Design of Electro-Hydraulic Circuits of Tri-adjustable Automated Heavy-Duty Industrial Handling System

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Abstract

Materials handling is one of the most essential aspects within manufacturing processes and/or industries. Transportation equipment used in manufacturing industries varies from pallet jack to forklift trucks and/or cranes. Materials handling equipment are mechanical equipment used for the movement, storage, control and protection of materials, goods and products throughout the process of manufacturing, distribution, consumption and disposal. The influence of global economy has led to changes in the conventional approaches for manufacturing companies. In this case, manufacturing companies in South Africa and globally have taken into consideration several essential characteristics such as real-time reaction to changes, quick and quality response in sustaining and satisfying customer requests and/or needs, in both hardware equipment and software modules by which the production processes are optimized for next generation manufacturing systems. In two previous papers we outlined the design of a heavy-duty handling system and its hydraulic lifting mechanism based on Industry 4.0 principles. Electro-hydraulic circuit modelling as well material selection for electro-hydraulic operation of the new designed system arepresented herein.

Keywords: Material Handling System, Industry, Electro-hydraulics, Relay, Automation, Design, heavy duty handling systems.

1. Introduction

Electro-hydraulic circuit consists of different components such as electric motor which converts electric energy into mechanical energy, the pump which converts mechanical energy into hydraulic energy and the actuator convert back hydraulic energy into mechanical energy. Control elements like valves are used which controls the fluid in the circuit such as direction control valves, flow control valves, solenoid valves & pressure relief valves, etc, see Figure 1 and Table 1.

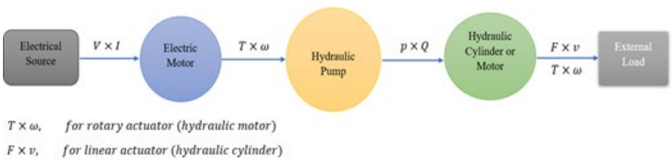

Figure 1: Tri-adjustable Automated Heavy-Duty Handling System [6].

Figure 1: Various energy conversions in hydraulics.

Nomenclature

$\boldsymbol{p} \times \boldsymbol{Q}$	Hydraulic pump power
$\boldsymbol{V} \times \boldsymbol{I}$	Electric power
$\boldsymbol{T} \times \boldsymbol{\omega}$	Electric/hydraulic Motor power
$F \times v$	Linear actuation power

1.1. Tri-adjustable Automated Heavy Duty Handling System Design

The system is designed using Autodesk Inventor as shown in Figure 2 [3, 5]. In this design, the dimensions and spaces of the equipment have been established by Mafokwane et al (2019) and Mafokwane (2021). The spreader beam is placed 103.9 mm away from the back and front frame to prevent the spreader beam from damaging the frame while lifting and lowering loads. The spreader beam is designed to be 3 m above from the ground. It is so important to maintain the specified distance for the spreader beam to have enough space while moving.

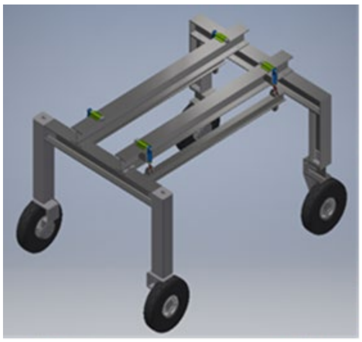

Figure 2: Tri-adjustable Automated Heavy-Duty Handling System [3, 5].

1.2. Conceptual Design of Electro-Hydraulic Circuits of Tri-adjustable Automated Heavy-Duty Industrial Handling System.

Referring to Figures 3 and 4, the system consists of a table like structure made up of bolt connected 305×305×158 mm Standard Parallel Flange H-section steel beams to form a strong frame. The standard H-section steel was chosen for its high UTS (Ultimate Tensile Stress) so that the frame can withstand critical heavy loads. The system also includes a hydraulic power circuit whereby four hydraulic wheel hubs are used for propelling the system, a hydraulic steering cylinder for steering front wheels and four heavy duty hydraulic lifting cylinder for lifting and lowering the load [4]. An electronic and electrical controls system is used for controlling the functionality of the system. The overall system is designed in such a way that it can facilitate ease of maintenance and has a safe loading and unloading which is done with a pushbutton pendant controller [4].

