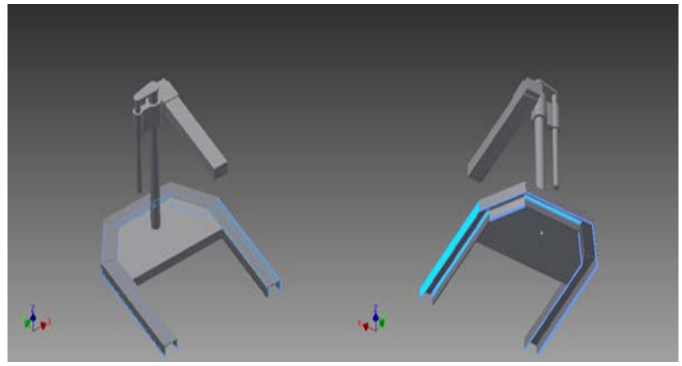

Fig. 4 The fixed constraints

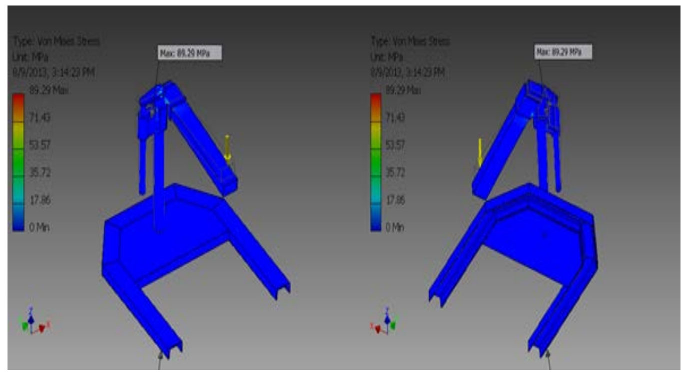

Fig. 5-1 Von Mises Stress

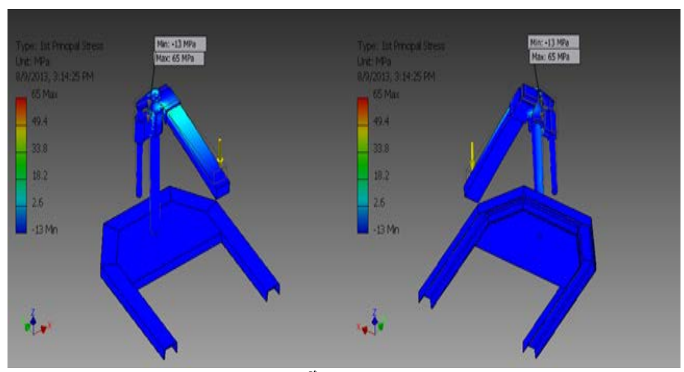

Fig. 5-2 1st Principal Stress

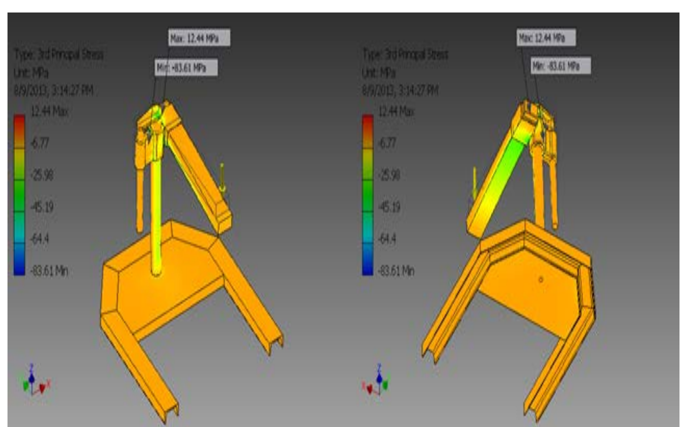

Fig. 5-3: 3rd Principal Stress

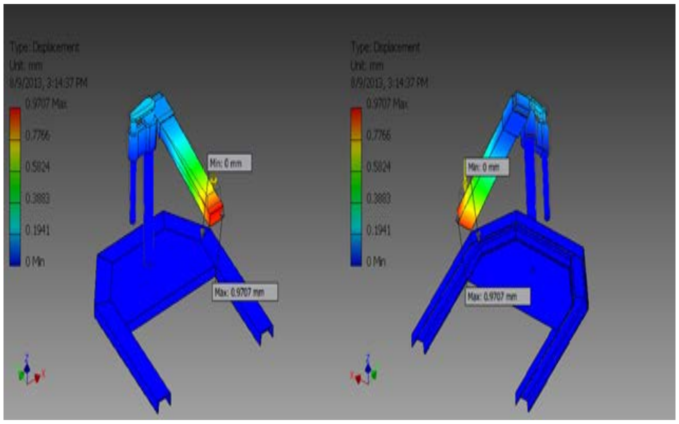

Fig. 6 Displacement

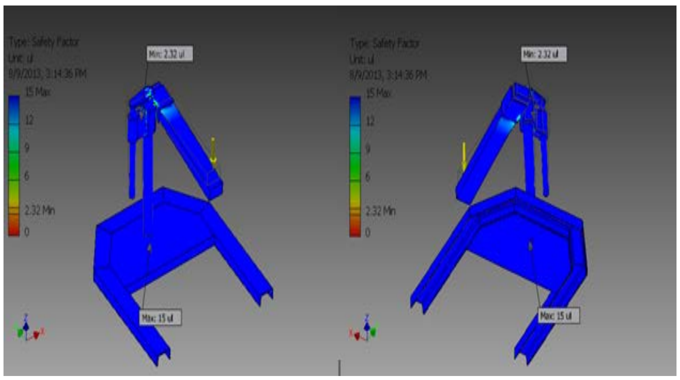

Fig. 7 Safety Factor

E. Material Modeling

Creation of material properties and assigning the material properties to the individual parts are discussed in this section. This governs the nature of the final results hence, understanding the material properties and inputting accurate values is of high importance. Properties assigned to the model were divided into four parts; general properties, elastic properties, plastic properties and creep properties. The general properties include density and other properties from user subroutines. For this paper, only density (1 g/cm3) was entered, and was constant for the entire model. Elastic properties can be defined as isotropic, orthotropic, anisotropic, and with engineering constants depending on the type of material. This was determined from the stress strain analysis in Fig 5-1 to 3.

F. Boundary Conditions

The boundary condition is one more important factor which governs the output of FEA. The load and boundary conditions were assigned in this section. The boundary conditions also depend on the step i.e. they can be modified in each step. In the case of dynamic explicit analysis, the amplitude must be predefined in assigning displacement boundary conditions. In an analysis step, amplitude ramps the load and prevents impact loading. Simulation results were shown in Table 1.

TABLE I
SIMULATION RESULT SUMMARY

Name	Minimum	Maximum
Volume	12576100 mm^3	
Mass	98.848 kg	
Von Mises Stress	0.00000000756952 MPa	89.2913 MPa
1st Principal Stress	-12.9988 MPa	65.0044 MPa