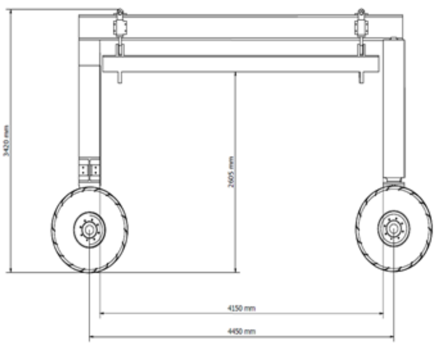

Figure 3: New System side view dimensions in (mm) [3, 5]

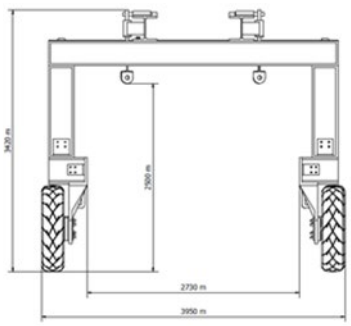

Figure 4: New System front view dimensions in (mm) [3, 5]

1.3. Industry 4.0 in the Field of Heavy-Duty Lifting Industries

The world has grown closer; new data architecture has bridged immense spaces. A global network has emerged in which people and their environment and machines can communicate continuously. This has led to a high standard of safety comfort and efficiency and has changed society in people's daily lives. Most of the work processes are coordinated by data streams. The entire lifecycle of a product is shaped by automated and highly networked processes [1]. The conception, production, delivery and service of products are digitally guided and share all their process information. People and intelligent machines cooperate efficiently. Real and digitalized processes have come together in one unit. The material handling system can communicate with each other and then assemble the goods. Therefore, it is significant to have an efficient and reliable material handling system at first so that it can be developed to be smart and automated to meet today's innovation and standardization and customer satisfaction [3, 4].

2. Methodology

The following steps are used in the development of the system:

- A CAD program (Autodesk Inventor Professional) was used to generate conceptual designs and technical drawings for the new system design. The software was used for analysis of static and dynamic stress of key components and frames.
- Vehicle dynamics equations and theories are used for population of projected motions, steering calculations and turning radius.
- Principles, laws and equations of thermodynamics and fluid mechanics were used for construction of hydraulic circuit and power pack of the new system.
- As the system is desired to be power driven by an electrical energy source, research & the study of digital electronics and electrical machines was done to formulate an electrical and electronic circuit for the distribution of electrical power and signals to solenoid valves, hydraulic pump, frequency drives and AC motor.
- For control and operation of the new system, a pushbutton tandem is used to control both the hydraulic cylinders (steering and lifting) and hydraulic wheel hub for moving the machine from point A to B.

3. Background of Electro - Hydraulic Systems

Hydraulics involves the use of hydraulic fluids to perform mechanical work. Hydraulics are electro-controlled by an electrical source, thus voltage supply then signals are generated through 24V and sent to control valves for directional control of hydraulic fluid. Mechanical work is necessary in order to carry out movements and generate forces. The function of hydraulic drives is to convert the energy stored in hydraulic fluid into motion [4].

3.1 Electro-hydraulic applications in Automation Industry

3.1.1 Stationary hydraulics:

- Production and assembly machines,
- Transfer lines,
- Lifting and conveying devices,
- Presses,
- FMCG machinery.

***3.1.2 Mobile Hydraulics**:*

- Construction machinery,
- Tippers, excavators, elevating platforms, Forklifts,
- Lifting and conveying devices (Material Handling systems),
- Agricultural machinery.

3.2 Selection Criteria for New Design System Components

3.2.1 Working media are:

- Electric current (electrics),
- Fluids (hydraulics),
- Combination of the above media.

3.2.2 Selection Criteria and System Properties

- Force,
- Storage ability,
- Type of movement (linear, swiveling, rotary),
- Speed,
- Service life,
- Reliability and precision,
- Energy costs,
- Operability.

3.3 Descriptions of Components for the New System Design

3.3.1 Frame structure is made up of Standard Steel Sections (I and/or H standard sections)

The new design structure presented in Figure 2, is made up of Beam-Beam (Web to Column and Column to Web) connected I & H Steel sections with fin connection consisting of length of plates to form a supporting member, to which the supported beam web is bolted to form a strong mechanism [6]. Beams are common members used to resist bending moments and shearing forces. Therefore, the force exerted by the systems. load application in Bending is resisted by flanges; shear is resisted by web as illustrated Figure 5 [5].

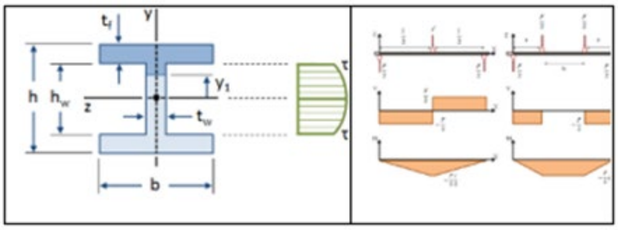

Figure 5: Shear and Bending stress illustration on system structure [2].

3.3.2 Hydraulic Motor

Hydraulic motors and semi rotary actuators drive (rotary drives) to generate rotary movements. The function of hydraulic drives is to convert the energy stored in hydraulic fluid into motion. In this paper Hydraulic Wheel Hubs are used to drive the overall structure of the new system design, figure 6.

Figure 6: Hydraulic motor [6].

3.3.3 Hydraulic Linear Cylinder

Cylinders (linear drives) are used for the generation of straight linear movements, thus enhancing the new design system to be able to lift and lower 30-ton load capacity. Cylinders (linear drives) also will also serve as steering system for the new design. The system will use four double acting cylinders for lifting the load through the support of spreader beam and another two double acting cylinders will be used for extension of the structure as the structure is adjustable. One double rod end hydraulic cylinder will be used for the steering mechanism of the system. Refer to Figure 7.

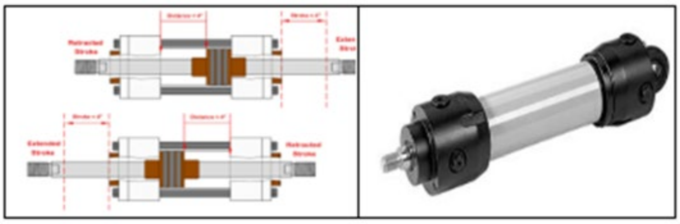

Figure 7: Hydraulic linear cylinder [6].

3.3.4 Hydraulic Power Pack

Hydraulic power pack is the hydraulic flow supplier to the system which is considered the power transmitter, Figure 8.

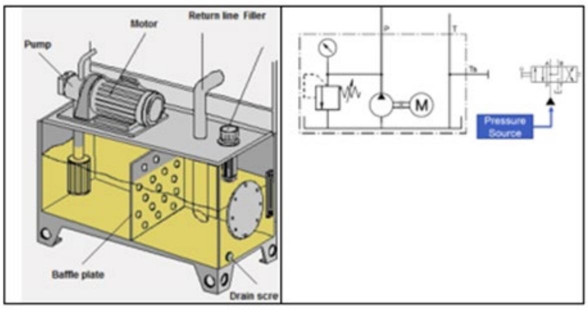

Figure 8: Hydraulic power pack diagram and circuit [6].

Components of Hydraulic Power Pack include:

- Drive Motor with Electrical Motor (Electrical Energy _ AC/DC),
- Pump,
- Reservoir,
- Filter,
- Pressure Relief Valve.

3.3.5 Accumulator

The accumulator is used in order to keep an even pressure in the system when the various valves open and close.