3rd Principal Stress	-83.6132 MPa	12.4372 MPa
Displacement	0 mm	0.970692 mm
Safety Factor	2.31826 ul	15 ul
Stress XX	-21.1448 MPa	18.1428 MPa
Stress XY	-24.3165 MPa	28.6235 MPa
Stress XZ	-22.7892 MPa	27.9695 MPa
Stress YY	-71.5556 MPa	45.9851 MPa
Stress YZ	-21.3555 MPa	45.0154 MPa
Stress ZZ	-45.607 MPa	48.0634 MPa
X Displacement	-0.000284784 mm	0.044681 mm
Y Displacement	-0.346489 mm	0.000545671 mm
Z Displacement	-0.915094 mm	0.0829024 mm
Equivalent Strain	0.0000000000000292646 ul	0.000345597 ul
1st Principal Strain	-0.0000018386 ul	0.000306384 ul
3rd Principal Strain	-0.000360294 ul	0.00000439612 ul

III. RECOMMENDATIONS AND CONCLUSION

In spite of the great power of FEA, the disadvantages of computer solutions must be kept in mind when using this and similar methods: they do not necessarily reveal how the stresses are influenced by important problem variables such as materials properties and geometrical features, and errors in input data can produce wildly incorrect results that may be overlooked by the analyst. By means of the finite element analysis software AUTODESK INVENTOR®, the three dimensional finite element mechanical model was established. The design of a robot for material handling was presented. The robot manipulator was tested for loads up to 1500kgs and was capable of achieving the desired goal. The robot model was analyzed using INVENTOR® so as to determine stress and strain values to aid during material selection and sizing of the structure. To a greater extent the prototype developed was capable performing all intended tasks thus achieving the set objectives. However challenges had been on the interfacing between the robot and the hand held Human Machine Interface (HMI) for the operator. To resolve the challenge the researchers recommended the use of a wireless HMI for further optimization of the design.

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