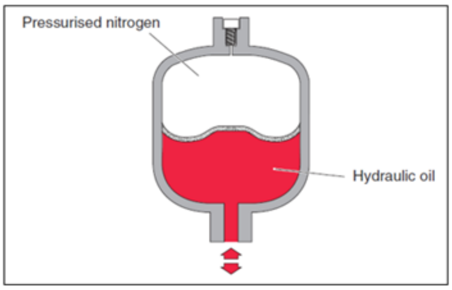

Figure 9: Accumulator Diagram [6].

When the hydraulic flow encounters resistance in a system, pressure is built up, Pressure Relief Valve (PRV) will then be opened, flow will be divided by PRV, flow to the circuit will be reduced, Figure 9.

3.4 Description of Electrical Components of the System

A relay is an electromagnetic switch operated by a relatively small electric current that can turn on or off a much larger electric current. The heart of a relay is an electromagnet (a coil of wire that becomes a temporary magnet when electricity flows through it), Figure 10.

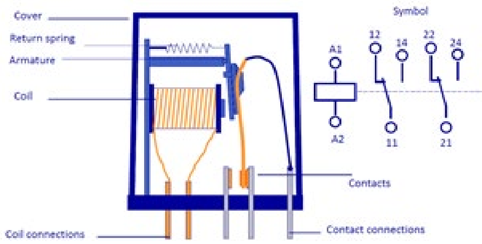

Figure 10: Relay [6].

3.4.1 Direct vs Indirect Relay Operation

Referring to Figures 11 and 12:

- The control circuit and main circuit operate with different voltages (such as 24 V and 230 V).
- The current through the coil of the directional control valve exceeds the permissible current for the pushbutton (such as where the current through the coil is 0.5 A and the permissible current through the pushbutton is 0.1 A).
- Several valves are operated with one pushbutton or one control switch.

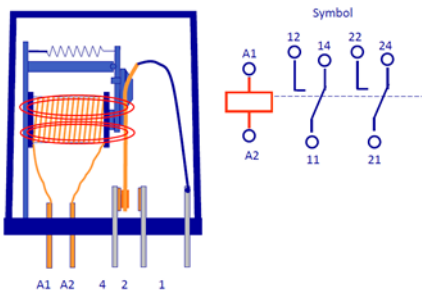

Figure 11: Energized relay illustration with magnetic field (Normally opened). [6].

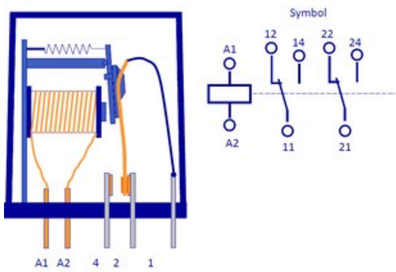

Figure 12: Un-energized relay illustration_ no magnetic field (Normally opened). [6].

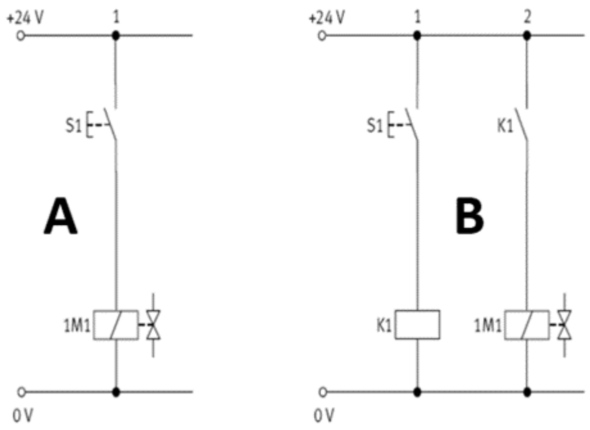

Figure 13: **A** illustrates direct operation; **B** illustrates indirect operation of solenoid valves [6].

3.4.2 Wiring Through Terminal

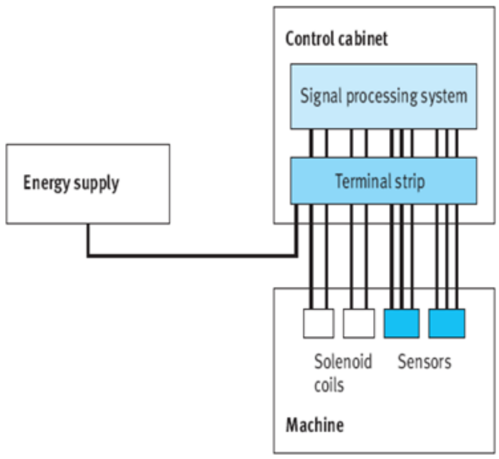

Figure 14: Single terminal connection. [6].

Referring to Figure 14:

- Cost effective setup (use of components that offer good optimization of the schematic diagram with respect to wiring complexity, use of components with a reduced number of connections).
- Easy fault finding (clear, easy to understand and precisely documented wiring). Quick repair.
- Quick repair (easy replacement of components by means of clamped or plug connections, no soldered-on components).

4. Testing and Modification of the Design

4.1 Lifting and Lowering of Load Circuit Illustration

This is done as follows:

a) The system consists of four double acting hydraulic lifting cylinders. Therefore, each hydraulic (linear) cylinder in four lifting cylinders will exert ¼ of 30-ton load capacity. Only one double acting hydraulic cylinder will be analyzed since all cylinders will be experiencing same force simultaneously when lifting and lowering loads.

b) Again, the new design system consists of two double acting cylinders to perform extraction and retraction enabling the system to be adjustable. Therefore, its retraction and extraction process are the same as for the lifting cylinders and they are explained below.

4.2. Relay-based Electro-hydraulic Systems

In the electrical actuation of a hydraulic valve, the necessary actuating force is obtained electrically with the help of a solenoid. The off-centre core of the solenoid coil is pulled towards the center of the coil when the electric current is passed through it. This discrete movement of the core is used to actuate the solenoid valve. The solenoid valve in an electro-hydraulic system acts as an interface between the hydraulic part and the electrical part of the system.

4.2.3 Indirect control of a double-acting hydraulic cylinder using a relay.

Two positions of a self-explanatory electro-hydraulic circuit for the indirect control of a double-acting hydraulic cylinder are given in Figure 15.

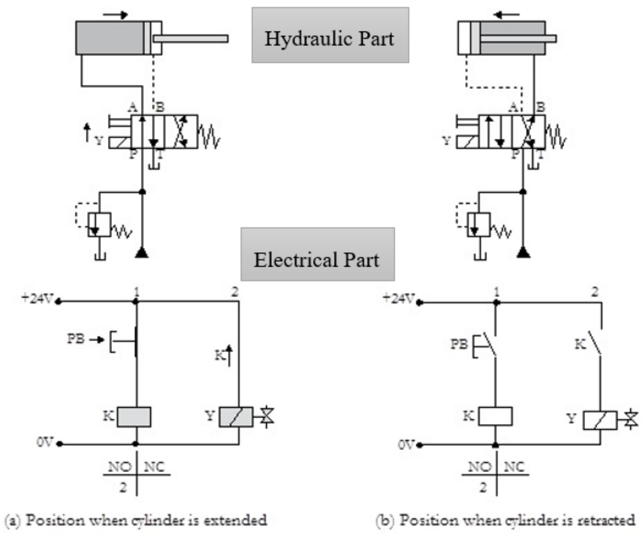

Figure 15 - Indirect control of a double-acting hydraulic cylinder using a relay [7].

4.2.4 Direct Control of a Double-acting Hydraulic Cylinder

Two positions of a self-explanatory electro-hydraulic circuit for the direct control of a double-acting cylinder are given in Figure 16. You may take a serious look at the circuit for the proper understanding of the electro-hydraulic system.

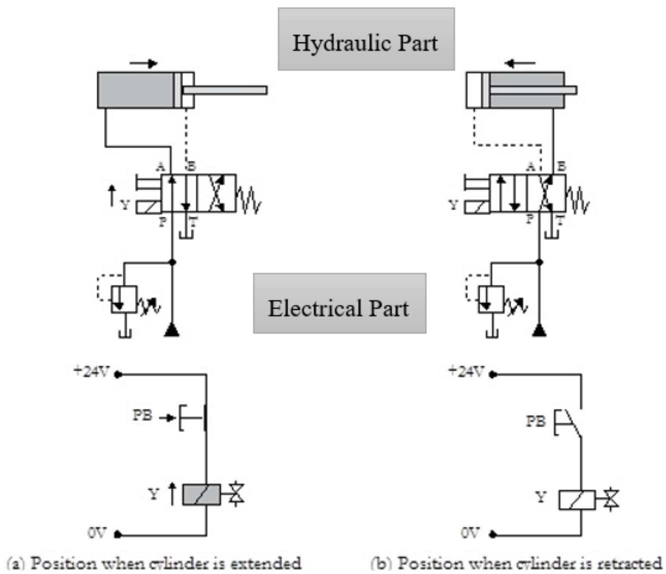

Figure 16 - Direct control of a double-acting hydraulic cylinder [7].

A) Solenoid Valve Functionality

In the normal position of the solenoid valve, the pressure port P is connected to the working port B, and the working port A is connected to the tank port T. The valve is actuated when the rated voltage is applied to the coil Y. In the actuated position of the valve, the port P is connected to the port A, and the port B is connected to the port T, Figure 17. When supply to the coil is cut off, the valve returns to its normal position. This valve can be used as the final control element for controlling a double-acting cylinder.

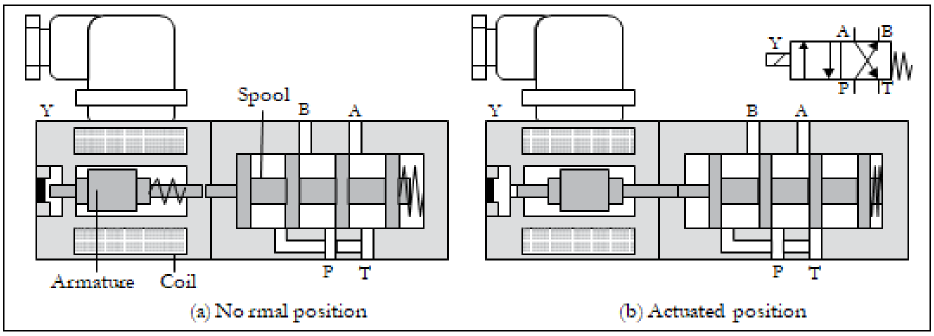

Figure 17 - 4/2-way Single-solenoid Valve, Spring Return [7].

5. Output Feedback Controller Design of Hydraulic Actuator Systems

The new system design consists of a hydraulic unit, a 486/66- based PLC equipped with a Metrabyte M5312 quadrature incremental encoder card and a DAS-16 analog/digital (AID) conversion card and, an external force source facility (as shown in figure 90 & 91). The pump provides constant operational supply pressure up to 300 MPa. The hydraulic valve is a low-cost closed-center four-way proportional valve. The positioning of the valve spool is based on the pulse width modulation principle. Load is used as an environment. Three pressure transmitters read the pump, supply line, and return line pressures with ±l% accuracy. An incremental encoder with sensing resolution of 0.06 mm reads the displacement of the cylinder piston. The control signal generated by the control algorithm is converted to an analog signal by the AID card and is transmitted to the hydraulic valve amplifier, as shown in Figure 18.

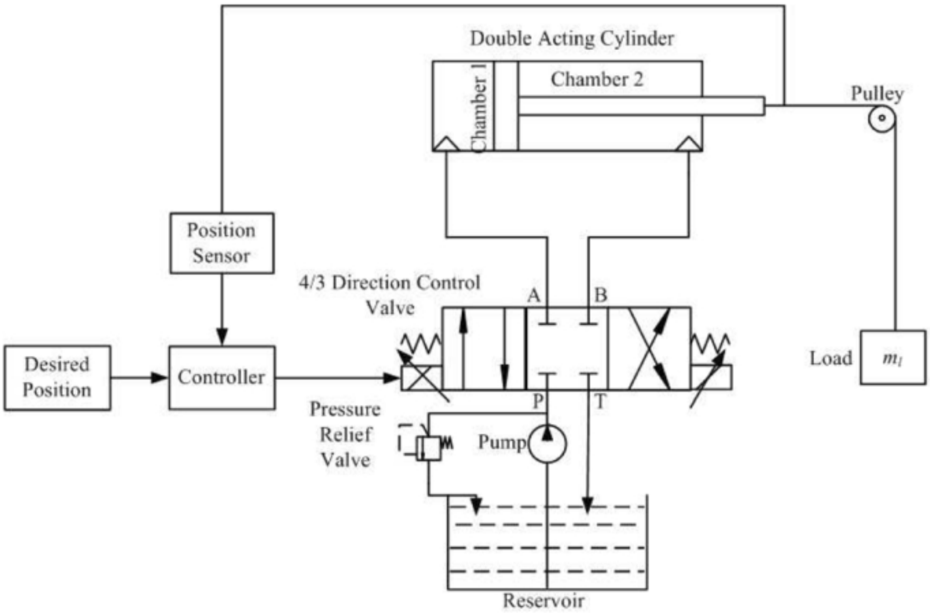

Figure 18 - Output feedback controller design of hydraulic actuator systems [8].

5. Conclusion

The new system has been designed and will consist of 4-double acting hydraulic cylinders responsible for lifting, 2-double acting hydraulic cylinders that will expand the system making it adjustable, a hydraulic steering cylinder for steering and 4 - hydraulic motors that will drive the system from point A to point B. Electric hydraulic components selection for new design system has been conducted. Through this paper and its analysis, it is proven that the use of internal combustion engines in heavy duty handling systems that are operated within indoor manufacturing factories and/or internal logistics can be eliminated and replaced with an eco-friendly electric hydraulic systems technology [3-5].

The use of 16-ton forklift trucks within indoor manufacturing industries poses health dangers to employees since the exhaust fumes of an internal combustion engine are toxic and has the economic effects of Carbon Monoxide (CO) poisoning. Carbon monoxide (CO) is odourless, tasteless, colourless, non-irritating and cannot be detected by any of the human senses. Because it cannot be detected, employees can be exposed to very high levels without realizing there is a problem. Therefore, the compilation of this document is aimed at designing a new handling system that will be hydraulically operated and powered by an electrical source (e.g. battery, motor etc.). In coming up with the system, it is believed that it will lower the rate of Carbon Monoxide (CO) exposure and thus the cost of workers compensation claims in South Africa.

Therefore, this new system design promotes Occupational Health and Safety of people working in industrial areas where Bulk Material Handling systems are in place.

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Biographies

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Dr Daramy Vandi Von Kallon is a Sierra Leonean holder of a PhD degree obtained from the University of Cape Town (UCT) in 2013. He holds a year-long experience as a Postdoctoral researcher at UCT. At the start of 2014 Dr Kallon was formally employed by the Centre for Minerals Research (CMR) at UCT as a Scientific Officer. In May 2014 Dr Kallon transferred to the University of Johannesburg as a full-time Lecturer and later a Senior Lecturer in the Department of Mechanical and Industrial Engineering Technology (DMIET). Dr Kallon has more than twelve (12) years of experience in research and six (6) years of teaching at University level, with industry-based collaborations. He is widely published, has supervised from Masters to Postdoctoral and has graduated seven (7) Masters Candidates. Dr. Kallon's primary research areas are Acoustics Technologies, Mathematical Analysis and Optimization, Vibration Analysis, Water Research and Engineering Education.